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(54) Titre : PROCEDE ET SYSTEME D'UTILISATION D'UNE SOURCE D'ENERGIE A TEMPERATURE RELATIVEMENT BASSE
(54) Title: METHOD AND SYSTEM FOR THE UTILIZATION OF AN ENERGY SOURCE OF RELATIVELY LOW TEMPERATURE

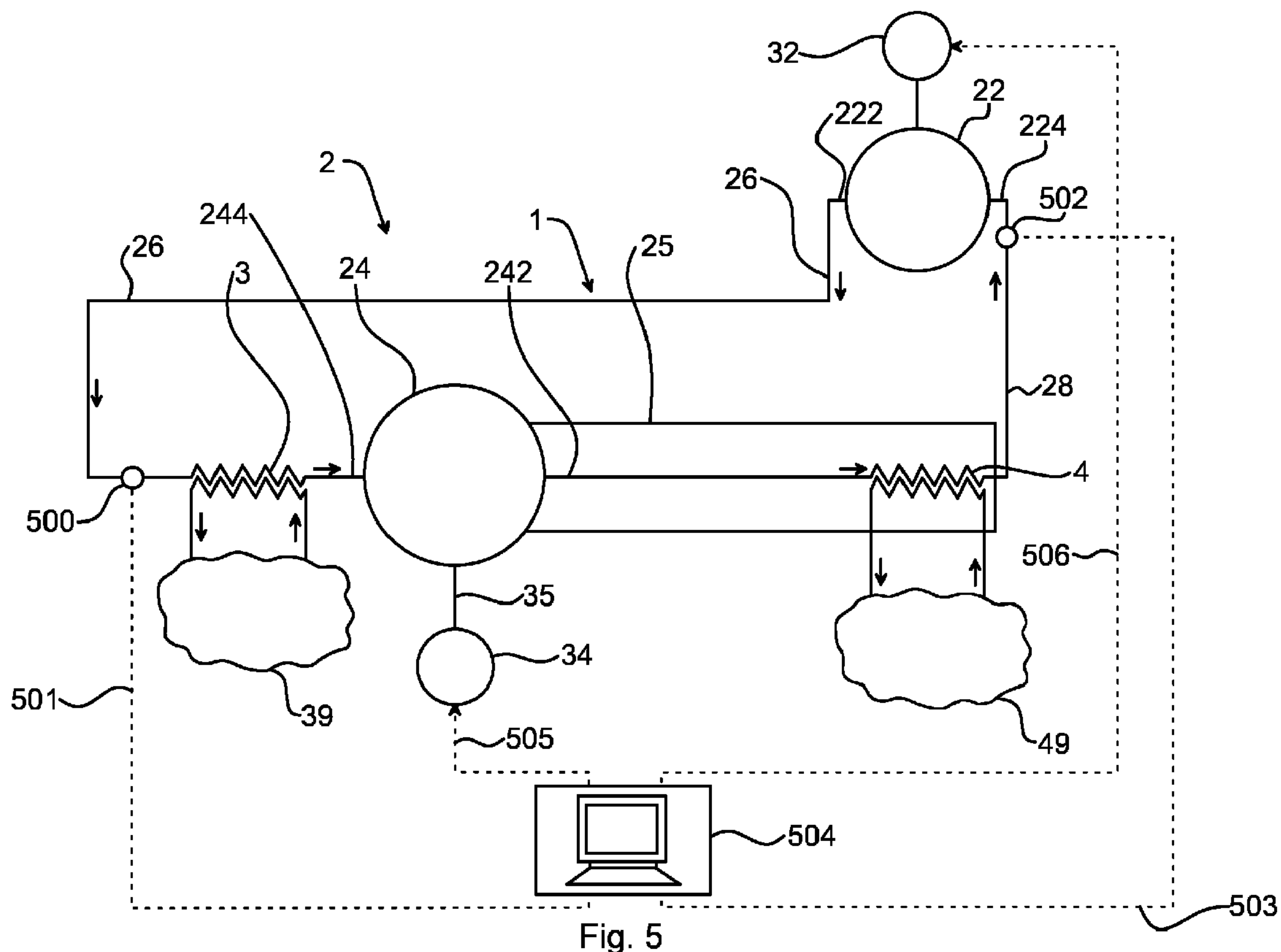


Fig. 5

(57) Abrégé/Abstract:

A method of extracting energy from an external heat source. The method comprises the steps of: a) compressing a medium in the liquid phase using an external power source to obtain a compressed liquid medium; b) heating the compressed liquid medium from



(57) **Abrégé(suite)/Abstract(continued):**

step a) using heat at least partly derived from the external heat source to expand the medium and obtain it in the supercritical state; c) reducing the pressure of the heated medium from step b) to a controlled degree by applying a variable load to generate electric power of a frequency; d) converting the frequency of step c) to a desired output frequency; and e) reducing the temperature and volume of the medium from step c) to obtain the medium in the liquid phase for recycling to step a), wherein the degree of compression in step a) is controlled independently of the load applied in step c). A corresponding system is also provided.

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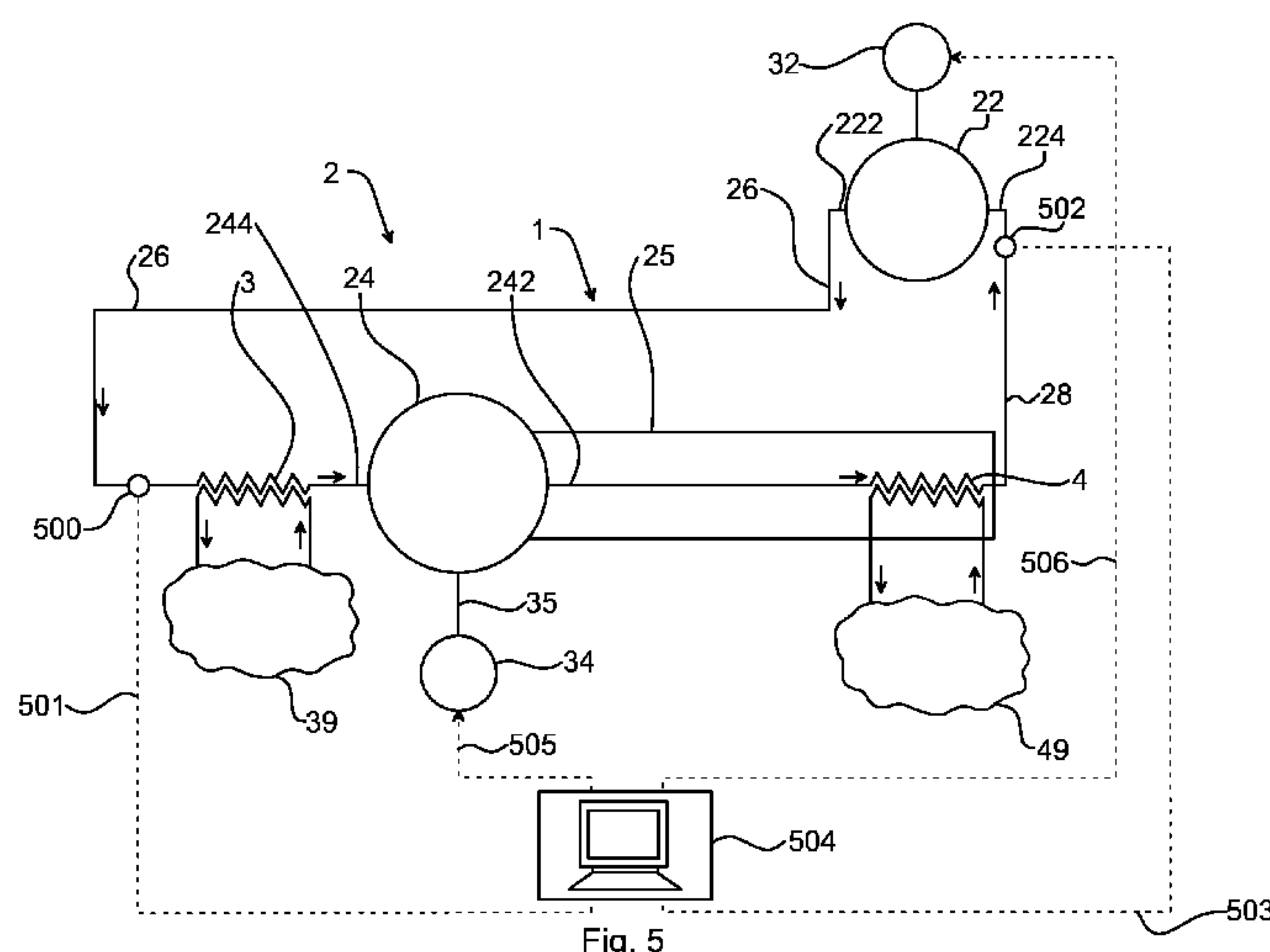


Fig. 5

(57) Abstract: A method of extracting energy from an external heat source. The method comprises the steps of: a) compressing a medium in the liquid phase using an external power source to obtain a compressed liquid medium; b) heating the compressed liquid medium from step a) using heat at least partly derived from the external heat source to expand the medium and obtain it in the supercritical state; c) reducing the pressure of the heated medium from step b) to a controlled degree by applying a variable load to generate electric power of a frequency; d) converting the frequency of step c) to a desired output frequency; and e) reducing the temperature and volume of the medium from step c) to obtain the medium in the liquid phase for recycling to step a), wherein the degree of compression in step a) is controlled independently of the load applied in step c). A corresponding system is also provided.

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Title

Method and system for the utilization of an energy source of relatively low temperature

Technical field

5 The present disclosure relates to energy extraction, e.g. from a low-temperature energy source such as exhaust gas or water. In some embodiments, the invention relates to a closed heat engine system containing a medium, which in a first part of the system is in a sub-critical phase and in a second part of the system is in a supercritical phase, and where the system
10 comprises a turbine to which the medium is supplied in its super-critical phase.

Background

Substances change phases according to the prevailing temperature and pressure. A familiar example is water, which at a pressure of 1 bar is a solid (i.e. ice) at a temperature below 0°C, a liquid at temperatures between 0 and
15 100 ° C, and a gas (vapor) when temperature is over 100 ° C. Heating a substance in a given phase requires a certain amount of energy per degree of temperature increase, while considerably more energy is required to bring the substance from one phase to another even though temperature does not increase. An illustrative example is water. A temperature increase of 1 K
20 (Kelvin) in ice requires 2.05 J/g. Phase transition from ice to water requires 334 J/g. A temperature increase of 1 K in water requires 4.18 J/g. The phase transition from water to steam requires 2257 J/g. Temperature increase of 1 K in the steam requires 2.08 J/g at 100 ° C.

Phase transition is dependent on ambient temperature and pressure and is
25 characteristic for each substance. This is presented visually in a (P, T) phase diagram well known within the art. Each substance is also characterized by its critical temperature and critical pressure, the so-called critical point. When both pressure and temperature are greater than their respective critical value, the substance enters a condition known as a super-critical fluid. Phase
30 transition between liquid and gas ceases and there is no related phase transition energy. In this state, the substance has both liquid and gas characteristics. It behaves like a gas as it will fill a container homogeneously, while it weighs only slightly less than its own weight in liquid phase. The super-critical point for water is for a pressure of 22.064 MPa (218 atm, 221 Bar) and

a temperature of 304 °C. In comparison, the critical point for CO₂ is a pressure of 7.380 MPa (72.8 atm, 73.8 Bar) and a temperature of 31.04 °C.

When a traditional Rankine Cycle comprising a steam turbine is employed, the temperature differential should be as big as possible; both to avoid drops of water to condense inside the delicate and high-speed rotating steam turbine, and to build as much thermo-dynamic energy into the steam as possible. The trend on e.g. concentrated solar power energy plants is to increase the steam temperature, and a temperature of 400-500 °C is often used. But also lower temperature systems using steam temperatures as low as 200-300 °C requires a heat source having a higher temperature to operate.

After the steam has been condensed in the condenser, the temperature is so low compared to the water fed into the boiler that it cannot be efficiently used to heat the inlet water. And it cannot be utilized to build temperature into the steam.

Both these effects are contributors to the inherent limitation of efficiency for the rankine based steam heat engines.

In thermal power plants using either fossil fuels such as coal or oil, or a radioactive source, energy is used to convert water into steam. Steam drives the steam turbine which drives generators to produce electrical energy. After the steam has flowed through the steam turbine, it is condensed to water and returned to heating. As mentioned above, the phase transition from water to steam requires a significant amount of energy. This same amount of energy is released when steam condenses back to water. In thermal power plants, little of the condensation energy can be re-used, and a large part of it is instead expelled with cooling water. This constitutes a significant waste of energy.

For refrigeration, air conditioning and heat pumps, a medium that undergoes a cycle between liquid and gas is used. Besides conventional refrigerants such as R-12 and R-22 also known as freon, it is known to use R-134a, ammonia or CO₂ as the refrigerant.

In a traditional heat pump, energy is obtained from a heat source at a rather low temperature. The heat pump evaporator is connected to the heat source, and under the pressure and temperature conditions prevailing in the evaporator, the medium in the heat pump has a boiling temperature that is lower than the temperature of the heat source. The medium is supplied with

energy in the evaporator. The evaporator is thus the heat pump energy collector and it is located upstream of the heat pump compressor. The compressor increases temperature and pressure in the medium vapor phase. In the heat pump condenser, the medium is cooled and goes from gas to liquid phase. There, the condensation heat is released to a heat sink in connection with the condenser. As an example, a heat pump heats consumption water or water in water-borne heating systems by harnessing energy in air, soil or water. The energy efficiency (or coefficient of performance) of a heat pump, which often is a factor of 3-4, depends on the temperature difference between the heat source and the heat sink. The same principle is applied in air-conditioning systems, cooling and freezing systems.

It is known in the field to use CO₂ as refrigerant in heat pumps where the CO₂ in parts of the heat pump is in a sub-critical phase and in other parts is in a super-critical phase. This is described as a trans-critical cycle. Patent publications WO90/07683, U.S. 6,877,340 and U.S. 7,674,097 describe such heat pumps. In these, the compressor is used to bring CO₂ into a supercritical phase. For these heat pumps to work, the CO₂ must be brought to sub-critical phase before reaching the heat absorber. In the heat absorber, CO₂ is heated, but remains in the subcritical phase. CO₂ is brought to subcritical phase before the heat absorber by means of a reducing valve as described in WO90/07683, or a so-called expander as described in U.S. 6,877,340 and U.S. 7,674,097. In the expander the volume is increased from the inlet to the outlet. The medium volume increases and the pressure decreases. CO₂ is thus brought to a subcritical phase before reaching the heat absorber. U.S. Patent 6,877,340 and U.S. 7,674,097 teach how an expander can be utilized to reduce energy consumption in the heat pump by partly driving the compressor by means of a shaft driven by the expander, or by driving an auxiliary compressor thanks to the expander. U.S. 6,877,340 also teaches that the expander can drive a generator to produce electrical energy.

Energy in solid wastes can be exploited by incineration to produce steam that can be used for industrial purposes, or to produce electricity in the same way as in a thermal power plant. Energy can also be used to heat water to be distributed in district heating networks. As is known from shipping, energy from exhaust gases can also be used to heat water.

Electrical energy has long been considered to be the most versatile form of energy, and efforts to turn the energy from wind, waves, tides and sunlight into

electricity have been considerable and fruitful. However, there is also considerable energy in the form of media not hot enough to produce steam, and it would be a great advantage to be able to produce electricity out of them.

Summary of the invention

5 The inventors have realized that it is important to be able to control/balance the pressure in various positions in/segments of the system in order to efficiently convert the heat from a medium of relatively low-temperature. That is, the pressure control should be achieved without substantial energy losses.

US3971211 discloses a system in which CO₂ is pressurized, heated with
10 energy from an external source, expanded over two turbines in series, cooled and returned for pressurization. The CO₂ is pressurized by means of a pump that is driven by the first turbine. This means that degree of compression in the pump is determined by the amount of heat supplied upstream the turbine and the degree of cooling downstream the turbine. Consequently, the means of
15 controlling the system of US3971211 are limited. Further, it will many times be impractical, if not impossible, to control the degree of heating and cooling, respectively in an industrial setting. To run the system of US3971211 it is probably necessary to install several valves controlling the flow and pressure of the medium, e.g. upstream the respective turbines. Such valves would
20 waste energy and thus decrease the efficiency of the system.

An example of system having such valves is disclosed in US 2009/0266075. In the system, liquid CO₂ is pressurized by a pump and transferred to a storage. Further, CO₂ from the storage is heated with an external heat source,
expanded in an "expansion machine", liquefied and returned to the pump. A
25 valve is arranged between the heating and the expansion, probably to control the pressure during the heating. Part of the energy taken up by the medium in the heating step will thus be wasted before the turbine. Further, the flow through the system appears to be controlled by controlling the supply of pressurized CO₂ to the heating step from the storage. This requires the use of
30 further valves, which further reduces the net efficiency of the system. Also, the storage requires bulky equipment which is expensive.

The present disclosure provides a heat engine system for extracting energy from an external heat source, comprising:

35 a pump for compressing a liquid medium to obtain a compressed liquid medium, said pump comprising an inlet, an outlet and an external motor

capable of controlling the degree of compression of the liquid medium in the pump;

a heating arrangement connected to the external heat source for heating and expanding the compressed liquid medium to obtain the medium in the supercritical state, said heating arrangement comprising an inlet connected to the pump outlet and an outlet;

a turbine for generation of mechanical work from the medium from the heating arrangement, said turbine comprising an inlet connected to the heating arrangement outlet and an outlet;

a electricity generator connected to the turbine, said electricity generator being capable of controlling the load of the turbine such that the pressure upstream of the turbine may be controlled;

a frequency converter connected to the electricity generator; and

a cooling arrangement for reducing the temperature and volume of the medium, said cooling arrangement comprising an inlet connected to the turbine outlet and an outlet connected to the pump inlet,

wherein the compression in the pump is controllable independently of the load of the turbine.

Further, there is provided a method of extracting energy from an external heat source, comprising the steps of:

a) compressing a medium in the liquid phase using an external power source to obtain a compressed liquid medium;

b) heating the compressed liquid medium from step a) using heat at least partly derived from the external heat source to expand the medium and obtain it in the supercritical state;

c) reducing the pressure of the heated medium from step b) to a controlled degree by applying a variable load to generate electric power of a frequency;

d) converting the frequency of step c) to a desired output frequency;

e) reducing the temperature and volume of the medium from step c) to obtain the medium in the liquid phase for recycling to step a),

wherein the degree of compression in step a) is controlled independently of the load applied in step c).

In the above system, the pump is not driven by a turbine arranged in the system as in US3971211. Instead, the pump is driven by an external motor and the degree of compression in the pump may be controlled independently of the work generated by a turbine in the system. The motor of the present

disclosure is typically a variable frequency drive motor capable of driving the pump at a desired speed. Thus, no energy-wasting valves are needed to control the flow to the step where the medium is heated by the external heat source.

5

Further, the load in turbine and thereby the pressure drop over the turbine is controlled by an electricity generator connected to the turbine, typically (but not necessarily) via a turbine shaft. The load may thus be controlled to obtain a pressure balance in the system that matches the heating capacity in the heating step and the cooling capacity on the cooling step.

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For example, the medium is pumped upstream the heating step and the flow of the medium is restricted downstream the heating step such that an overpressure is obtained in the heating step. In prior art systems, an energy wasting valve is arranged downstream the heating system to restrict the flow. In the present disclosure, the turbine and generator arrangement is instead adapted to variably restrict the flow and thereby control the pressure in the heating step without wasting energy.

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In the system of the present disclosure, it is also possible to restrict the pressure drop over the turbine such that the pressure of medium never falls below its supercritical pressure. Accordingly, it is possible to reduce the amount of energy consumed by the motor of the pump to reach the pressure desired for the heating step.

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A consequence of the variable load in the turbine is that the frequency of the electricity generated will not always match the desired output frequency. Therefore, a frequency converter is connected to the electricity generator. In contrast, traditional turbines are set to a fixed frequency that matches the desired output frequency.

30

A principal difference between most prior art disclosures and the present disclosure is that an expansion of the medium is used to generate the work producing electricity in the prior art, while the present disclosure relies on a pressure reduction of the medium with minimal expansion to generate work and electricity. The uncontrolled expansion in the prior art disclosures normally results in a temperature of the medium after the turbine that is so low that its energy cannot be recovered. However, the medium from the turbine of the

35

present disclosure may for example be used for heating the pressurized medium from the pump (internal heating) or a medium of a district heating system (external heating).

- 5 The system of the present disclosure may be liken to a hydraulic system wherein the expansion of the medium during the heating is controlled and utilized by the turbine, which has an hydraulic capacity that corresponds to volume of the medium after the expansion, and the pump has an hydraulic capacity that corresponds volume of the medium before the expansion.

10 **Figures**

Figure 1 shows a schematic piping diagram of a heat engine system according to a first embodiment.

Figure 2 shows a schematic piping diagram of a heat engine system according to a second embodiment.

- 15 Figure 3 shows a schematic piping diagram of a heat engine system according to a third embodiment.

- Figure 4 shows a phase diagram for carbon dioxide, in which the x-axis represents the temperature (K) and the y-axis represents the pressure (bar). The cycle to the left in the figure illustrates the inventive method, while the cycle to the right in the figure illustrates an alternative configuration of the
20 inventive method.

Figure 5 shows a schematic piping and control diagram of a heat engine system according to a fourth embodiment.

Detailed Description

- 25 As a first aspect of the present invention, there is thus provided a method of extracting energy from an external heat source, comprising the steps of:
- a) compressing a medium in the liquid phase using an external power source to obtain a compressed liquid medium;
 - b) heating the compressed liquid medium from step a) using heat at least
30 partly derived from the external heat source to expand the medium and obtain it in the supercritical state;

- c) reducing the pressure of the heated medium from step b) to a controlled degree by applying a variable load to generate electric power of a frequency;
d) converting the frequency of step c) to a desired output frequency;
e) reducing the temperature and volume of the medium from step c) to
5 obtain the medium in the liquid phase for recycling to step a),
wherein the degree of compression in step a) is controlled independently of the load applied in step c).

In step a), the medium is thus maintained in the liquid phase, and
10 subsequently, in step b), it is transformed to a supercritical fluid by heating it above the critical point. The compression of step a) is thus performed to such an extent that the medium can become supercritical during the heating of step b). When the medium becomes supercritical during step b), its volume increases. During step c), the pressure drop, which is controlled by the applied
15 load, is recovered as electrical energy. Thus, the pressure may be dropped to a predetermined level and the expansion of the medium may be restricted. In practice, step c) is normally performed by a turbine connected to an electricity generator, which is capable of controlling the load applied in the turbine. In step e), the volume is decreased. In order to prevent or at least minimize a
20 transition of the medium to the gas phase, it is advantageous to perform step e) as soon as possible after the pressure reduction and energy extraction of step c). In practice, one or more heat exchangers for performing step e) may therefore be directly connected to an outlet of a turbine performing step c). The compression of step a) is preferably performed using a pump driven by
25 motor capable of controlling the degree of compression of the liquid medium. The pump may thus have a frequency-controlled electric drive.

In an embodiment, the medium is compressed in several, such as two, three or four, stages. In such an embodiment, the medium may be heated between
30 two compression stages. Accordingly, the heating of the medium may also be performed in several stages with intermediate compressions of the medium. All such embodiments are encompassed by the present disclosure as long as it is a heating and not a compression that finally causes the transition of the medium to the supercritical state.

35 Likewise, in an embodiment the pressure reduction is performed in several, such as two, three or four stages. In such an embodiment, the medium may be cooled between two pressure reduction stages, e.g. to prevent a transition of

the medium to the gas phase. Accordingly, the step of reducing the pressure and volume of the medium may be performed in several, such as two, three or four, stages with intermediate pressure reductions of the medium.

5 The method may further comprise sensing the pressure between steps a) and c) and controlling the load of step c) and/or the degree of compression of step a) at least partly depending on the sensed pressure. The skilled person understands that “between steps a) and c)” in this context refers to downstream step a), but upstream step c).

10 Also, the method may further comprise sensing the pressure between steps c) and a) and controlling the load of step c) and/or the degree of compression of step a) at least partly depending on the sensed pressure. The skilled person understands that “between steps c) and a)” in this context refers to
15 downstream step c), but upstream step a).

Preferably, the two examples are combined such that load of step c) and/or the degree of compression of step a) is/are controlled depending on both the pressure sensed between steps a) and c) and the pressure sensed between
20 steps c) and a).

In an embodiment, the sensed pressure(s) are compared to (a) reference value(s) and the load and/or degree of compression is controlled according to the result of the comparison. For example, if the pressure of the medium in a
25 position downstream of the turbine is below a first reference pressure, such as the critical pressure of the medium, the turbine may be controlled to increase the pressure on its downstream side to at least the first reference pressure. One reason for stopping the pressure from falling below the critical pressure is to avoid a transition of the medium to the gas phase. Likewise, if the pressure
30 of the medium in a position downstream of the turbine is above a second reference pressure, the turbine may be controlled to decrease the pressure on its downstream side to a pressure below the second reference value by increasing the load, which results in that more electricity may be generated.

35 Also, the compression in the pump and the load in the turbine may be controlled to reach a target pressure for the position upstream of the turbine and the position downstream of the turbine, respectively. In turn, the target

pressures may depend on the amount of external heating and/or cooling capacity available.

Thus, a sensed pressure between steps a) and c) may be compared to a first target pressure and the compression and/or load may adjusted to reduce the difference between the sensed pressure and the first target pressure.

Concurrently, the sensed pressure between steps c) and a) may be compared to a second target pressure and the compression and/or load may adjusted to reduce the difference between the sensed pressure and the second target pressure.

Further parameters of the medium may also be measured and the measured values may be used in the control of the method. For example, the volumetric flow rate of the medium may be measured with (a) flow meter(s) between steps a) and b), between steps b) and c), between steps c) and e) and/or between steps e) and a). Also, the temperature of the medium may be measured with (a) temperature sensor(s) between steps a) and b), between steps b) and c), between steps c) and e) and/or between steps e) and a). The measured volumetric flow rate and/or temperature value(s) may also, e.g. after comparisons with reference values, be used for controlling the system, e.g. the degree of compression of the medium in step a), the load in step c), the flow rate/supply of an external heating medium (from the external heat source) to the heating of step b) and/or the flow rate/supply of a external cooling medium to the cooling of step e).

In prior art energy extraction methods, a liquid medium is often transformed to a gas. This transformation requires a lot of energy (due to the enthalpy of vaporization), which can only be recovered to a small extent later in the method. According to the method of the present disclosure, energy is extracted without any substantial vaporization of the medium, and the heat from an external energy source, in particular a low-temperature energy source, may be effectively utilized. Thus, in some embodiments of the invention, the temperature of the external energy source is less than 150°C, such as less than 100, 90, 80, 70, 60, 50, 40 or 30°C.

In embodiments of the invention, heat recovered from step e) may be used for heating the compressed liquid. This may be accomplished in a direct and/or indirect manner. That is, heat from the medium from step c) may be

transferred to the compressed liquid from step a) in a heat exchanger and/or a cooling medium circuit may be employed. When the cooling medium circuit is employed, step e) comprises heating the cooling medium to obtain a heated cooling medium and step b) comprises heating the compressed liquid medium using the heated cooling medium to obtain a cooled cooling medium which is recycled to step e). Consequently, the heat exchanger and/or the cooling medium circuit is/are part of both the heating of step b) and the cooling of step e).

10 The use of heat recovered during the step e) for the heating of step b) increases the efficiency of the method.

The cooling medium circuit may involve heat pumping in a conventional manner. Consequently, the heated cooling medium from step e) may be compressed before it is used for heating the compressed liquid medium in step b) and the cooled cooling medium from step b) may be expanded before it is recycled to step e). If heat pumping is employed in the cooling medium circuit, the internally recovered energy may be supplied to the heating step as a high-temperature medium, which increases the efficiency of at least some of the embodiments of the inventive method.

In step b), heat from one or more of the following sources may thus be supplied:

- the medium from step c) (direct internal heating);
- 25 -the heated cooling medium (indirect internal heating); and
- the external heat source.

For example, the compressed medium from step a) may first be heated with internal heat and then with the external heat. If both direct and indirect internal heating is performed, the compressed medium from step a) may be heated with the direct internal heat before it is heated with the indirect internal heat. An example of such a set-up is shown in figure 3.

However, heat recovered from the cooling step may also be recovered for an external use. For example, step e) may comprise the heating of a medium (e.g. water) for a district heating system. This embodiment is particularly attractive when the method is performed close to a city having a suitable

infrastructure including such a district heating system..

Exhaust gases and industrial cooling medium (e.g. cooling water) are examples of external heat sources that may be employed in step b), in particular if the method is performed close to an industrial site or plant.

Electricity produced by the method of the present disclosure may in such case be supplied back to the site or plant. Other examples of external heat sources are a medium (e.g. water) heated by a solar collector and geothermal heat sources. Yet other examples are ground water, sea water and fresh water.

The external heat source of the inventive method may also be a medium heated by a heat pump utilizing any of the above-mentioned heat sources.

This alternative may be particularly interesting if the available heat source is ground water, sea water or fresh water, since such heat sources may be available in large quantities but normally has a relatively low temperature.

Ground heat is another example of such a low-temperature heat source. However, the external heat source may also, in some embodiments, be a high-temperature heat source, such as an open flame. The open flame may be provided by combustion of a suitable fuel, such as coke, petroleum, waste or organic material. Thus, the external heat source may be an incineration process. Also, the external heat source may be a radiation source.

In some embodiments of the inventive method, the temperature of the external heat source is at least 5 °C higher, such as at least 10 °C higher, than the critical point for the medium at the prevailing pressure when the heat from the external heat source is supplied. Consequently, the temperature of the external heat source is sufficient for transforming the compressed medium to the supercritical phase. This is however not a requirement; the temperature of the external heat source may actually be below the critical point in question if internally generated heat of a higher temperature (e.g. after heat pumping, see above) is supplied after the external heat.

Various mediums may be used in the inventive method. Examples of preferred mediums are carbon dioxide (CO₂), ethylene (C₂H₄), diborane (B₂H₆), ethane (C₂H₆) and nitrous oxide (N₂O). Carbon dioxide is particularly preferred as it is abundant and has a relatively low toxicity. Further, the temperature of the critical point of the CO₂ is 31 °C allowing heat sources having a relatively low temperature, such as 35-125 °C or 45-100 °C, to be employed.

The pressure reduction during step c) may for example be controlled so as to balance the pressure in the method. This may be achieved by controlling the load of a turbine employed for step c) (see below). In some embodiments, the method comprises one or more further step(s) of increasing or decreasing the pressure for balancing purposes. Consequently, it is not a requirement that the pressure increase of step a) equals the pressure decrease of step c).

If carbon dioxide is employed, the pressure may for example be increased by 30-110 bar during step a). Accordingly, the pressure drop during step c) may for example be 30-110 bar. The inventor has found that some compression ranges are particularly beneficial from a thermal efficiency standpoint for some temperatures of the external heat source when the medium is carbon dioxide. Thus, in some embodiments of the inventive method, the pressure of the liquid medium is increased by:

35-55 bar, such as 40-50 bar, if the temperature of the external heat source is 35-65 °C;
45-65 bar, such as 50-60 bar if the temperature of the external heat source is 66-75 °C;
55-75 bar, such as 60-70 bar if the temperature of the external heat source is 76-95 °C; and
65-105 bar, such as 70-100 bar if the temperature of the external heat source is 96-125 °C.

In step c), a pressure difference is maintained. Thus, in embodiments of the inventive method, a device capable of doing so, such as a positive displacement turbine or a reversed centrifugal pump, is employed for step c).

However, any device which has got a substantially leakage free barrier between the inlet and the outlet, and which can be controlled by a variable load, can be used to control the pressure drop to a predetermined level during step c). The barrier can be implemented by design, or it can be created as an operational state, at which a barrier is formed. An example of the latter is the reversed centrifugal pump, which utilizes the inertia of the medium to build up barriers between the stator and the rotor, and thus between the inlet and the outlet.

In contrast to the normal behavior of a medium in a traditional turbine, the medium of the present disclosure is preferably not allowed to expand

extensively in the turbine. In embodiments of the present disclosure, the density of the medium is thus not decreased or decreased by less than 40 %, such as less than 30 %, such as less than 25 %, during step c).

5 Also, in order to facilitate an efficient internal heat exchange, the temperature of the medium is preferably not decreased in step c) to below a temperature which is 10 °C higher than that of the compressed medium from step a),

10 The steps of an embodiment of the inventive method are illustrated in the phase diagram for carbon dioxide showed in figure 4 (see the left cycle): step a) increases the pressure of the liquid carbon dioxide above the pressure of the critical point (the temperature is however still too low for the carbon dioxide to transform to the supercritical state); step b) increases the temperature of the carbon dioxide above temperature of the critical point such that it transforms to
15 a supercritical fluid (and expands); and steps c) and e) reduces the pressure and temperature (and volume) such that the carbon dioxide is obtained as a liquid again.

20 In an alternative configuration of the present invention, the medium is always in the supercritical state. The alternative configuration thus comprises the steps of: a') compressing the supercritical medium using an external power source to obtain a compressed liquid medium; b) heating and expanding the compressed supercritical medium from step a') using heat at least partly derived from the external heat source; c') reducing the pressure of the heated
25 supercritical medium from step b') by applying a variable load to generate electric power of a frequency; d') converting the frequency of step c') to a desired output frequency; e') reducing the temperature and volume of the supercritical medium from step c') and recycling it to step a'), wherein the degree of compression in step a') is controlled independently of
30 the load applied in step c').

35 The inventor has found that the expansion during the heating of a supercritical medium, such as supercritical carbon dioxide, is sufficient for efficiently extracting energy from an energy source. The fact that a cycle operating within the supercritical state would require higher temperatures of the external heat source is however a drawback of the alternative configuration in comparison with the invention defined in the appending claims. On the other hand, a

process according to the alternative configuration may be less complicated to control and thereby cheaper.

5 The steps of an embodiment of the alternative configuration are also illustrated in the phase diagram for carbon dioxide showed in figure 4 (see the right cycle). It can be seen that the medium (carbon dioxide) is supercritical in each stage of the cycle.

10 The skilled person understands how to adapt the teachings of the present disclosure to the alternative configuration, and the embodiments of the first and the second aspect described herein applies *mutatis mutandis* to the alternative configuration.

15 As a second aspect of the present invention, there is thus provided a heat engine system for extracting energy from an external heat source, comprising:

a pump for compressing a liquid medium to obtain a compressed liquid medium, said pump comprising an inlet, an outlet and an external motor capable of controlling the degree of compression of the liquid medium in the pump;

20 a heating arrangement connected to the external heat source for heating and expanding the compressed liquid medium to obtain the medium in the supercritical state, said heating arrangement comprising an inlet connected to the pump outlet and an outlet;

25 a turbine for generation of mechanical work from the medium from the heating arrangement, said turbine comprising an inlet connected to the heating arrangement outlet and an outlet;

a electricity generator connected to the turbine, said electricity generator being capable of controlling the load of the turbine such that the pressure upstream of the turbine may be controlled;

30 a frequency converter connected to the electricity generator; and

a cooling arrangement for reducing the temperature and volume of the medium, said cooling arrangement comprising an inlet connected to the turbine outlet and an outlet connected to the pump inlet,

35 wherein the compression in the pump is controllable independently of the load of the turbine.

The pump/compressor is adapted for compressing liquids. The skilled person is capable of selecting an appropriate device for the compression. The heating

arrangement may comprise one or more heat exchangers. For example, it may comprise at least one heat exchanger for transferring heat from the medium from the turbine to the medium from the pump, at least one heat exchanger for transferring heat from a heated cooling medium to the medium from the compressor and/or at least one heat exchanger for transferring heat from the external heat source to the medium from the compressor. The heat exchangers may be arranged in any order. It is however preferred that the heat exchanger connected to the heat source of the lowest temperature is arranged first (furthest upstream) and the heat exchanger connected to the heat source of the highest temperature is arranged last (furthest downstream). Also, the cooling arrangement normally comprises one or more heat exchangers. A heat exchanger may in some embodiments be shared by the heating arrangement and the cooling arrangement.

The cross-sectional area of the channels of the heat exchangers connected to the outlet of the turbine may be equal to or smaller than the cross-sectional area of the outlet of the turbine in order to prevent expansion (and transfer to the gas phase) of the medium.

The various embodiments of the method of the first aspect, and their corresponding benefits, apply *mutatis mutandis* to the heat engine system of the second aspect. However, some embodiments of the heat engine system are anyway discussed below.

The heat engine system may further comprise a pressure sensor arranged for sensing a pressure of the medium at a position upstream of the turbine and a control device arranged to receive the sensed pressure from the pressure sensor and control the load of the turbine and/or the degree of compression of the medium in the pump at least partly depending on the sensed pressure.

The skilled person understands that the “a position upstream of the turbine” in this context refers to a position upstream of the turbine, but downstream of the pump, such that the pressure in the heating arrangement can be determined.

The heat engine system may also further comprise a pressure sensor arranged for sensing a pressure of the medium at a position downstream of the turbine and a control device arranged to receive the sensed pressure from the pressure sensor and control the load of the turbine and/or the degree of compression of the medium in the pump at least partly depending on the

sensed pressure. The skilled person understands that the “a position downstream of the turbine” in this context refers to a position downstream of the turbine, but upstream of the pump. Thus, the position may for example be between the turbine and the cooling arrangement or between the cooling
5 arrangement and the pump.

The control device receiving the sensed pressure from the position upstream of the turbine is preferably, but not necessarily, the same as the control device receiving the sensed pressure from the position downstream of the turbine. A
10 common control device enables a more accurate and efficient control of the pressures in the whole system and thus provides for higher over-all efficiency in the energy extraction.

The control device(s) is/are normally operatively connected to the pressure
15 sensor(s) and the electricity generator (to control the load) and/or the external motor (to control the degree of compression), preferably via signal lines.

The heat engine system may also further comprise one or more flow meters and/or one or more temperature sensors. Such a meter or sensor may be
20 arranged to measure the volumetric flow rate or temperature of the medium in one or more of the following positions: between the pump outlet and the heating arrangement inlet; within the heating arrangement; between the heating arrangement outlet and the turbine inlet; between the turbine outlet and the cooling arrangement inlet; within the cooling arrangement; and
25 between the cooling arrangement outlet and the pump inlet.

The flow meter(s) and/or temperature sensor(s) may be operatively connected to the control device discussed above or to one or more other control device(s). The control device(s) may thus be arranged to receive the
30 measured volumetric flow rate(s) and/or temperature(s) and control the load of the turbine and/or the degree of compression of the medium in the pump at least partly depending on the measured volumetric flow rate(s) and/or temperature(s).

Further, control device(s) may also be arranged to control the supply of a
35 cooling medium to the cooling arrangement and/or the supply of a heating medium to the heating arrangement in response to the input data discussed above. Accordingly, the control device(s) may be operatively connected to first

valve arranged on a cooling medium supply line connected to the cooling arrangement and/or a second valve arranged on a heating medium supply line connected to the heating arrangement.

5 Thus, the control of the system may be even more refined, which allows for an even more efficient energy extraction.

An example of a turbine capable of generating mechanical work while maintaining the pressure difference between the upstream and the
10 downstream side of it is a volumetric turbine, such as a positive displacement turbine. In the volumetric turbine, the torque may be higher than in many other types of turbines and the speed of the turbine may be about equal to the volumetric flow rate of the medium. Another example is a reversed centrifugal pump, which utilizes the inertia of the medium to build up a pressure behind it.

15 The turbine is connected to an electricity generator, for example through a shaft of the turbine.

Preferred embodiments of the turbine are disclosed in the patent applications
20 NO20092085 and WO2008004880, which are incorporated herein by reference in their entirety. Consequently, the turbine of the present disclosure may be defined as in the any one of the claims of NO20092085/ WO2010137992 or WO2008004880.

25 In order to reduce the expansion of the medium in the turbine, the area of the outlet of the turbine may be less than 1.5 times the area of the inlet of the turbine. In some embodiments, the outlet area is less than 1.3 times, such as less than 1.1 times, the inlet area.

30 As mentioned above, the load (and thus the energy output) of the turbine is controllable. Consequently, the pressure drop of the turbine may be controlled by controlling the load, and the pressure in the different segments of the system may be balanced. In some embodiments, the system further comprises at least one pressure control device of known type, such as at least
35 one pressure reduction valve, arranged upstream and/or downstream of the turbine. The purpose of such a device is also to balance the pressure in the system. However, the skilled person understands that the use of such a device

may imply a loss in efficiency.

As mentioned above, the heat exchanger arrangement may in some
embodiments comprise a heat exchanger connected to the pump outlet and
the turbine outlet such that heat can be transferred from the medium from the
turbine to the compressed medium from the pump.

Further, the cooling arrangement may comprise a heat exchanger connected
to a cooling medium circuit. The cooling medium circuit may also be
connected to the heat exchanging arrangement such that the cooling medium
can be used for cooling in the cooling arrangement and heating in the heating
arrangement.

The cooling circuit may further comprise a cooling medium compressor and a
cooling medium expansion device, wherein the cooling medium compressor is
arranged downstream the cooling arrangement and upstream the heating
arrangement in the cooling circuit and the cooling medium expansion device is
arranged downstream the heat exchanging device and upstream the cooling
arrangement in the cooling circuit.

The inventive finding may also be described with the following itemized
embodiments. The various embodiments of the first and second aspect
described above as well as their benefits apply to the items below *mutatis
mutandis*.

1. Method of extracting energy from an external heat source, comprising
the steps of:
 - a) compressing a medium in the liquid phase to obtain a compressed
liquid medium;
 - b) heating the compressed liquid medium from step a) using heat at least
partly derived from the external heat source to expand the medium and obtain
it in the supercritical state;
 - c) reducing the pressure of the heated medium from step b) under the
extraction of energy;
 - d) condensing the medium from step c) to obtain the medium in the liquid
phase for recycling to step a).

2. Method according to item 1, wherein part of the heat supplied in the heating step b) is derived from the condensing step d).
3. Method according to item 2, wherein heat from the medium from step c) is transferred to the compressed liquid from step a) in a heat exchanger.
4. Method according to any one of the preceding items, wherein step d) comprises heating a cooling medium to obtain a heated cooling medium and step b) comprises heating the compressed liquid medium using the heated cooling medium to obtain a cooled cooling medium which is recycled to step d).
5. Method according to item 4, wherein the heated cooling medium from step d) is compressed before it is used for heating the compressed liquid medium in step b) and the cooled cooling medium from step b) is expanded before it is recycled to step d).
6. Method according to item 4 or 5, wherein step b) comprises:
b1) transferring heat from the medium from step c) to the compressed liquid from step a) in a heat exchanger;
b2) heating using heat from the heated cooling medium; and
b3) heating using heat from the external heat source.
7. Method according to any one of the preceding items, wherein step d) comprises heating water for a district heating system.
8. Method according to any one of the preceding items, wherein the external heat source is selected from exhaust gases, industrial cooling water, heated water from a solar collector, geothermal heat sources, ground water, sea water or fresh water.
9. Method according to any one of the preceding items, wherein the temperature of the external heat source is less than 100 °C.
10. Method according to any one of the preceding items, wherein the temperature of the external heat source is at least 5 °C higher, such as at least 10 °C higher, than the critical point for the medium at the prevailing pressure

when the heat from the external heat source is supplied.

11. Method according to any one of the preceding items, wherein the medium is selected from carbon dioxide (CO₂), ethylene (C₂H₄), diborane (B₂H₆), ethane (C₂H₆) and nitrous oxide (N₂O).

12. Method according to anyone of the preceding item, wherein the pressure reduction during step c) is controlled to balance the pressure in the energy extraction method.

13. Heat engine system for extracting energy from an external heat source, comprising:

a compressor for compressing a liquid medium to obtain a compressed liquid medium, said compressor comprising an inlet and an outlet;

a heat exchanging arrangement connected to the external heat source for heating and expanding the compressed liquid medium to obtain the medium in the supercritical state, said heat exchanging arrangement comprising an inlet connected to the compressor outlet and an outlet;

a turbine for generation of mechanical work from the medium from the heat exchanging arrangement while maintaining a pressure difference between the upstream and the downstream side of it, said turbine comprising an inlet connected to the heat exchanging arrangement outlet and an outlet; and

a condensing arrangement for condensing the medium from the turbine to a liquid, said condensing arrangement comprising an inlet connected to the turbine outlet and an outlet connected to the compressor inlet.

14. Heat engine system according to item 13, wherein the turbine is a positive displacement turbine or a reversed centrifugal pump.

15. Heat engine system according to item 13 or 14, wherein the turbine comprises a shaft and the electricity generator is mechanically connected to the turbine shaft.

Detailed description of example embodiments

In the drawings, reference number 1 refers to a heat engine system where a medium in a closed-loop and fluid-tight circuit 2 undergoes a transcritical

cycle. The closed-loop and fluid tight circuit 2 is provided with a pump or compressor 22, a turbine 24, a pipe 26 which is in fluid connection with the compressor outlet 222 and the turbine inlet 244, and a pipe 28 that is in fluid connection with the turbine outlet 242 and pump inlet 224. The medium flows
5 through circuit 2 in a direction indicated by arrows on the drawings.

In a first embodiment shown in Figure 1, part of the pipe 26 downstream of the pump 22 outlet 222 is provided with a heat exchanger 3. The heat exchanger 3 may have a first side in fluid contact with the circuit 2 and a second side arranged to contain a second medium, which may be different from the
10 medium in the closed circuit 2, in heat-exchanging indirect contact with the medium in the circuit 2. Heat exchanger 3 can be e.g. a counter-current plate heat exchanger of known type, and will not be discussed further. Heat exchanger 3 can be supplied with energy from an energy source 39 through the second medium. The energy source 39 may comprise, without being
15 limited to, a boiler for fossil fuels, exhaust gas, cooling water from industry, cooling water from thermal power plants, hot water from a solar collector, a geothermal source, groundwater, seawater, fresh water from a lake or a river. The energy source 39 may be warmer than the medium in circuit 2. Alternatively, the energy source 39 may include a medium that is colder than
20 the medium in circuit 2, but which by means of a heat pump of known type (not shown), supplies heat to the medium in the closed circuit 2. The flow direction of the second medium is indicated by arrows.

In a section of the pipe 28 upstream the pump inlet 224, the pipe 28 is provided with a second heat exchanger 4 having a first side in fluid contact
25 with the circuit 2. The heat exchanger 4 has a second side arranged to contain a third medium, which may be different from the medium in circuit 2 and the second medium in heat exchanger 3, in heat-exchanging indirect contact with the medium in circuit 2. Heat exchanger 4 can be e.g. a countercurrent heat exchanger plate of known type, and will not be discussed further. Heat
30 exchanger 4 can deliver energy to an energy sink 49 through the third medium. The energy sink 49 may comprise, without being limited to, groundwater, seawater, fresh water lake or river or a heat engine that supplies energy to a district heating system. The flow direction of the third medium is indicated by arrows.

35 A second embodiment is shown in Figure 2. The same items as in the embodiment of figure 1 are specified with the same reference numbers and

are not discussed further. In a section of the pipe 26 downstream of the pump outlet 222 and upstream of the heat exchanger 3, the pipe 26 is provided with a third heat exchanger 5. The heat exchanger 5 has a first side in fluid contact with the pipe 26 and a second side in fluid contact with pipe 28. The heat
5 exchanger 5 can be e.g. a countercurrent heat exchanger plate of known type, and will not be discussed further.

A third embodiment is shown in Figure 3. The same items as in the embodiments from figure 1 and 2 are specified with the same reference numbers and are not discussed further. In a part of pipe 26 downstream of the
10 third heat exchanger 5 and upstream of the first heat exchanger 3, the pipe 26 is provided with a fourth heat exchanger 6. Heat exchanger 6 has a first side in fluid contact with the pipe 26 and a second side in fluid contact with the second heat exchanger 4. Heat exchanger 6 can be e.g. a countercurrent heat exchanger plate of known type, and will not be discussed further. In this
15 embodiment, it is advantageous if the second heat exchanger 4 and the fourth heat exchanger 6 are parts of a single heat pump 7. The second heat exchanger 4 is thus the evaporator 74 of the heat pump 7 and the fourth heat exchanger 6 is thus the condenser 76 of the heat pump 7. As is known in the art, the heat pump is further provided with a compressor 72 and a reducing
20 valve 78. Instead of a reduction valve 78, the heat pump 7 may be provided with an expander 78'. The heat pump 7 is a closed-loop and fluid tight circuit where the heat pump 7 components are in fluid contact with closed pipes 71. The medium in the heat pump 7 may be any suitable medium known in the field, including CO₂. The heat pump 7 may be of a type shown in the
25 publications WO90/07683, U.S. 6,877,340 and U.S. 7,674,097.

A fourth embodiment is shown in Figure 5. The same items as in the embodiment of figure 1 are specified with the same reference numbers and are not discussed further. The pump 22 is driven by an electrical motor 32. The motor 32 is capable of controlling the/frequency/speed of the pump and
30 thus the degree of compression of the medium in the pump. The turbine 2 is connected to a electricity generator 34 via the shaft 35 of the turbine 24 such that the electricity generator 34 may control the load applied in the turbine. The electricity generator 34 is connected to a frequency converter (not shown). Further, a pressure sensor 500 is arranged in the pipe 26 at a position
35 between the outlet 222 of the pump 22 and the inlet 244 of the turbine 24 and another pressure sensor 502 is arranged in the pipe 28 at a position between the outlet of the cooling arrangement 25 and the inlet 224 of the pump 22.

Signal lines 501, 503 connects the respective pressure sensors 500, 502 to a control device/computer 504 adapted to receive the sensed pressures. The control device/computer 504 is connected to the electricity generator 34 and the motor 32 of the pump 22 via signal lines 505, 506. The control
 5 device/computer 504 is adapted to process the sensed pressures (i.e. pressure values) and send control signals to the electricity generator 34 and motor 34, respectively, which control signals are functions of the sensed pressures and optionally other parameters. The processing may for example comprise comparing the pressure values to reference or target values.

10 The pump or compressor 22 is designed to be able to bring the pressure in the medium in circuit 2 to a pressure above the supercritical limit. Such pumps 22 are known in the art and will not be discussed further.

The turbine 24 can be a differential pressure turbine. Examples of a suitable turbine are described in the applicant's own publication NO20092085.

15 Differential pressure turbines are liquid tight in that fluid cannot leak through the turbine housing. The only fluid passing the house is the volume trapped and transported in the compartment between the vanes when the impellers are rotating. The amount of fluid that flows through the turbine housing depends on the impeller(s) rotation speed. By slowing the impeller(s), by
 20 applying load to the shaft, the amount of fluid that flows through the turbine housing and the fluid pressure downstream of the impeller can be controlled. Consequently, the pressure can be controlled by controlling the flow of fluid through the turbine. A reverse centrifugal pump or a piston pump of known type are examples that can also be used for this purpose.

25

The heat engine system will be described in the following examples. Basis for the examples apply the following table values:

	Temperature (° C)			
	0		60	
	Pressure (MPa)		Pressure (MPa)	
	3.5	8.0	3.5	8.0
Enthalpy (kJ / kg)	200.0	196.5	508.6	458.1

Specific weight (kg / dm ³)	0.928	0.961	0.064	0.192
Specific volume (dm ³ / kg)	1.078	1.040	15.66	5.219
Viscosity (cP)	0.994	0.109	0.017	0.020

The following examples are simplifications, and a person skilled in the art will be able to complete the calculations and energy balances.

Example 1

5 The medium used in the heat engine system is CO₂. The example assumes that the heat engine system is dimensioned for a medium capacity of 100 kg/s. The example further assumes that the medium at the pump inlet 224 has a temperature of 0 °C and a pressure of 3.5 MPa (corresponding to 35 bar). Under these conditions, the CO₂ is in sub-critical phase.

10 Pump 22 increases pressure in the medium to 8.0 MPa. 100 kg CO₂ at 0 °C and 3.5 MPa results in a volume of 0.1078 m³. The pressure differential is 4.5 MPa. The work performed by the pump 22 is thus:

$$100 \text{ kg/s} \times 1078 \text{ dm}^3/\text{kg} \times 4.5 \text{ MPa} = 485.1 \text{ kW.}$$

15 Downstream of the pump 22, by the outlet 222, 100 kg CO₂ will constitute a volume of 0.1049 m³. The medium temperature will be 1,488 °C and the enthalpy 200.0 kJ/kg. Under these conditions, the CO₂ is in subcritical phase.

The pressure in the pipe 26 is maintained at 8.0 MPa as the mass of CO₂ that flows through the turbine 24 per unit of time is the same as the mass that flows through the pump 22 per unit of time.

20 To the heat exchanger 3, a work of 25813 kJ/s, or 25,830 kW is supplied. The temperature of the medium increases from 1.488 °C to 60 °C and the medium transforms to the supercritical state under these conditions. The enthalpy is 458.1 kJ/kg. The enthalpy increase over the heat exchanger 3 is thus 458.1 kJ/kg - 200.0 kJ/kg = 258.1 kJ/kg. The specific volume is 5.219 dm³/kg and the
25 medium is in the supercritical state.

The turbine 24 is designed to have a capacity of 0.5219 m³/s supercritical fluid at a temperature of 60 °C and a pressure of 8.0 MPa. The turbine 24 drives a generator (not shown) producing electrical energy in a known manner. The

turbine 24 reduces pressure in the medium from 8.0 MPa to 3.5 MPa. The turbine 24 performs a work of $0.5219 \text{ m}^3 \times 4.5 = 2348 \text{ kW}$.

The turbine 24 can be of a known type, as long as it is designed to perform a controlled pressure reduction between the turbine inlet 244 and the turbine outlet 242, where the first pressure is higher than the second one.

The example assumes that the turbine 24 is followed immediately by the cooling arrangement 25 provided with the second heat exchanger 4, and the cooling arrangement 25 is designed to be able to bring the temperature and pressure of the CO₂ medium to 0 °C and 3.5 MPa, respectively. In the cooling arrangement 25 or the heat exchanger 4, 23,483 kW are removed from the medium. The medium is returned to pump 22 in this state.

Theoretical net energy gain for a cycle of 100 kg/s medium is: Energy harvested from the turbine 24 - energy flow in the pump 22: $2348 \text{ kW} - 485 \text{ kW} = 1863 \text{ kW}$. The relationship between the energy supplied in the form of heat exchanger 3 and the energy harvested in the turbine 24 provides a net theoretical effect of 7.2%.

Example 2

Example 2 assumes the same conditions as in Example 1. The pipe 26 routes the medium from the outlet 222 of the pump 22, to the cooling arrangement 25 and through a third heat exchanger 5 which is arranged immediately downstream of the outlet 242 of the turbine 24. The medium will in a third heat exchanger 5 be heated to 40 °C. The pressure is 8.0 MPa. Under these conditions, the medium has an enthalpy of 402.9 kJ/kg and a specific volume of $3.599 \text{ dm}^3/\text{kg}$. The medium is in supercritical state.

From the third heat exchanger 5, the medium is routed through the pipe 26 to the heat exchanger 3 where it receives 5523 kW. The medium is thereby heated to 60 °C. Then, it flows into the inlet 244 of the turbine 24 in supercritical state at 8.0 MPa and 60 °C.

Downstream of the turbine 24 outlet 242, the medium flows through the third heat exchanger 5 and transfers energy to countercurrent medium as described above. Downstream of the heat exchanger 5, the medium flows through the heat exchanger 4 and then to the cooling arrangement 25. Heat exchanger 4 is designed to bring CO₂ to 0 °C and 3.5 MPa. In the heat exchanger, 43166.7 kW are removed from the medium.

Theoretical net energy gain for a cycle of 100 kg/s medium is: Energy harvested from the turbine 24 - energy flow in the pump 22: $2348\text{kW} - 485\text{ kW} = 1863\text{ kW}$. The relationship between the energy supplied in the form of heat energy recorder 3 and the energy harvested in the turbine 24 provides a theoretical net effect of 34.1%.

Example 3

Scenario 3 assumes the same conditions as in example 1 and 2. In this example, heat exchanger 4 represents the evaporator 74 of the heat pump 7, as shown in Figure 3.

In Example 3, we assume that the heat pump 7 efficiency is 50%. Thereby heat pump 7 transfers 1583 kW from the evaporator 74 and to the fourth heat exchanger 6. In the heat exchanger 3 downstream of the heat exchanger 6, 3940 kW is supplied to the medium.

Theoretical net energy gain for a cycle of 100 kg/s medium is: Energy harvested from the turbine 24 - energy flow in the pump 22: $2348\text{kW} - 485\text{ kW} = 1863\text{ kW}$. The relationship between the energy supplied in the form of heat supplied to heat exchanger 3 and the energy harvested in turbine 24 provides a net theoretical effect of 47.4%.

Example 4

As an illustrative example, a system comprising pipes having an inner diameter of 100 mm is described. Thus, the cross-section area is 78.5 cm^2 and one meter of the pipe contains 7.85 liters of medium. If 7.85 liters per second is pumped, the velocity of the medium will be 1 m/s.

For example, if 50 kg of CO_2 is pumped from a pressure to 73 bar to a pressure of 100 bar, the density of the medium will be 0.95 kg/l if the temperature is 4 °C. Thus, the volume will be 5235 l, resulting in a velocity of 6.67 m/s. If the medium is then heated to 100 °C, the density will be 0.189 kg/l resulting in a speed of 33.76 m/s.

The inlet and the outlet of the turbine have the same cross-section area. Thus, the medium is not allowed to expand to the same degree as in an expander or an expansion turbine. To reduce the pressure back to 73 bar between the inlet and the outlet, the work will be 14.31 kJ/kg and the temperature, density and velocity of the medium will be 74.5 °C, 0.150 kg/l and 42.5 m/s, respectively, after the turbine. Heat is transferred from the medium from the turbine outlet to

the medium from the pump, preferably in a counter-flow heat exchanger, such that the temperature of the medium is reduced directly downstream the turbine. For example, the pressure may be reduced to 73 bar and a temperature of 49.4 °C, at which point the density of medium is the same as at 100 bar and 100 °C. The “internal cooling” of the medium from the turbine is followed by “external cooling” such that the temperature of the medium is reduced below the critical temperature, i.e. below 31°C. Thus, the turbine will be controlled such that the medium reaches a target pressure (e.g. 73 bar) downstream of it, but the efficiency of the cooling of the medium will determine at which speed the turbine may run to maintain the target pressure provided that enough external energy is available for further heating the pressurized medium from the “internal” heat exchange.

Amended Claims (February 22, 2013)

1. Method of extracting energy from an external heat source, comprising the steps of:

a) compressing a medium in the liquid phase using an external power source to obtain a compressed liquid medium;

b) heating the compressed liquid medium from step a) using heat at least partly derived from the external heat source to expand the medium and obtain it in the supercritical state;

c) reducing the pressure of the heated medium from step b) to a controlled degree by applying a variable load to generate electric power of a frequency;

d) converting the frequency of step c) to a desired output frequency; and

e) reducing the temperature and volume of the medium from step c) to obtain the medium in the liquid phase for recycling to step a),

wherein the degree of compression in step a) is controlled independently of the load applied in step c) and step c) is performed by a turbine connected to an electricity generator, which is capable of controlling the load applied in the turbine.

2. Method according to claims 1, further comprising sensing the pressure between steps a) and c) and controlling the load of step c) and/or the degree of compression of step a) at least partly depending on the sensed pressure.

3. Method according to claim 1 or 2, further comprising sensing the pressure between steps c) and a) and controlling the load of step c) and/or the degree of compression of step a) at least partly depending on the sensed pressure.

4. Method according to any one of the preceding claims, wherein part of the heat supplied in the heating step b) is derived from step e).

5. Method according to claim 4, wherein heat from the medium in step e) is transferred to the compressed liquid medium from step a) in a heat exchanger.

6. Method according to any one of the preceding claims, wherein step e) comprises heating a cooling medium to obtain a heated cooling medium and step b) comprises heating the compressed liquid medium using the heated cooling medium to obtain a cooled cooling medium that is recycled to step e).
- 5 7. Method according to claim 6, wherein the heated cooling medium from step e) is compressed before it is used for heating the compressed liquid medium in step b) and the cooled cooling medium from step b) is expanded before it is recycled to step e).
8. Method according to claim 6 or 7, wherein step b) comprises:
- 10 b1) transferring heat from the medium from step c) to the compressed liquid from step a) in a heat exchanger;
- b2) heating using heat from the heated cooling medium; and
- b3) heating using heat from the external heat source.
9. Method according to any one of the preceding claims, wherein step e)
15 comprises heating water for a district heating system.
10. Method according to any one of the preceding claims, wherein the external heat source is selected from exhaust gases, industrial cooling media, heated media from a solar collector, geothermal heat sources, ground water, sea water and fresh water.
- 20 11. Method according to any one of the preceding claims, wherein the temperature of the external heat source is less than 100 °C.
12. Method according to any one of the preceding claims, wherein the temperature of the external heat source is at least 5 °C higher, such as at least 10 °C higher, than the critical point for the medium at the prevailing pressure
25 when the heat from the external heat source is supplied.
13. Method according to any one of the preceding claims, wherein the medium is selected from carbon dioxide (CO₂), ethylene (C₂H₄), diborane (B₂H₆), ethane (C₂H₆) and nitrous oxide (N₂O).

14. Method according to anyone of the preceding claims, wherein the pressure reduction during step c) is controlled to balance the pressure in the energy extraction method.

15. Method according to any one of the preceding claims, wherein the
5 density of the medium is not decreased or decreased by less than 40 %, such as less than 30 %, such as less than 25 %, during step c).

16. Method according to any one of the preceding claims, wherein temperature is not decreased in step c) to below a temperature which is 10 °C higher than that of the compressed medium from step a),

10 17. Heat engine system for extracting energy from an external heat source, comprising:

a pump for compressing a liquid medium to obtain a compressed liquid medium, said pump comprising an inlet, an outlet and an external motor capable of controlling the degree of compression of the liquid medium in the
15 pump;

a heating arrangement connected to the external heat source for heating and expanding the compressed liquid medium to obtain the medium in the supercritical state, said heating arrangement comprising an inlet connected to the pump outlet and an outlet;

20 a turbine for generation of mechanical work from the medium from the heating arrangement, said turbine comprising an inlet connected to the heating arrangement outlet and an outlet;

a electricity generator connected to the turbine, said electricity generator being capable of controlling the load of the turbine such that the
25 pressure upstream of the turbine may be controlled;

a frequency converter connected to the electricity generator; and

a cooling arrangement for reducing the temperature and volume of the medium, said cooling arrangement comprising an inlet connected to the turbine outlet and an outlet connected to the pump inlet,

30 wherein the compression in the pump is controllable independently of the load of the turbine.

18. Heat engine system according to claim 17, further comprising a pressure sensor arranged for sensing a pressure of the medium at a position upstream of the turbine and a control device arranged to receive the sensed pressure from the pressure sensor and control the load of the turbine and/or the degree of compression of the medium in the pump at least partly depending on the sensed pressure.
19. Heat engine system according to claim 17 or 18, further comprising a pressure sensor arranged for sensing a pressure of the medium at a position downstream of the turbine and a control device arranged to receive the sensed pressure from the pressure sensor and control the load of the turbine and/or the degree of compression of the medium in the pump at least partly depending on the sensed pressure.
20. Heat engine system according to any one of claims 17-19, wherein the turbine is a volumetric turbine or a reversed centrifugal pump.
21. Heat engine system according to any one of claims 17-20, wherein the turbine comprises a shaft and the electricity generator is mechanically connected to the turbine shaft.
22. Heat engine system according to claim 17-21, wherein the area of the outlet of the turbine is less than 1.5 times the area of the inlet of the turbine.

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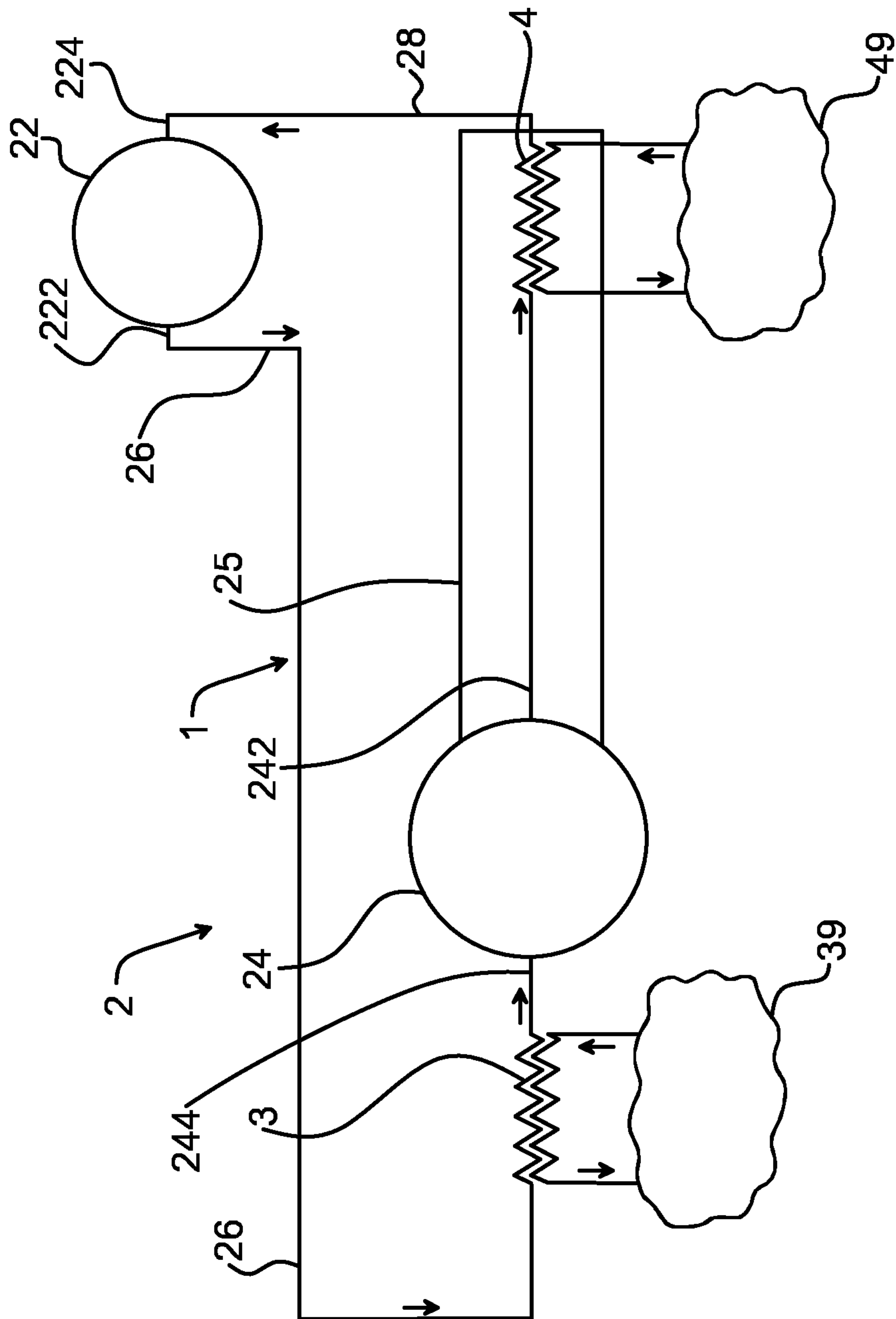


Fig. 1

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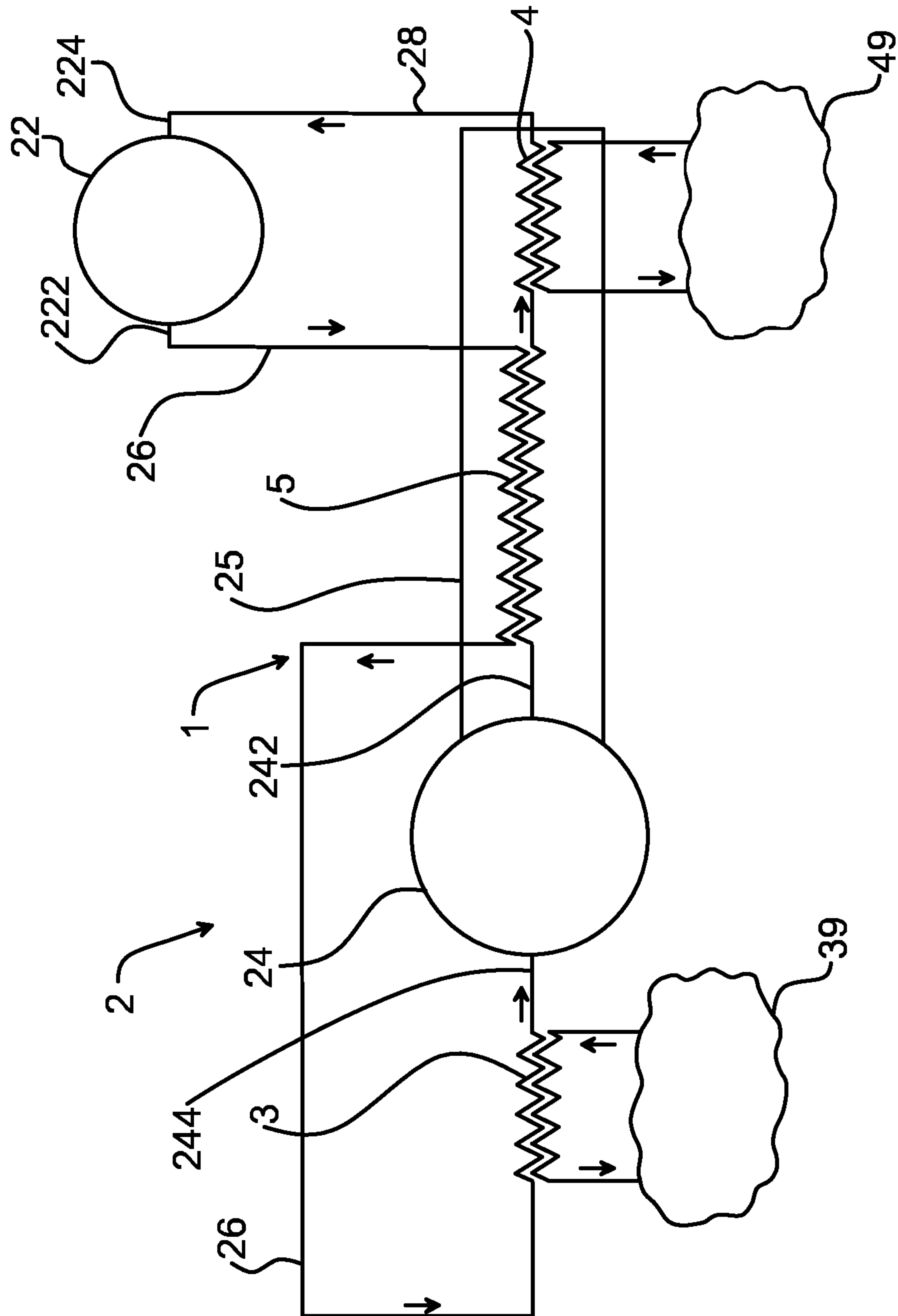


Fig. 2

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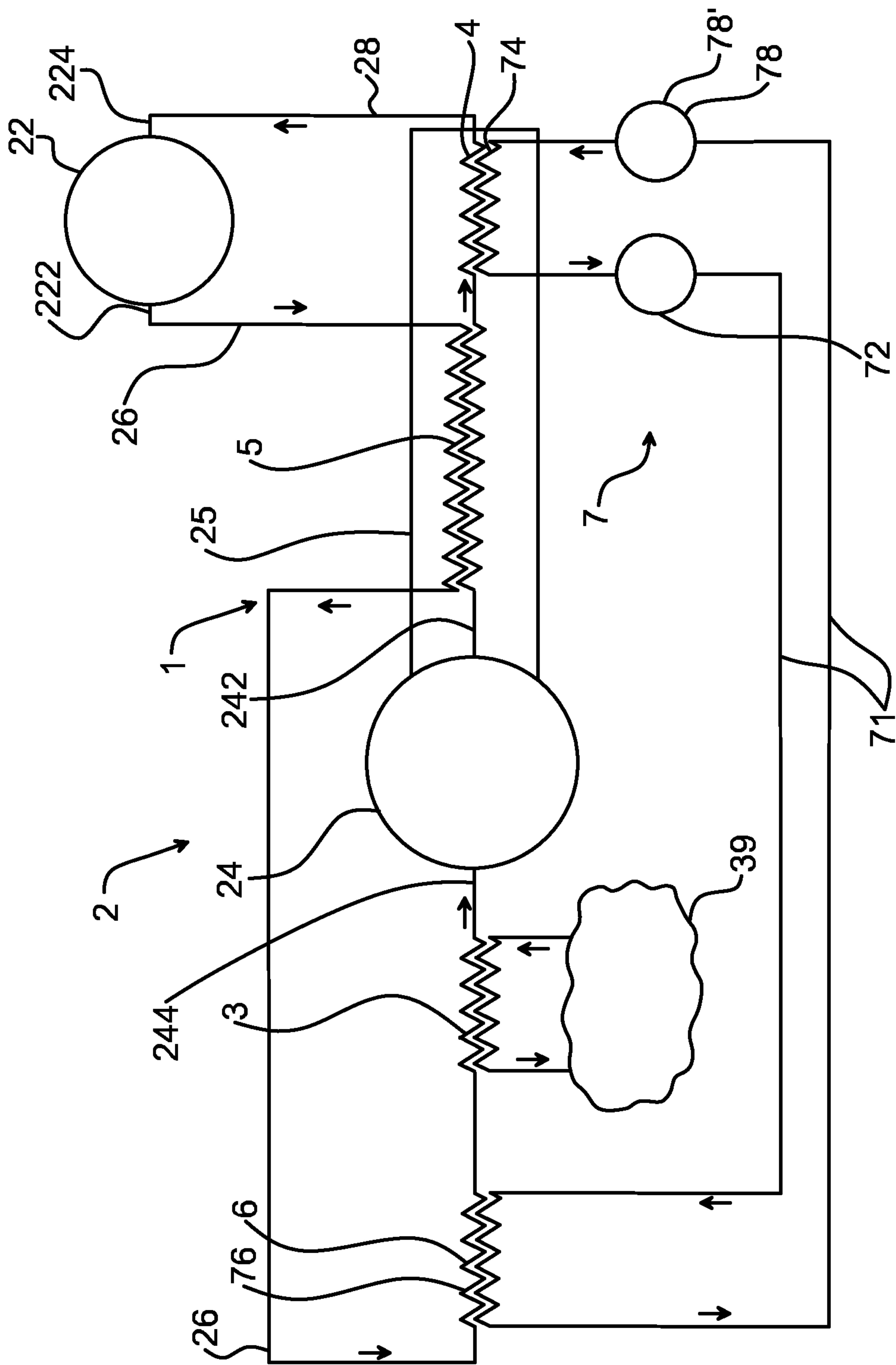


Fig. 3

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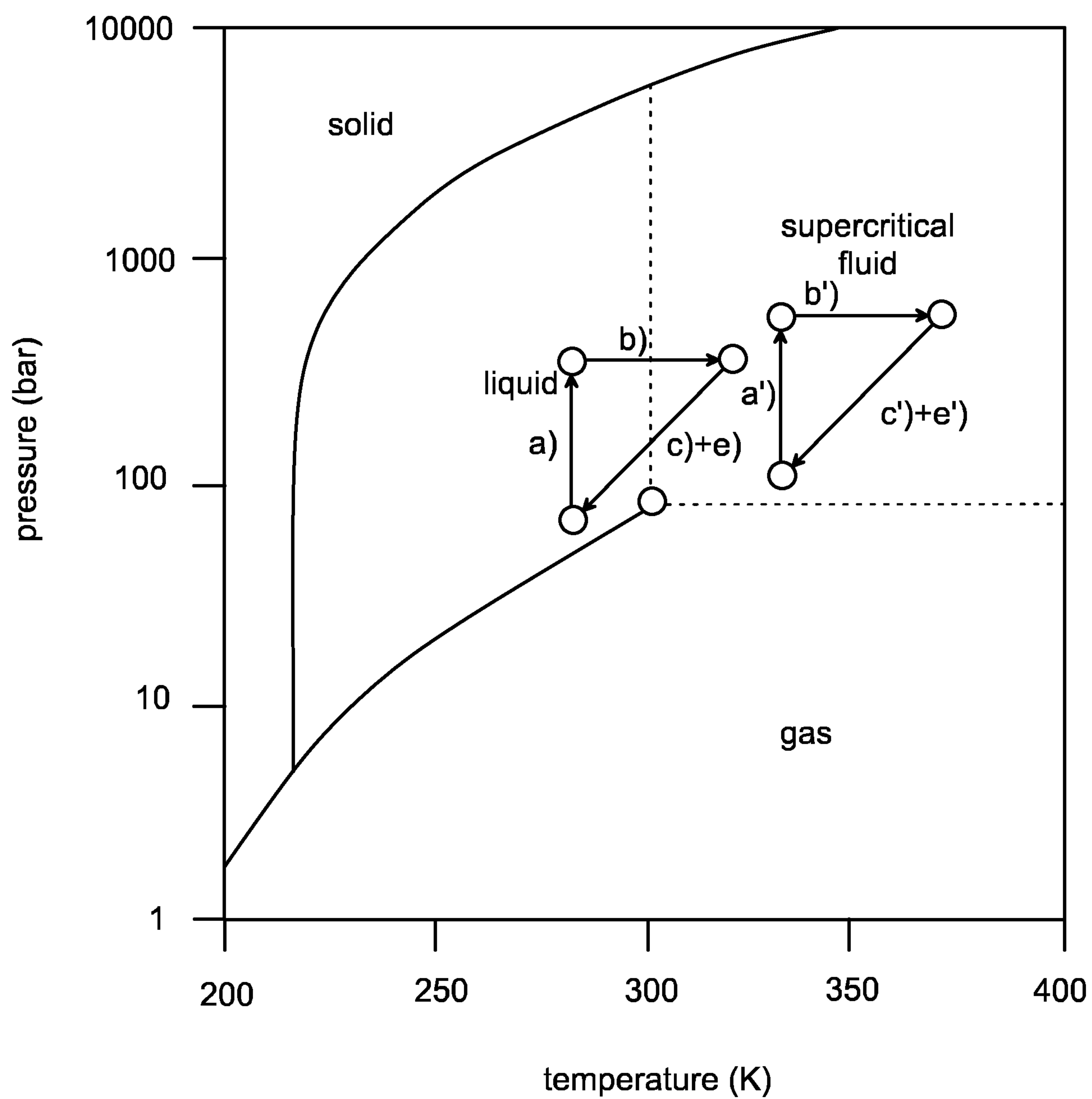
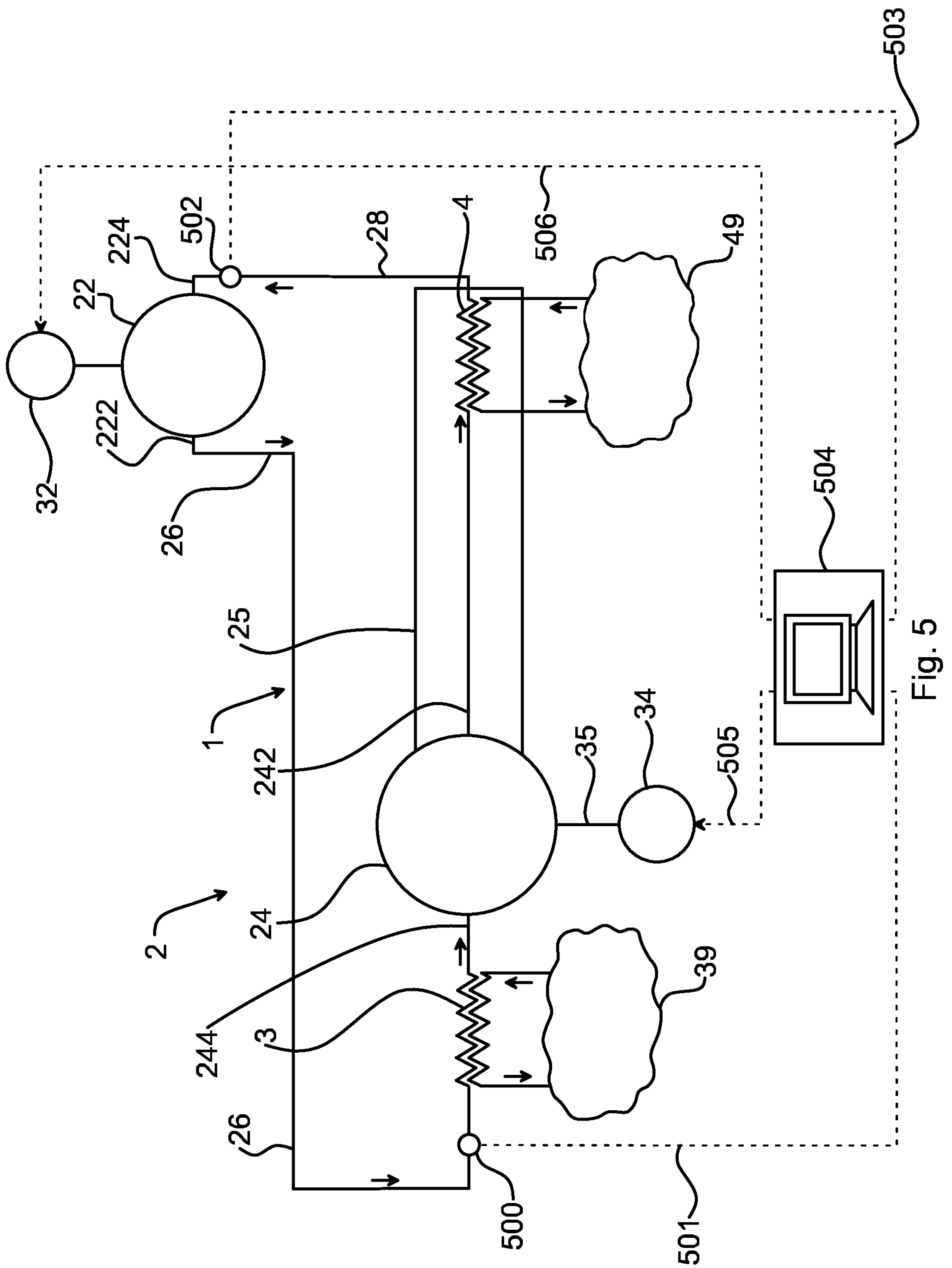


Fig. 4



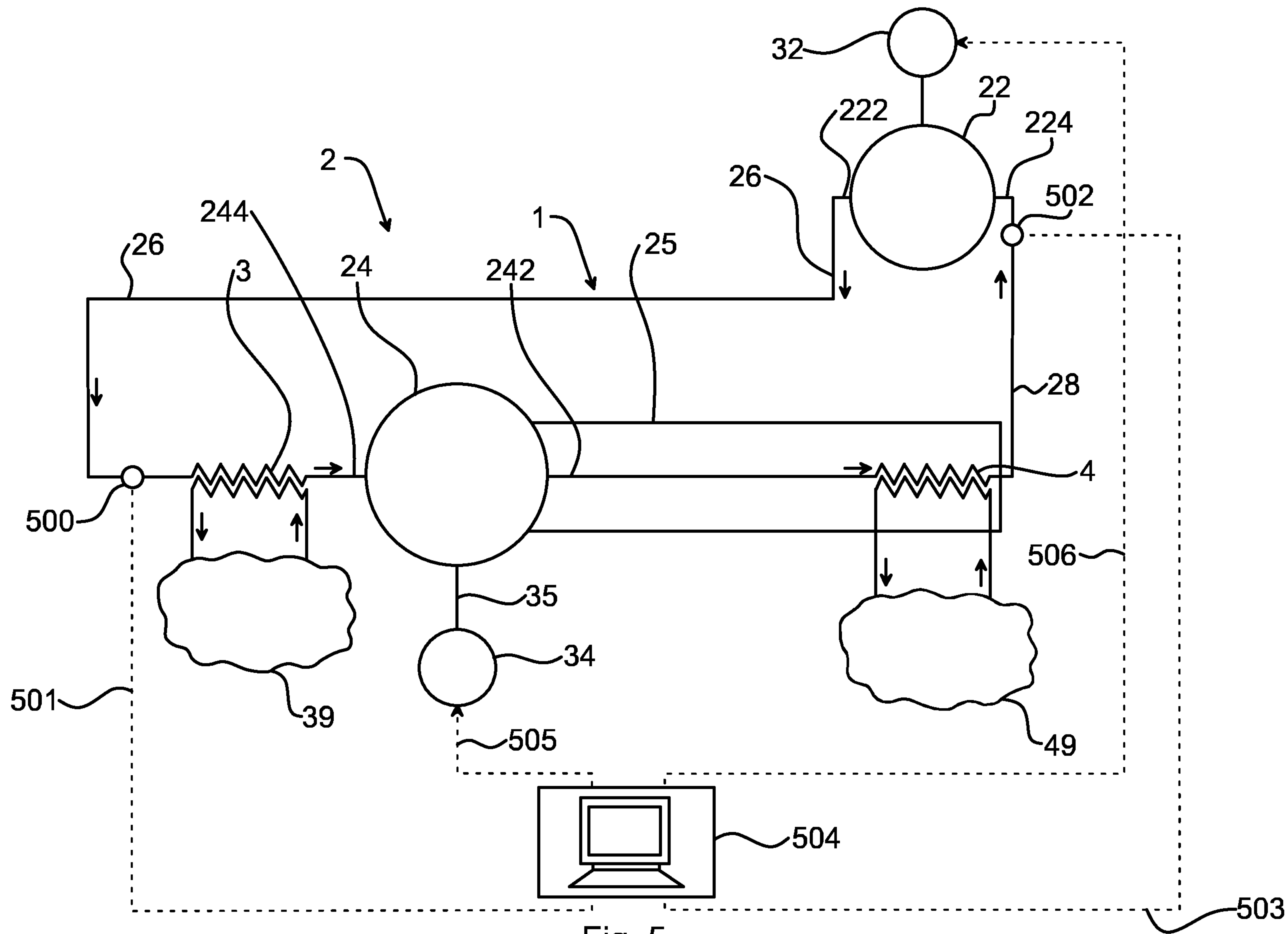


Fig. 5