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(54) MULTI-LEVEL ORGANIC RANKINE CYCLE SYSTEM EQUIPPED WITH A SINGLE REGENRATOR

(57) A two or more pressure level organic Rankine cycle system (100), operated by a heat source flow (5) and working fluid flows (10, 12, 15), the system (100) having a single regenerator (50) provided with a casing (55) containing within it at least one finned battery (60, 65) for each pressure level of the system (100), and wherein the regenerator (50) is configured to perform a heat exchange between a single flow (12) of working fluid in the vapor phase and two or more flows (10, 15) of working fluid in the liquid phase, wherein each flow (10, 15) of working fluid in the liquid phase is at a different pressure level and flows in a respective finned battery (60, 65).

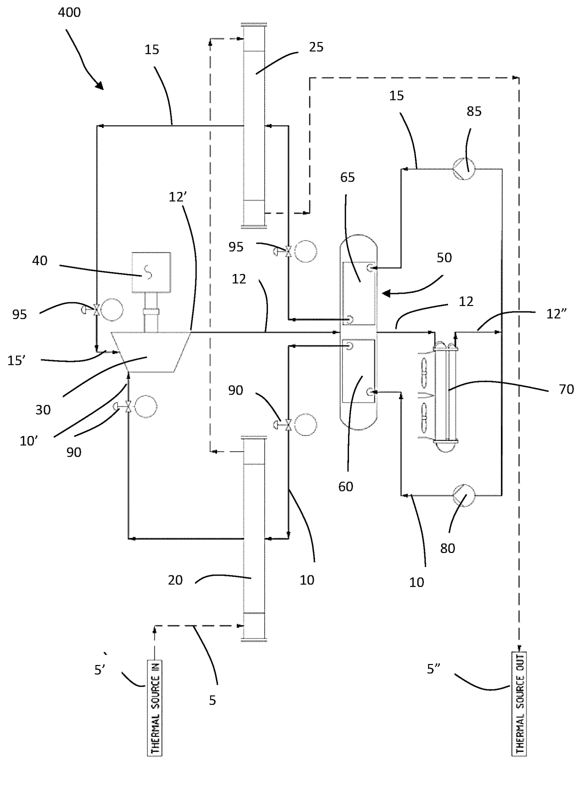

Fig. 4

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Description

Technical field of the invention

[0001] The present invention relates to a multi-level organic Rankine cycle system (ORC system) equipped with a single regenerator.

[0002] The adopted solution is particularly suitable for organic Rankine cycle systems built on multiple levels, in which there is a notable difference between the evaporation temperature and the condensation temperature of the organic working fluid.

Background art

[0003] As is known, a thermodynamic cycle is defined as a finite succession of thermodynamic transformations (for example isothermal, isochore, isobaric or adiabatic) at the end of which the system returns to its initial state.

[0004] Such cycle can be direct, for example an ORC cycle (Organic Rankine Cycle), in which a thermal source is used to produce mechanical/electrical energy and heat at a lower temperature than that of the thermal source, or it can be inverse, for example a heat pump in which electrical energy is used to transfer heat from a source at a lower temperature to one at a higher temperature.

[0005] In particular, an ideal Rankine cycle is a thermodynamic cycle composed of two adiabatic and two isobaric transformations. In the case of a direct cycle, its purpose is to transform heat into work. This cycle is generally adopted especially in thermo-electrical power systems for the production of electrical energy and uses water as a driving fluid, both in liquid form and in form of steam, with the so-called steam turbine.

[0006] More specifically, organic Rankine cycles (ORC) have been hypothesized and implemented that use high molecular mass organic fluids for the most diverse applications, in particular also for the exploitation of low-medium enthalpy thermal sources. As in other steam cycles, the system for an ORC cycle includes one or more feed pumps for moving the organic working fluid in the liquid state from the low pressure zone to the high pressure zone, at least one heat exchanger (also called pre-heater or evaporator, depending on the function performed) to perform the preheating, vaporization and possible superheating or heating phases in supercritical conditions of the same working fluid, at least one turbine for the expansion of the fluid, mechanically connected to an electrical generator, a condenser that returns the organic working fluid to the liquid state.

[0007] It is also known that in ORC cycles the use of high molecular mass organic fluids very often involves the need to introduce, downstream of the turbine and upstream of the condenser, a further heat exchanger called a 'regenerator' or 'recuperator' which recovers a good portion of the sensible heat of the low pressure organic fluid vapor, which heat is used to preheat the organic working fluid in the liquid phase downstream of the cycle feed pump and upstream of the pre-heater.

[0008] In many applications the type of regenerator used is the 'finned coil' type (Tube Fin Heat Exchangers, also called 'finned coil heat exchangers'), commonly used also in the civil sector, for air heat pumps, for coolers or condensers in general, to release or absorb heat from the ambient air.

[0009] In traditional multi-pressure level ORC cycles, typically one turbine is used for each level, which converts the enthalpy change of each level into mechanical energy.

[0010] The turbine exhaust is a very important section at a thermodynamic level as a load loss in this area greatly affects the generation of electrical energy, since this load loss constitutes a back pressure that adds to the condensation pressure, reducing the expansion ratio that the turbine can exploit. It is therefore essential to take the best care of this exhaust area, by minimizing load losses. Each turbine, in known configurations, has its own exhaust that leads to a regenerator, which is made of:

- tube side: a working fluid in liquid state coming from the pump, at the pressure of the level that is appropriate for that turbine, and
- shell side: a steam exhausted from the turbine.

[0011] In ORC cycles according to the state of the technique it is usual to have a regenerator for each pressure level; each regenerator has the function of recovering the enthalpy of the steam, which typically is very superheated, bringing it closer to saturation, to the benefit of the liquid phase which, under pressure, is far from its saturated state and due to the heat exchange in the regenerator, approaches the saturation condition, relieving the incoming heat source from this task, so as to increase cycle efficiency. Fig. 1 represents the scheme of an ORC cycle system 100, at two pressure levels, made according to known technique with two turbines and two separate regenerators. The solid lines represent the path of the organic working fluid, the dashed lines the path of the heat source. The high pressure cycle 110 comprises an evaporator 120, a turbine 130, mechanically connected to an electrical generator 140, a regenerator 150, a condenser 160 and a feed pump 170. The cited components perform the functions described above. Similarly, the low pressure cycle 110' comprises an evaporator 120', a turbine 130', mechanically connected to the same electrical generator 140, a regenerator 150', a condenser 160' and a feed pump 170'.

[0012] Each regenerator 150, 150', in ORC cycles according to the state of the technique, therefore exchanges heat between the vapor phase and the liquid phase of the same process fluid, in particular, between the exhaust vapor phase of a respective turbine 120, 120' and the liquid phase delivered by the respective feed pump 170, 170'.

[0013] With reference to figures 2a and 2b, in other cases it is convenient to use, always according to the known technique, a two-pressure level cycle having a single turbine, comprising axial or radial and axial stages. An example of this second solution is described in the Applicant's patent EP 2805034 B1. In this case, therefore, the turbine discharge is single and the traditional scheme involves the use of two separate regenerators, which can be arranged, with reference to the vapor side, in parallel (as in Fig. 2a) or in series (as in Fig. 2b) . In particular, figure 2a represents the scheme of an ORC cycle system 200 (always with two pressure levels), in which the high pressure cycle 210 comprises an evaporator 220, a turbine 230, mechanically connected to an electrical generator 240, a regenerator 250, a condenser 260 and a feed pump 270. The low pressure cycle 210' includes an evaporator 220', the same turbine 230 as the high pressure cycle, the electrical generator 240, a regenerator 250', a condenser 260' and a feed pump 270' .

[0014] In this system the exhaust steam flow 235 from the turbine 230 is divided into a first flow 245 which feeds the regenerator 250 of the high pressure cycle 210, and a second flow 245' which feeds the regenerator 250' of the low pressure cycle.

[0015] Figure 2b represents the scheme of an ORC cycle system 300 (always with two pressure levels), in which the high pressure cycle 310 comprises an evaporator 320, a turbine 330, mechanically connected to an electrical generator 340, a regenerator 350, a condenser 360 and a feed pump 370. The low pressure cycle 310' comprises an evaporator 320', the same turbine 330 of the high pressure cycle, the electrical generator 340, a regenerator 350', the same condenser 360 of the high pressure cycle and a feed pump 370'.

[0016] According to the diagram in figure 2b, the exhaust steam flow 335 from the turbine 330 is first conducted into a first regenerator 350, at high pressure, and then into a second regenerator 350', at low pressure.

[0017] In summary, the scheme in figure 1 presents the variant with two single turbines in parallel, each operating on its own reference pressure levels (high pressure cycle and low-pressure cycle), whereas the schemes in figures 2a and 2b present the configuration with a single turbine for the two pressure levels.

[0018] In any case, whatever the scheme adopted, the two regenerators (high and low pressure) are two separate components, each with its own casing. This implies an increase in construction and system complications and, consequently, in ORC system costs. Furthermore, in some applications, these system schemes according to the state of the art for cycles with multiple pressure levels introduce a loss that reduces the overall performance of the system due to the back pressures created by the circuit complication downstream of the two steam flows, exhausted from the single turbine or from the two separate turbines.

Summary of the invention

[0019] The solution to the technical problems referred to in the previous paragraph is obtained, according to the present invention, with a single regenerator for ORC systems with two or more pressure levels. Such a regenerator comprises at least two finned batteries and a single containment casing. According to one aspect of the present invention, therefore, a multi-pressure level organic Rankine cycle system is described, the regenerator of which is provided with a single casing containing more than one battery and having the characteristics set forth in the independent product claim annexed to the present description.

[0020] Further preferred and/or particularly advantageous ways of implementing the aforementioned system are described according to the characteristics set out in the attached dependent claims.

Brief description of the drawings

[0021] The invention will now be described with reference to the attached drawings, which illustrate some non-limiting embodiments of a regenerator for multi-level ORC systems, wherein:

- figure 1 schematically illustrates a scheme of a two-pressure level ORC system, equipped with two turbines and two separate regenerators, each capable of receiving the steam at the turbine outlet and the liquid at the pump outlet of the reference cycle, according to known technique,
- figure 2a schematically illustrates a scheme of a two-pressure level ORC system, equipped with a single turbine that processes, in different stages, the steam coming from the two cycles, one of high pressure and one of low pressure, with parallel regenerators, according to known techniques,
- figure 2b schematically illustrates a scheme of a two-pressure level ORC system, equipped with a single turbine that processes, in different stages, the steam coming from the two cycles, one of high pressure and one of low pressure, with regenerators in series, according to the known technique,
- figure 3 illustrates a single regenerator for a two-pressure level ORC system, according to a preferred embodiment of the present invention, and
- figure 4 schematically illustrates a scheme of a two-pressure level ORC system, equipped with a single turbine that processes, in different stages, the steam coming from the two cycles, one of high pressure and one of low pressure, with the single regenerator of figure 3 and with a parallel power supply of the regeneration batteries contained within it.

Detailed description

[0022] The single regenerator, according to the present invention and the relative ORC system with multiple pressure levels that comprises it, will be described below with reference to figures 3 and 4 in which a single regenerator for an ORC system with two pressure levels and the relative ORC system are illustrated in an exemplary and non-limiting manner. The invention, by means of considerations known to a person skilled in the art, is equally relevant to ORC system with more than two pressure levels.

[0023] In the following description and considering, for example, two pressure levels, such pressure levels of the ORC system will be defined for simplicity as "high pressure" and "low pressure" and are to be understood as the pressures delivered by the respective feed pumps to the organic working fluid. The pressure levels are conveniently chosen based on the fluid and the properties of the thermal source, in such a way as to have the ratio between the maximum pressure of the high-pressure cycle and the maximum pressure of the low-pressure cycle comprised between 1.5 and 2.7. The maximum pressure of the high-pressure cycle does not exceed 34 bar absolute and that of the low-pressure cycle does not fall below 10 bar absolute, and in any case the ratio between the maximum pressure of the high-pressure cycle and the maximum pressure of the low-pressure cycle falls within the range indicated above. The upper limit for the high-pressure cycle of 34 bar absolute is a physical limit imposed by the type of fluid used: it is generally preferable not to exceed 80% of the critical pressure of the fluid, so as not to suffer the effects of instability due to proximity to the critical point.

[0024] The lower limit of 10 bar for the low-pressure cycle is instead an indication of a technical-economic nature: if for example the low pressure cycle were to be established at a pressure level below the value of 1.5 - 2.7, compared to the high-pressure cycle, its presence would be difficult to justify in terms of economic convenience compared to a single-level cycle. We can therefore say that these pressure levels are mutually correlated both by physical aspects and by cycle optimization aspects, in the case of two-level cycles.

[0025] A single regenerator 50 for a multi-pressure level ORC system according to the present invention, comprises a casing 55 containing within it at least one finned battery for each pressure level of the ORC system. In the illustrated example, the casing 55 comprises three high-pressure finned batteries 60 and a further two low-pressure finned batteries 65 and a parallel power supply of the regeneration batteries contained therein is achieved. It should be noted that, regardless of the number of finned batteries, what is most relevant is that the pressure ratio cited above (comprised between 1.5 and 2.7) also influences the ratio between the exchange surfaces of the at least one high-pressure battery with respect to the at least one low-pressure battery: such ratio is conveniently chosen in a similar way to the pressure ratio and this is conveniently comprised between 1 and 3.

[0026] The steam flow 12 that hits the regenerator 50 is that coming from the turbine exhaust, whereas within the finned batteries there is a flow of liquid phase 10, 15 corresponding to a pressure level of the cycle (Fig. 4): if a cycle has two pressure levels, within the casing 55 of the regenerator 50 there will be at least two finned batteries 60, 65, each of which regenerates a pressure level.

[0027] Typically, such solution is suitable for geothermal systems in which the characteristics of the thermal source tend to increase the size of the system components and to conveniently use a multi-level pressure cycle. In the case studied the thermal source cannot be cooled below a limit temperature (for example, to avoid a precipitation of the salts contained within it) and regeneration is therefore advantageous to respect this constraint, as preheating the organic liquid reduces its capacity to cool the geothermal source; furthermore, the multi-level cycle allows to optimize the thermodynamic efficiency despite the limitation on the re-injection temperature of the thermal source.

[0028] According to the present innovation, therefore, the single steam flow 12 exiting the turbine enters the single casing of the regenerator, is divided into 2 parallel steam flows and hits the high-pressure and low-pressure batteries.

[0029] The liquid phase organic working fluid from the working fluid feed pumps circulates in the finned batteries 60, 65 of the regenerator 50, which are divided into a high-pressure side and a low-pressure side within a single casing 55. The turbine exhaust steam flow 12 flows as a single flow in the casing and heats both the high-pressure and low-pressure finned batteries.

[0030] Within the regenerator casing 55, it may be preferable to insert baffles to convey the steam towards the regenerator batteries in a more orderly and homogeneous manner.

[0031] According to an alternative solution, as illustrated in figure 3, instead of the baffles there can be a plurality of perforated plates 57, 58, with a variable number of holes so as to have the same steam flow passing through all the finned batteries 60, 65.

[0032] Although not described, the present invention can also be effectively used to create a series power supply of the batteries, by installing suitable stem divisions and baffles within the casing.

[0033] With reference to figure 4, an example of an organic Rankine cycle system 100 with a thermodynamic cycle at two or more pressure levels (two in the described configuration) and using the single regenerator solution, is described below.

[0034] The system 400 includes:

- a first high pressure evaporator 20 and a second low pressure evaporator 25, to heat and vaporize (possibly also to superheat) respective flows of organic working fluid (hereinafter, more simply, a working fluid),
- a turbine 30 for expanding working fluid vapor flows, downstream of evaporators 20, 25. The turbine, conveniently, may be a single turbine, comprising

only axial stages or radial and axial stages and having two inlets for respective working fluid flows and a single outlet for an expanded vapor flow. The system, however, may alternatively comprise two separate turbines, one for high pressure and one for low pressure,

- an electrical generator 40 mechanically connected to the turbine 30 for the production of electrical energy,
- a single regenerator 50, downstream of the turbine 30, provided with a single casing 55 and containing at least a first high pressure battery 60 and at least a second low pressure battery 65. The regenerator 50 operates by transferring heat from the exhaust steam flow from the turbine 30 to respective flows of working fluid in liquid phase,
- a condenser 70, downstream of the regenerator 50, to condense the expanded vapor flow, and
- a first feed pump 80 and a second downstream feed pump 85 for compressing, at high pressure and low pressure, respective flows of working fluid in liquid phase.

[0035] The system can also be equipped with appropriate control valves 90, 95, to regulate the working fluid flows.

[0036] The flow (indicated by dotted lines) of the thermal source 5 used, for example a geothermal source, from a withdrawal point 5' (THERMAL SOURCE IN) passes through the first high pressure evaporator 20 and the second low pressure evaporator 25 sequentially, releasing heat to the respective working fluid flows, to reach then a reinjection point 5" (THERMAL SOURCE OUT). Different and more efficient schemes than those schematically reported here can be adopted to create a cycle with 2 or more pressure levels such as the one reported in GB 2 162 583 A (in this scheme, however, the regenerators are not present.

[0037] The organic working fluid (whose paths are represented by solid lines) is a single flow in the vapor phase, from the exhaust of the turbine 30 to downstream of the condenser 70, whereas it is divided into two flows at high pressure and low pressure, concerning the rest of the path. More precisely, a single flow 12 of working fluid in the vapor phase departs from the exhaust point 12' of the turbine 30, downstream of all the expansion stages of the turbine itself, and passes through the regenerator 50 and the condenser 70. At the outlet of the condenser, evidently, there will be a single flow 12 of working fluid, but in the liquid phase. Once a branch 12" is reached, the working fluid is divided into two flows: a first flow 10 is sucked by the first feed pump 80 and compressed at high pressure, whereas a second flow 15 is sucked by the second feed pump 85 and compressed at low pressure. Alternatively, instead of two separate pumps in parallel, it may be convenient to have a single line on which a first low pressure pump is installed which processes the sum of the two required flow rates and a second pump in series which, starting from the main flow rate, detaches and pressurizes the fraction needed to feed the high-pressure cycle.

[0038] The first flow 10 of working fluid, in liquid phase and at high pressure, passes through the regenerator 50 and, more precisely, the high pressure battery 60, to absorb heat from the expanded vapor flow 12. It then reaches the first high pressure evaporator 20, to heat up further and vaporize and finally, through a first inlet 10', it reaches the turbine 30, upstream of all the expansion stages of the turbine itself.

[0039] The second flow 15 of working fluid, in liquid phase and at low pressure, passes through the regenerator 50 and, more precisely, through the low pressure battery 65, to absorb heat from the expanded vapor flow 12. It then reaches the second low pressure evaporator 25, to heat up further and vaporize and finally, through a second inlet 15', it reaches the turbine 30 in an intermediate expansion stage of the turbine itself.

[0040] The solution according to the present invention, in which a single regenerator is used for two or more levels of an ORC system, has several advantages.

[0041] The main advantage lies in the fact that the regenerator requires a single casing, therefore the construction simplification of the component is notable.

[0042] As a result, the cost of the component and the costs associated with its maintenance are also significantly reduced.

[0043] Furthermore, such solution does not require that the steam flow exhausted from the turbine be separated, or divided into two different flows to reach the two separate regenerators, as is currently the case: this is a further advantage as the back pressure that would be created in the division of the two flows would in fact be added to the condensation back pressure, reducing the enthalpy jump in the turbine and, depending on the application, risking to penalize the cycle efficiency.

[0044] Another advantageous feature of this unique regenerator is that it powers the two high pressure and low pressure batteries, in parallel, with the same temperature difference. In fact, if the finned batteries were put in series, the second battery downstream of the first could receive heat at too low a temperature, with consequent problems of condensation of the exhaust steam from the turbine and/or problems of insufficient heat exchange.

[0045] If it is true that such feature can also be obtained with two separate regenerators in parallel as per the state of the art (scheme in Fig. 2a), the present invention does not imply problems of balancing the steam flow rates in the two different channels, ensuring better regeneration efficiency.

[0046] In addition to the ways of implementing the invention, as described above, it is to be understood that there are numerous further variations. It is also to be understood that said ways of implementing are only exemplifying and do not limit either the object of the invention, or its applications, or its possible configurations. On the contrary, although the above description makes it possible for a skilled person to implement the present invention at least according to an exemplifying configuration thereof, it is to be understood that numerous variations of the described components are conceivable, without thereby departing from the object of the invention, as defined in the attached claims.

Claims

1. Organic Rankine cycle system (400) with two or more pressure levels, operated by a flow (5) of thermal source and by flows (10, 12, 15) of working fluid, the system (400) being **characterized by** the fact that, in combination:

   - the system (400) includes a single recuperator (50) provided with a casing (55) which contains within it at least one finned battery (60, 65) for each pressure level of the system (400), and
   - the recuperator (50) is configured to carry out a heat exchange between a single flow (12) of working fluid in the vapor phase and two or more flows (10, 15) of working fluid in the liquid phase, in which each flow (10, 15) of working fluid in the liquid phase is at a different pressure level and flows into at least one respective finned battery (60, 65).

2. System according to claim 1, wherein the organic Rankine cycle is at two pressure levels and the ratio between the maximum pressure of the higher pressure level and the maximum pressure of the lower pressure level is between 1.5 and 2.7.

3. System (400) according to claim 1 or 2, wherein inside the casing (55) the ratio between the exchange surface between the at least one high pressure battery (60) and the at least one low pressure battery (65) is between 1 and 3.

4. System (400) according to any of the previous claims, wherein within the casing (55) of the recuperator (50) there is at least one baffle to convey the steam towards the finned coils (60, 65) of the regenerator (50).

5. System (400) according to any of claims 1 to 3, in which within the casing (55) of the recuperator(50) there is a plurality of perforated plates (57, 58) with a variable number of holes in order to have the same steam flow rate that passes through all the finned coils (60, 65).

6. System (100) according to any of the previous claims, further comprising:

   - a first high pressure evaporator (20) and a second low pressure evaporator (25), to heat and vaporize respective flows (10, 15) of working fluid,
   - an expansion turbine (30) downstream of the evaporators (20, 25).
   - a condenser (70), downstream of the recuperator (50), to condense the single flow (12) of working fluid in the vapor phase, and
   - a first feed pump (80) and a second downstream feed pump (85) to compress, at high pressure and at low pressure, respective flows (10, 15) of working fluid in the liquid phase.

7. System (100) according to claim 6, in which the turbine (30) is a single turbine, comprising only axial or radial and axial stages and having two inlets for respective flows (10, 15) of working fluid and one outlet of the single flow (12) of working fluid in vapor phase.

8. System (100) according to any of the previous claims, in which the heat source flow (5) is configured to pass through, from a withdrawal point (5’), sequentially, the first high pressure evaporator (20) and the second low pressure evaporator (25) and then to reach a reinjection point (5").

9. System (100) according to claim 8, wherein the thermal source is a geothermal source.

10. System (100) according to any of claims 6 to 9, wherein the single flow (12) of working fluid in vapor phase is configured to start from an exhaust point (12’) of the turbine (30) and to pass through the recuperator (50) and the condenser (70).

11. System (100) according to one of claims 6 to 10, wherein a first high-pressure flow (10) of the two or more flows (10, 15) of working fluid in liquid phase is configured for:

    - being sucked in by the first feed pump (80) and compressed at high pressure,
    - passing through the high-pressure battery (60) of the regenerator (50),
    - passing through the first evaporator (20) at high pressure, and
    - through a first inlet (10’), reaching the turbine (30) upstream of all the expansion stages of the turbine itself.

12. System (100) according to one of claims 6 to 11, wherein a second low pressure flow (15) of the two or more flows (10, 15) of working fluid in liquid phase is configured for:

    - being sucked in by the second feed pump (88) and compressed at low pressure,

- passing through the low pressure battery (65) of the regenerator (50),
- passing through the second evaporator (25) at low pressure, and
- through a second inlet (15'), reaching the turbine (30) in an intermediate expansion stage of the turbine itself.

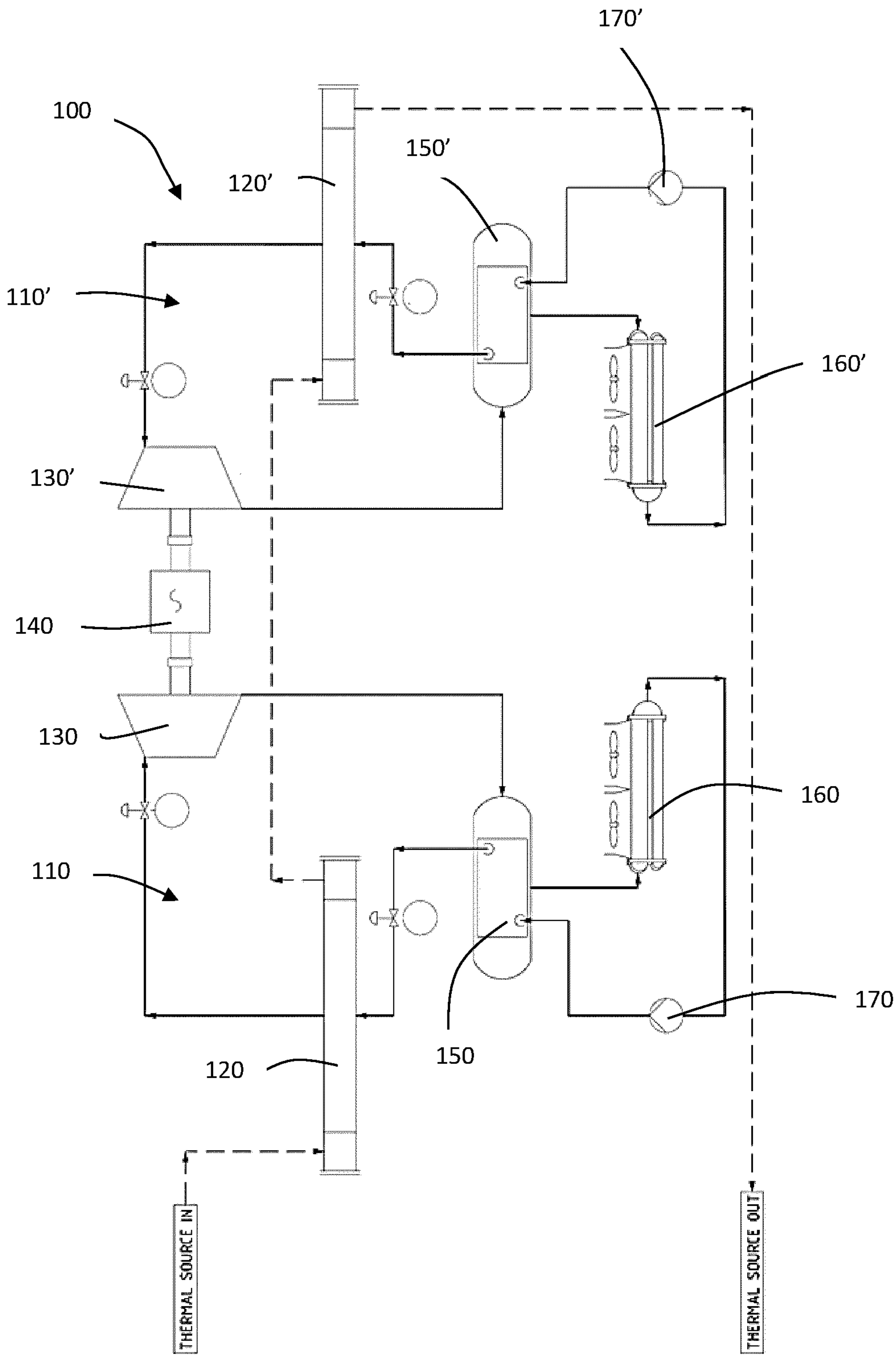

Fig. 1 – Prior art

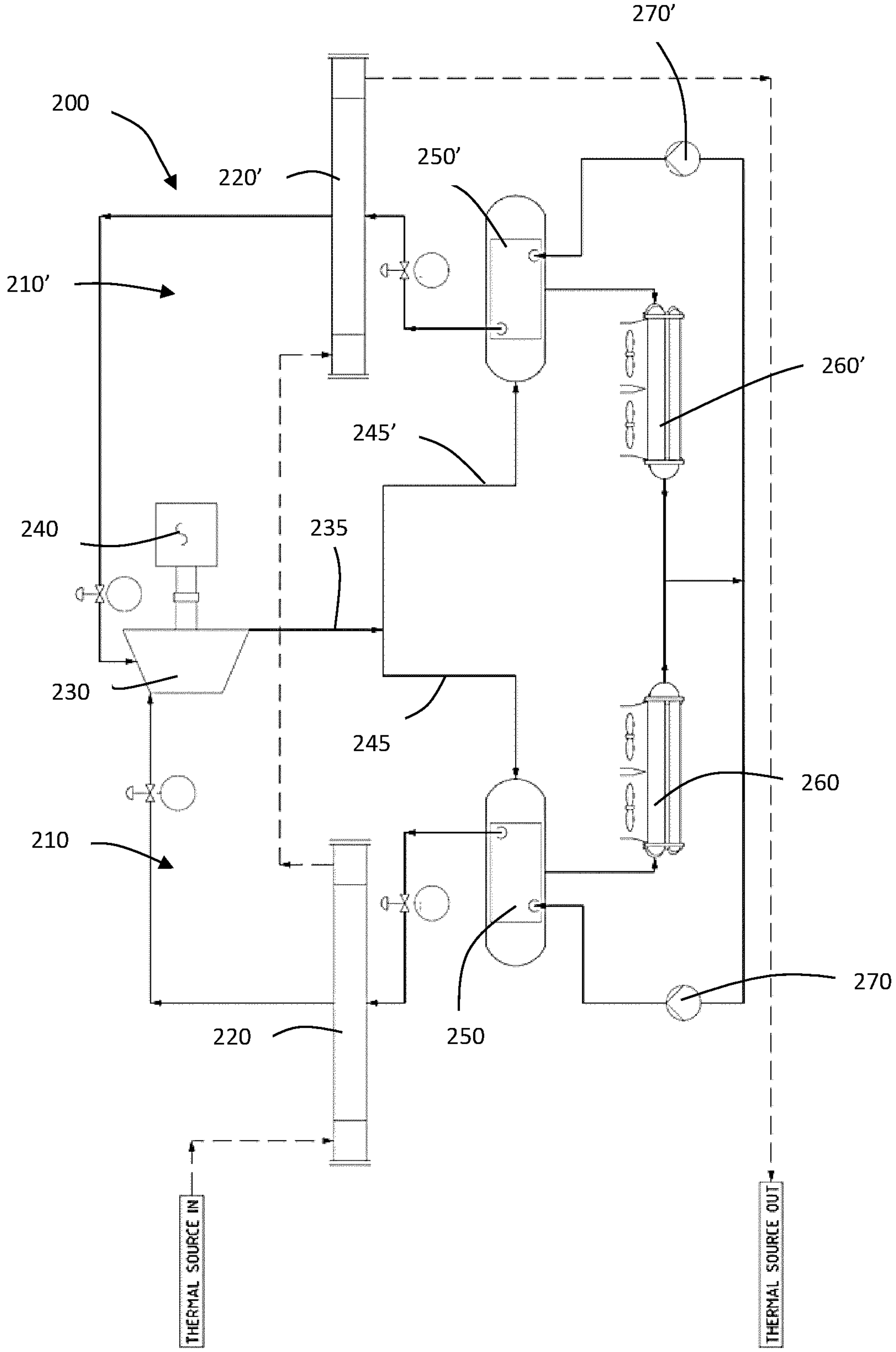

Fig. 2a – Prior art

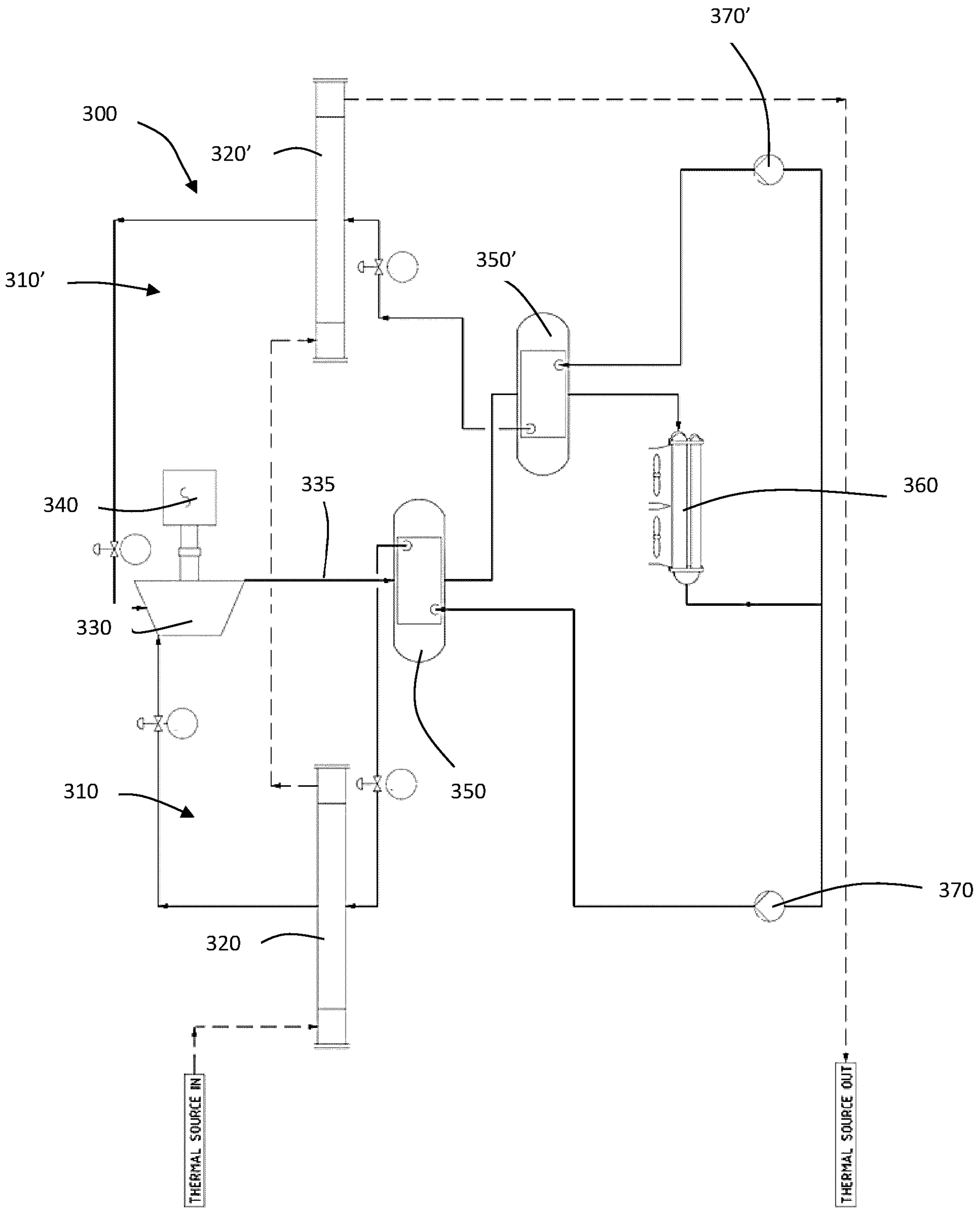

Fig. 2b – Prior art

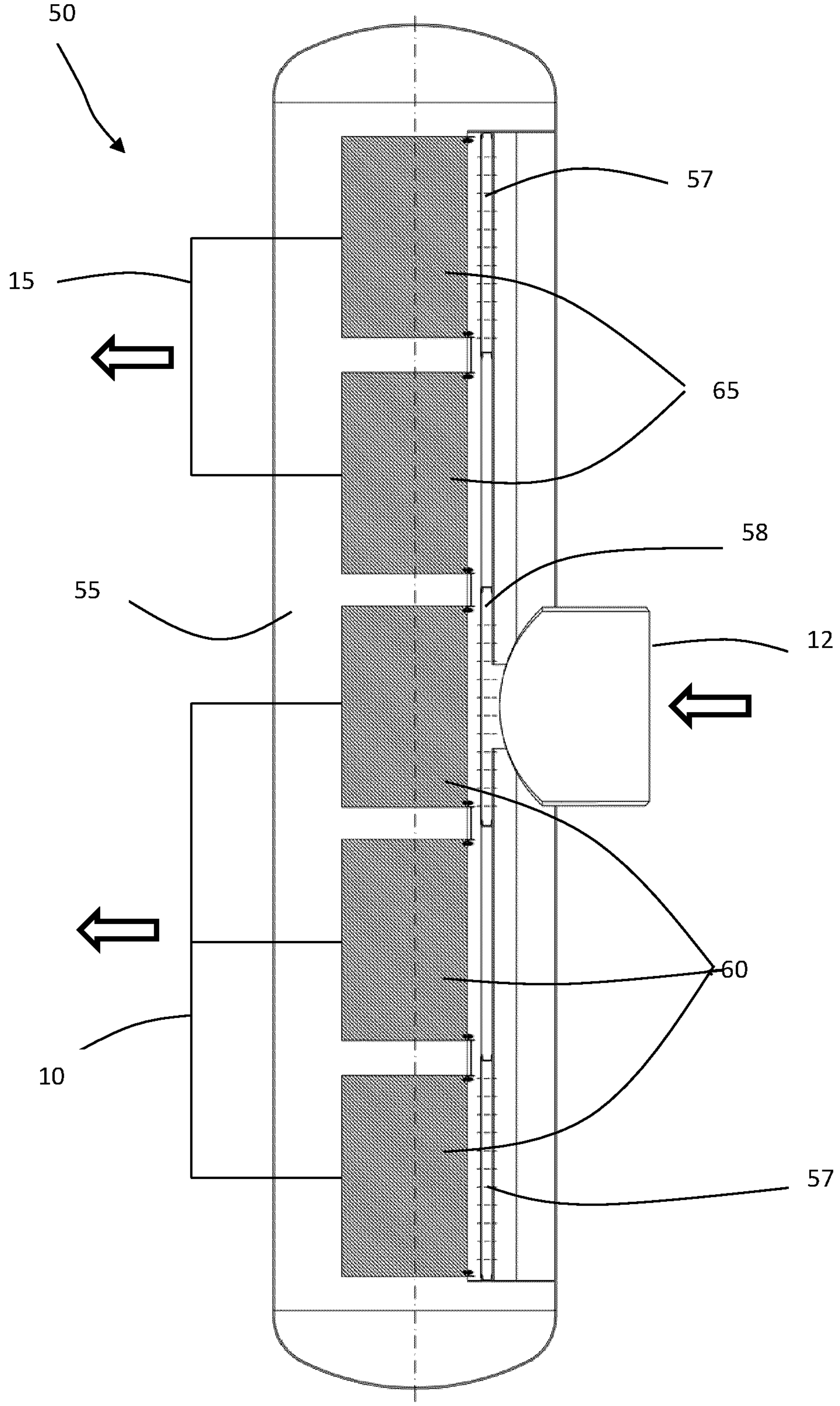

Fig. 3

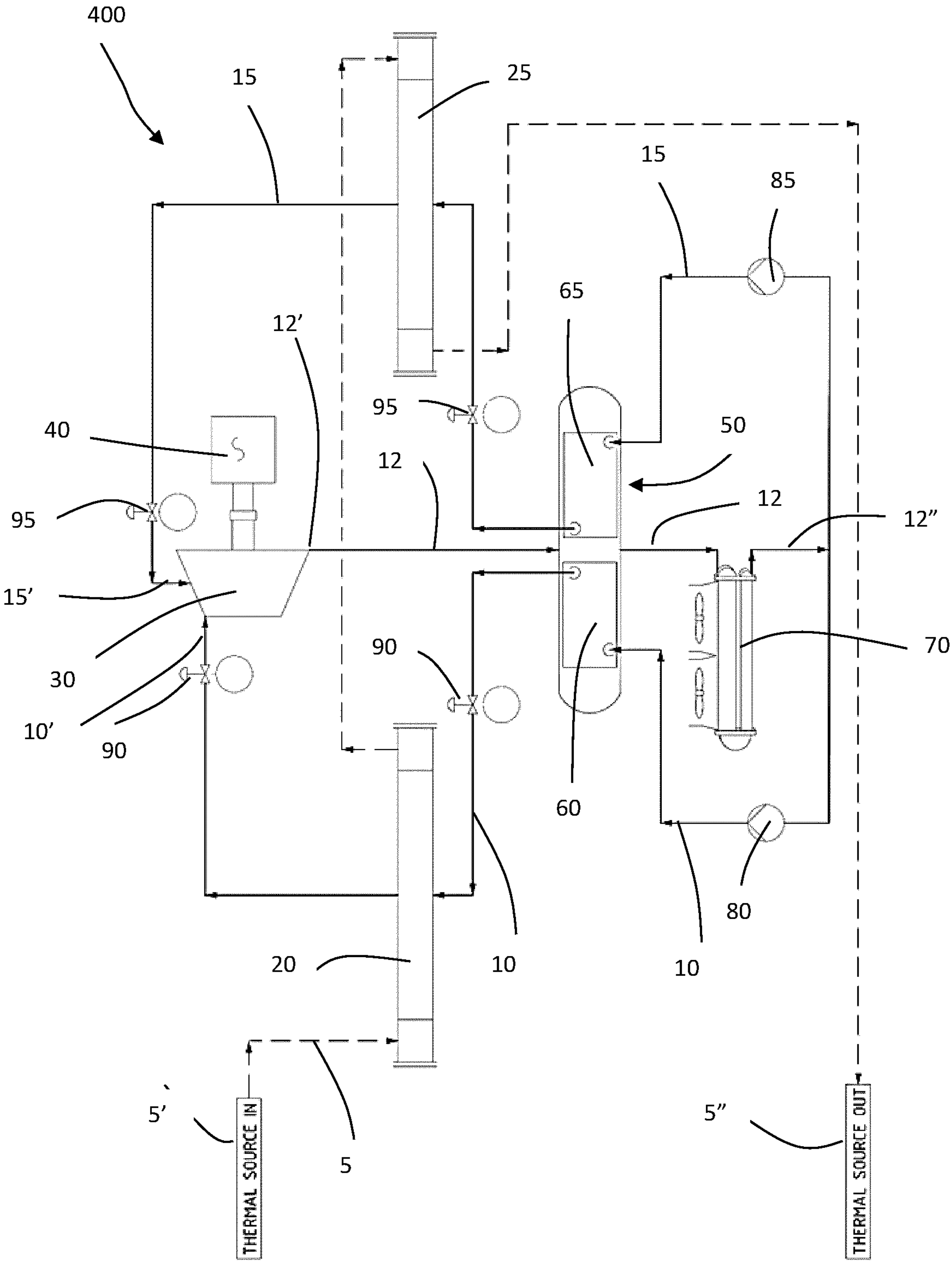
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Fig. 4

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EUROPEAN SEARCH REPORT

Application Number
EP 24 21 8221

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
A	EP 3 835 556 A1 (TURBODEN SPA [IT]) 16 June 2021 (2021-06-16) * paragraph [0017] - paragraph [0032]; claims; figures 1, 3-5 * * abstract *	1-12	INV. F01K7/06 F01K25/08
A	IT MI20 110 243 A1 (EXERGY ORC S R L) 19 August 2012 (2012-08-19) * the whole document *	1-12	
A	US 9 359 919 B1 (BERRY JAMES E [US]) 7 June 2016 (2016-06-07) * column 5, line 41 - column 8, line 67; claims; figures; tables 1-4 * * abstract *	1-12	
A	US 2015/252692 A1 (HONKATUKIA JUHA [FI] ET AL) 10 September 2015 (2015-09-10) * paragraph [0016] - paragraph [0020]; claims; figures * * abstract *	1-12	

TECHNICAL FIELDS SEARCHED (IPC)

F01K

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
Munich	6 May 2025	Zerf, Georges

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CATEGORY OF CITED DOCUMENTS

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