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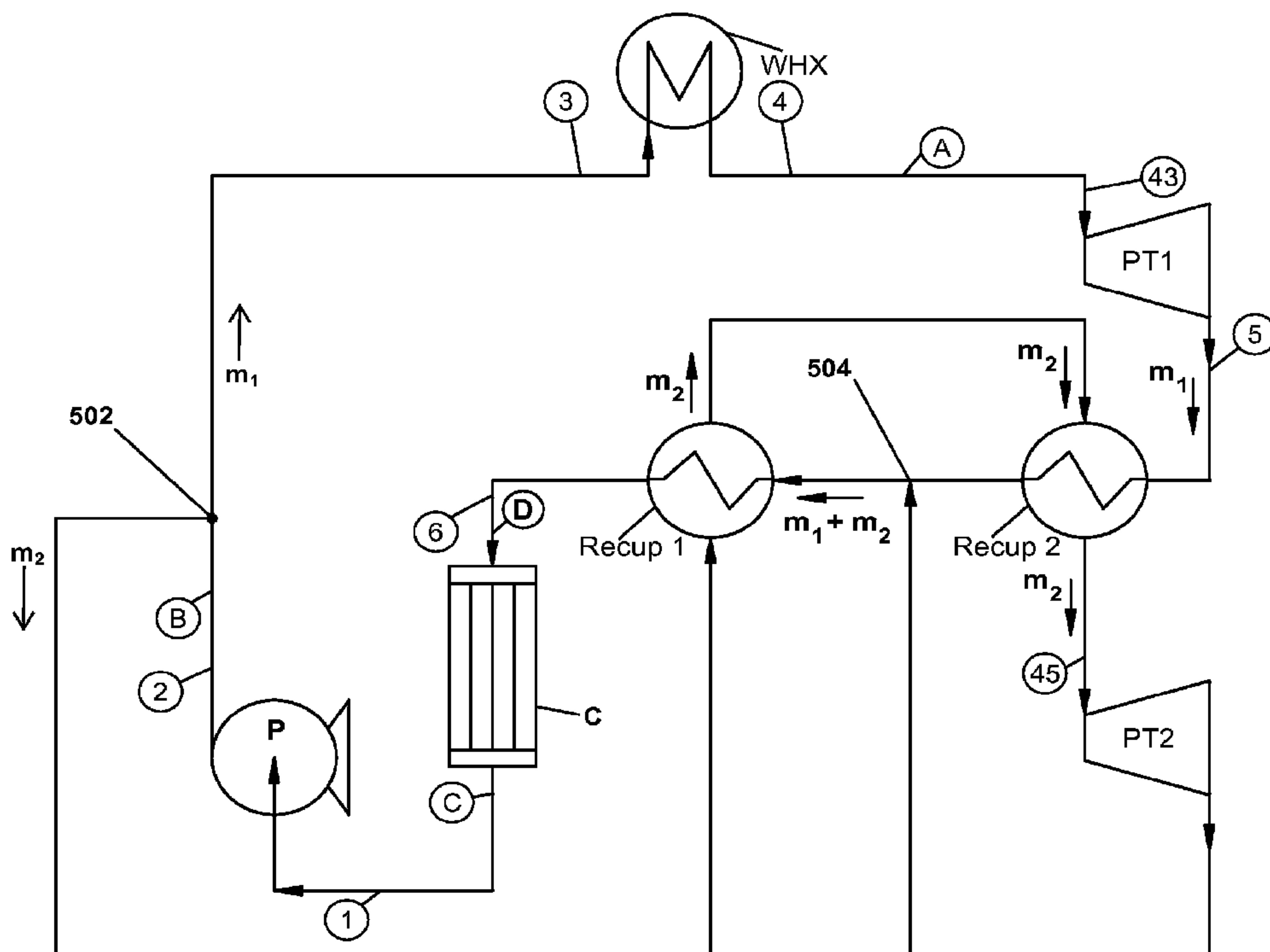
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Cascade thermodynamic energy conversion cycles use multiple power turbines in a working fluid circuit for conversion of waste heat energy, with each turbine inlet temperature optimized to operate in a temperature spectrum to use a greater amount of thermal energy from each cycle. Various accompanying recuperator arrangements are also disclosed, and working fluid mass management systems integrated with the cascade cycles.

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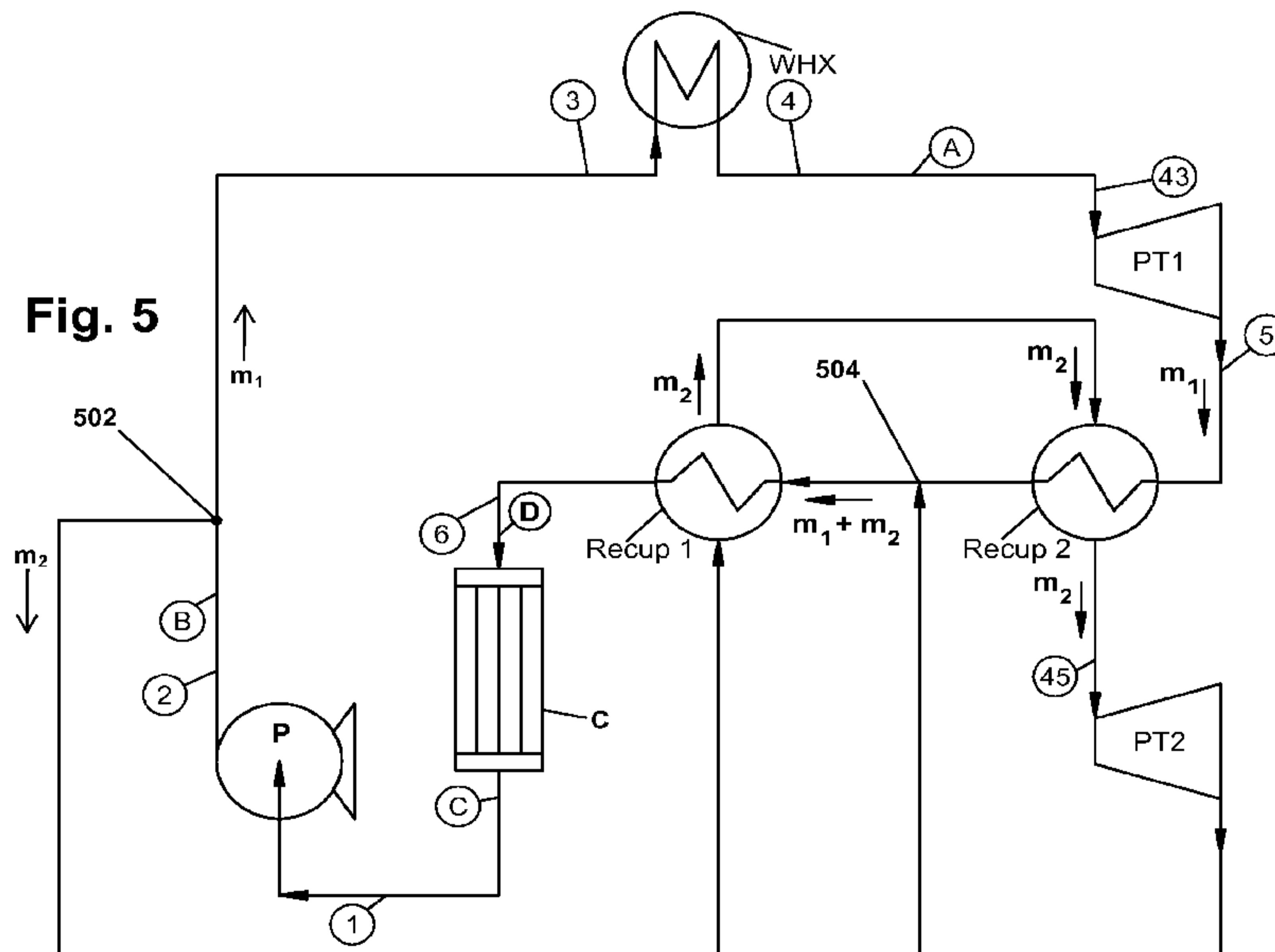
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## HEAT ENGINES WITH CASCADE CYCLES

### Background

**[0002]** Heat is often created as a byproduct of industrial processes where flowing streams of liquids, solids or gasses that contain heat must be exhausted into the environment or otherwise removed from the process an effort to maintain the operating temperatures of the industrial process equipment. Sometimes the industrial process can use heat exchanging devices to capture the heat and recycle it back into the process via other process streams. Other times it is not feasible to capture and recycle this heat because it is either too low in temperature or there is no readily available means to use as heat directly. This type of heat is generally referred to as "waste" heat, and is typically discharged directly into the environment through, for example, a stack, or indirectly through a cooling medium, such as water. In other settings, such heat is readily available from renewable sources of thermal energy, such as heat from the sun (which may be concentrated or otherwise manipulated) or geothermal sources. These and other thermal energy sources are intended to fall within the definition of "waste heat," as that term is used herein.

**[0003]** Waste heat can be utilized by turbine generator systems that employ thermodynamic methods, such as the Rankine cycle, to convert heat into work. Typically, this method is steam-based, wherein the waste heat is used to raise steam in a boiler to drive a turbine. However, at least one of the key short-comings of a steam-based Rankine cycle is its high temperature requirement, which is not always practical since it generally requires a relatively high temperature (600°F or higher) waste heat stream or a very large overall heat content. Also, the complexity of boiling water at multiple pressures/temperatures to capture heat at multiple temperature levels as the heat source stream is cooled is costly in both equipment cost and operating labor. Furthermore, the

steam-based Rankine cycle is not a realistic option for streams of small flow rate and/or low temperature.

**[0004]** The organic Rankine cycle (ORC) addresses the short-comings of steam-based Rankine cycles by replacing water with a lower boiling-point fluid, such as a light hydrocarbon like propane or butane, or a HCFC (e.g., R245fa) fluid. However, the boiling heat transfer restrictions remain, and new issues such as thermal instability, toxicity or flammability of the fluid are added.

**[0005]** To address these short-comings, supercritical CO<sub>2</sub> power cycles have been used. The supercritical state of the CO<sub>2</sub> provides improved thermal coupling with multiple heat sources. For example, by using a supercritical fluid, the temperature glide of a process heat exchanger can be more readily matched. However, single cycle supercritical CO<sub>2</sub> power cycles operate over a limited pressure ratio, thereby limiting the amount of temperature reduction, *i.e.*, energy extraction, through the power conversion device (typically a turbine or positive displacement expander). The pressure ratio is limited primarily due to the high vapor pressure of the fluid at typically available condensation temperatures (e.g., ambient). As a result, the maximum output power that can be achieved from a single expansion stage is limited, and the expanded fluid retains a significant amount of potentially usable energy. While a portion of this residual energy can be recovered within the cycle by using a heat exchanger as a recuperator, and thus pre-heating the fluid between the pump and waste heat exchanger, this approach limits the amount of heat that can be extracted from the waste heat source in a single cycle.

**[0006]** Accordingly, there exists a need in the art for a system that can efficiently and effectively produce power from not only waste heat, but also from a wide range of thermal sources.

## Summary

**[0007]** The present disclosure is in the general field of thermodynamics and energy conversion, and more particularly applicable to conversion of thermal energy to work. The present disclosure improves the efficiency of a supercritical CO<sub>2</sub> power cycle by "cascading" the residual energy back to a higher pressure fluid source, and expanding this fluid through an additional power conversion device. In addition, the unique characteristics

of the CO<sub>2</sub> cycle require active management of the main pump suction pressure and temperature relationship to provide optimal cycle efficiency. The present disclosure includes equipment and control strategies that enable superior performance to be achieved with the cascade CO<sub>2</sub> cycle described herein.

**[0008]** Certain exemplary embodiments can provide a working fluid circuit for waste heat recovery, comprising: a pump operative to direct a working fluid within the working fluid circuit to a waste heat exchanger fluidly coupled to the pump; a first expansion device fluidly coupled to the waste heat exchanger and configured to receive the working fluid from the waste heat exchanger; a first recuperator fluidly coupled to the first expansion device and configured to receive the working fluid from the first expansion device and transfer heat from the working fluid to a downstream portion of the working fluid; a second expansion device fluidly coupled to the pump downstream from the pump and configured to receive the downstream portion of the working fluid; a second recuperator fluidly coupled to the second expansion device and configured to receive the downstream portion of the working fluid from the second expansion device; and a mass management system having a first system tie-in fluidly coupled upstream from the first expansion device and a second system tie-in fluidly coupled upstream from the pump, the mass management system having a mass control tank configured to selectively receive the working fluid from the working fluid circuit via the first system tie-in and to selectively input the working fluid into the working fluid circuit via the second system tie-in.

**[0009]** Certain exemplary embodiments can provide a working fluid circuit for waste heat recovery, comprising: a pump configured to direct a working fluid within the working fluid circuit to a waste heat exchanger fluidly coupled to the pump, the working fluid being separated into a first portion and a separated portion, wherein the first portion passes through the waste heat exchanger; a first recuperator configured to receive the separated portion of the working fluid and to increase the temperature of the separated portion; a first expansion device fluidly coupled to the waste heat exchanger and configured to receive the first portion of the working fluid from the waste heat exchanger; a second recuperator fluidly coupled to the first expansion device and

configured to receive the first portion of the working fluid from the first expansion device, the second recuperator also configured to receive the separated portion of the working fluid following the first recuperator and to further increase the temperature of the separated portion; a second expansion device configured to receive the separated portion of the working fluid from the second recuperator; and a mass management system having a first system tie-in fluidly coupled upstream from the first expansion device and a second system tie-in fluidly coupled upstream from the pump, the mass management system having a mass control tank configured to selectively receive the working fluid from the working fluid circuit via the first system tie-in and selectively input the working fluid into the working fluid circuit via the second system tie-in

**[0010]** Certain exemplary embodiments can provide a method of recovering waste heat in a working fluid circuit, comprising: pumping a first portion of a working fluid within the working fluid circuit by a pump to a waste heat exchanger fluidly coupled to the pump; pumping a separated portion of the working fluid by the pump through a first recuperator; transferring thermal energy from the first recuperator to the separated portion of the working fluid; expanding the first portion of the working fluid in a first expansion device fluidly coupled to the waste heat exchanger; transferring thermal energy from the first portion of the working fluid to the separated portion of the working fluid in a second recuperator fluidly coupled to the first expansion device, the second recuperator being configured to receive the separated portion of the working fluid following the first recuperator; expanding the separated portion of the working fluid in a second expansion device configured to receive the separated portion from the second recuperator; re-combining the first portion and the separated portion of the working fluid to pass through the first recuperator; and controlling an amount of working fluid mass in the working fluid circuit with a mass management system having a mass control tank fluidly coupled to a first system tie-in and a second system tie-in, the first system tie-in being fluidly coupled upstream from the first expansion device and the second system tie-in being fluidly coupled upstream from the pump.

**[0010a]** Certain exemplary embodiments can provide a working fluid circuit for waste heat recovery, comprising: a pump operative to direct a working fluid within the working fluid circuit to a waste heat exchanger fluidly coupled to the pump; a first expansion device fluidly coupled to the waste heat exchanger and configured to receive the working fluid from the waste heat exchanger; a first recuperator fluidly coupled to the first expansion device and configured to receive the working fluid from the first expansion device and transfer heat from the working fluid to a downstream portion of the working fluid; a second expansion device fluidly coupled to the pump downstream from the pump and configured to receive the downstream portion of the working fluid; a second recuperator fluidly coupled to the second expansion device and configured to receive the downstream portion of the working fluid from the second expansion device; a mass management system having a first system tie-in fluidly coupled upstream from the first expansion device and a second system tie-in fluidly coupled upstream from the pump, the mass management system having a mass control tank configured to selectively receive the working fluid from the working fluid circuit via the first system tie-in and selectively input the working fluid into the working fluid circuit via the second system tie-in; a condenser having an upstream side and a downstream side, the condenser being fluidly coupled to the pump on the downstream side and fluidly coupled to the first and second recuperators on the upstream side; and a starter pump fluidly coupled to a downstream side of the condenser and a downstream side of the pump, wherein the working fluid is comprises carbon dioxide and is in a supercritical state through a portion of the working fluid circuit.

**[0010b]** Certain exemplary embodiments can provide a working fluid circuit for waste heat recovery, comprising: a pump configured to direct a working fluid within the working fluid circuit to a waste heat exchanger fluidly coupled to the pump, the working fluid being separated into a first portion and a separated portion, wherein the first portion passes through the waste heat exchanger, wherein the working fluid is carbon dioxide, and achieves a supercritical state through a portion of the working fluid circuit; a first recuperator configured to receive the separated portion of the working fluid and to increase the temperature of the separated portion; a first expansion device fluidly

coupled to the waste heat exchanger and configured to receive the first portion of the working fluid from the waste heat exchanger; a second recuperator fluidly coupled to the first expansion device and configured to receive the first portion of the working fluid from the first expansion device, the second recuperator also configured to receive the separated portion of the working fluid following the first recuperator and to further increase the temperature of the separated portion; a second expansion device configured to receive the separated portion of the working fluid from the second recuperator; a mass management system having a first system tie-in fluidly coupled upstream from the first expansion device and a second system tie-in fluidly coupled upstream from the pump, the mass management system having a mass control tank configured to selectively receive the working fluid from the working fluid circuit via the first system tie-in and selectively input the working fluid into the working fluid circuit via the second system tie-in; and a control system for controlling a flow of working fluid to the working fluid circuit and to the pump, the control system being configured to maintain a pressure at an inlet of the pump between a low pressure level greater than a saturation pressure of the working fluid and a high pressure level greater than the low pressure level.

**[0010c]** Certain exemplary embodiments can provide a method of recovering waste heat in a working fluid circuit, comprising: pumping a first portion of a working fluid within the working fluid circuit by a pump to a waste heat exchanger fluidly coupled to the pump; pumping a separated portion of the working fluid with the pump through a first recuperator; transferring thermal energy from the first recuperator to the separated portion of the working fluid; expanding the first portion of the working fluid in a first expansion device fluidly coupled to the waste heat exchanger; transferring thermal energy from the first portion of the working fluid to the separated portion of the working fluid in a second recuperator fluidly coupled to the first expansion device, the second recuperator being configured to receive the separated portion of the working fluid following the first recuperator; expanding the separated portion of the working fluid in a second expansion device configured to receive the separated portion from the second recuperator; re-combining the first portion and the separated portion of the working fluid

to pass through the first recuperator; controlling an amount of working fluid mass in the working fluid circuit with a mass management system having a mass control tank fluidly coupled to a first system tie-in and a second system tie-in, the first system tie-in being fluidly coupled upstream from the first expansion device and the second system tie-in being fluidly coupled upstream from the pump; receiving the working fluid from the working fluid circuit into the mass control tank via the first system tie-in; inputting the working fluid into the working fluid circuit via the second system tie-in; and controlling with a control system a flow of working fluid to the working fluid circuit and to the pump, the control system being configured to maintain a pressure at an inlet of the pump between a low pressure level greater than a saturation pressure of the working fluid and a high pressure level greater than the low pressure level.

#### **Brief Description of the Drawings**

**[0011]** The present disclosure is best understood from the following detailed description when read with the accompanying Figures. It is emphasized that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

[0012] Figure 1 is a schematic of a simple thermodynamic waste heat recovery cycle.

[0013] Figure 2 is a schematic of an embodiment of a cascade thermodynamic waste heat recovery cycle, according to one or more embodiments disclosed.

[0014] Figure 3 is a schematic of another cascade thermodynamic waste heat recovery cycle, according to one or more embodiments disclosed.

[0015] Figure 4 is a schematic of another cascade thermodynamic waste heat recovery cycle, according to one or more embodiments disclosed.

[0016] Figure 5 is a schematic of another cascade thermodynamic waste heat recovery cycle, according to one or more embodiments disclosed.

[0017] Figure 6 is a schematic of a mass management system (MMS) which can be used in connection with the disclosed cascade thermodynamic waste heat recovery cycles, according to one or more embodiments disclosed.

[0018] Figure 7 is a schematic of another mass management system (MMS) which can be used in connection with the disclosed cascade thermodynamic waste heat recovery cycles, according to one or more embodiments disclosed.

[0019] Figures 8 and 9 schematically illustrate different system arrangements for inlet chilling of a separate fluid stream (e.g., air) by utilization of the working fluid which can be used in the exemplary heat engine cycles disclosed herein.

[0020] Figure 10 illustrates an exemplary waste heat recovery system including a mass management system, according to one or more embodiments disclosed.

## **Detailed Description**

[0021] It is to be understood that the following disclosure describes several exemplary embodiments for implementing different features, structures, or functions of the invention. Exemplary embodiments of components, arrangements, and configurations are described below to simplify the present disclosure; however, these exemplary embodiments are provided merely as examples and are not intended to limit the scope of the invention. Additionally, the present disclosure may repeat reference numerals and/or letters in the various exemplary embodiments and across the Figures provided herein. This repetition is

for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various exemplary embodiments and/or configurations discussed in the various Figures. Moreover, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed interposing the first and second features, such that the first and second features may not be in direct contact. Finally, the exemplary embodiments presented below may be combined in any combination of ways, *i.e.*, any element from one exemplary embodiment may be used in any other exemplary embodiment, without departing from the scope of the disclosure.

**[0022]** Additionally, certain terms are used throughout the following description and claims to refer to particular components. As one skilled in the art will appreciate, various entities may refer to the same component by different names, and as such, the naming convention for the elements described herein is not intended to limit the scope of the invention, unless otherwise specifically defined herein. Further, the naming convention used herein is not intended to distinguish between components that differ in name but not function. Additionally, in the following discussion and in the claims, the terms "including" and "comprising" are used in an open-ended fashion, and thus should be interpreted to mean "including, but not limited to." All numerical values in this disclosure may be exact or approximate values unless otherwise specifically stated. Accordingly, various embodiments of the disclosure may deviate from the numbers, values, and ranges disclosed herein without departing from the intended scope. Furthermore, as it is used in the claims or specification, the term "or" is intended to encompass both exclusive and inclusive cases, *i.e.*, "A or B" is intended to be synonymous with "at least one of A and B," unless otherwise expressly specified herein.

**[0023]** The disclosure is made with reference to various embodiments as schematically depicted by the accompanying Figures. It should be noted that representative operative temperatures, pressures, and flow rates are indicated as examples only and are not in any way limiting to the scope of the disclosure.

**[0024]** Figure 1 illustrates a baseline recuperated "simple" thermodynamic cycle wherein a working fluid, such as supercritical CO<sub>2</sub>, is pumped through a working fluid circuit in thermal communication with a waste heat exchanger WHX. A power turbine PT is fluidly coupled to

the waste heat exchanger WHX downstream thereof. The working fluid is subsequently expanded in the power turbine PT in order to generate power or work. It will be appreciated, that the power turbine PT may include any type of expansion device without departing from the scope of the disclosure. The working fluid is cooled at a recuperator RC1 and returned to a low temperature state at a condenser C. The working fluid is then directed to a pump P to commence the fluid circuit anew. Depending upon the achievable temperature at the suction inlet of the pump P, and based on the available cooling supply temperature and condenser C performance, the suction pressure at the pump P may be either subcritical or supercritical. As will be described in more detail below, a "mass management system" may also be included in each of the working fluid circuits disclosed to add or remove working fluid (*i.e.*, mass) from the system, and thereby make the system more efficient by increasing the overall system pressure ratio to the maximum possible extent while maintaining pump suction pressure at an acceptable level.

**[0025]** Figure 2 schematically illustrates an exemplary embodiment of a "cascade" cycle in which the residual energy following the first-stage power turbine PT1 (*i.e.*, state 51) is used to preheat additional high pressure working fluid, or a downstream portion of the working fluid, to a temperature within approximately 5 to 10°C of the fluid at state 51. The downstream portion of the working fluid may subsequently be expanded through a second power turbine PT2 (or second stage turbine) adapted to drive a work-producing device. In one embodiment, the work-producing device may be an electrical generator either coupled by a gearbox or directly driving a high-speed alternator. It is also possible to connect the output of PT2 with the work-producing device, or generator, being driven by PT1. In other embodiments, the first and second stage power turbines PT1, PT2 may be integrated into a single piece of turbomachinery, such as a multiple-stage turbine using separate blade/disks on a common shaft, or as separate stages of a radial turbine driving a bull gear using separate pinions for each radial turbine.

**[0026]** The remainder of the cycle in Figure 2 may be substantially similar to the recuperated form of the cycle shown in Figure 1, with the exception that the discharge from both recuperators RC1 and RC2 may be combined together to enter the condenser C. That is, exhaust from the second power turbine PT2 may pass through a second recuperator RC2 in order to reduce the temperature of the separated portion of the working fluid prior to being recombined with the remaining portion of working fluid preceding the

condenser C. Pump P provides fluid pressure to flow the working fluid through the working fluid circuit of the cycle.

**[0027]** Each of the recuperators RC1, RC2 and condensers C disclosed in Figure 2, and those disclosed below in Figures 3-5, may, in at least one embodiment, include or employ one or more printed circuit heat exchange panels. Such heat exchangers and/or panels are known in the art, and are described in U.S. Pat. Nos. 6,921,518; 7,022,294; and 7,033,553.

**[0028]** By using multiple turbines PT1, PT2 at similar pressure ratios, a larger fraction of the available heat source from the waste heat exchanger WHX is utilized and residual heat from the turbines PT1, PT2 is recuperated. Consequently, additional heat is extracted from the waste heat source through multiple temperature expansions. As can be appreciated, using multiple turbines PT1, PT2 at similar pressure ratios utilizes a larger spectrum of the available heat source and the residual heat from each turbine PT1, PT2 can be recuperated and combined with any residual waste heat.

**[0029]** In one or more embodiments, the arrangement of the recuperators RC1, RC2 in any of the embodiments disclosed herein can be optimized in conjunction with the waste heat exchanger WHX to maximize power output of the multiple temperature expansion stages. Also, both sides of each recuperator RC1, RC2 can be balanced, for example, by matching heat capacity rates and selectively merging the various flows in the working fluid circuits through waste heat exchangers and recuperators;  $C = m \cdot c_p$ , where C is the heat capacity rate, m is the mass flow rate of the working fluid, and  $c_p$  is the constant pressure specific heat. As appreciated by those skilled in the art, balancing each side of the recuperators RC1, RC2 provides a higher overall cycle performance by improving the effectiveness of the recuperators RC1, RC2 for a given available heat exchange surface area.

**[0030]** The waste heat exchanger(s) WHX used in the various embodiments disclosed herein may be any type of waste heat exchange device or medium operative to transfer thermal energy from a waste heat source or other heat source to the working fluid. In at least one embodiment, the waste heat exchanger WHX may include a printed circuit heat exchanger.

**[0031]** Figure 3 is similar to Figure 2, but with one key exception. In Figure 3, the second power turbine PT2 may be coupled to the pump P either directly or through a gearbox. The motor that drives the pump P may still be used to provide power during system startup, and may provide a fraction of the drive load for the pump P under some conditions. In other cases, however, it is possible to utilize the motor as a generator, particularly if the second power turbine PT2 is able to produce more power than the pump P requires for system operation.

**[0032]** Figure 4 is a variation of the system of Figure 3, whereby the motor-driven pump P is replaced by or operatively connected to a high-speed, direct-drive turbopump TP. As illustrated, a small "starter pump" SP or other pumping device may be used during system startup, but once the turbopump TP generates sufficient power to "bootstrap" itself into steady-state operation, the starter pump SP can be shut down. Additional control valves CV1 and CV2 may be included to facilitate operation of the turbopump TP under varying load conditions. The additional control valves CV1, CV2 may also be used to get heat into the turbopump TP before the main power turbine PT has started. For example, at system startup the shut off valve SOV1 may be closed and the first control valve CV1 opened such that the heated working fluid discharged from the waste heat exchanger WHX may be directed to the turbopump TP in order to drive the system pump P until achieving steady-state operation. Once at steady-state operation, the control valve CV1 may be closed and simultaneously open the shut off valve SOV1 in order to direct heated working fluid from the waste heat exchanger WHX to the power turbine PT.

**[0033]** Figure 5 schematically illustrates an exemplary embodiment of a dual cascade cycle which can be implemented in a heat engine cycle. Following the pump P, the working fluid may be separated at point 502 into a first portion  $m_1$  and a separated portion  $m_2$ . The first portion  $m_1$  may be directed to the waste heat exchanger WHX and subsequently expanded in the first stage power turbine PT1. Residual energy in the exhaust working fluid  $m_1$  following the first stage power turbine PT1 (e.g., state 5) may be used to preheat the separated portion  $m_2$  in a second recuperator (Recup2) after the separated portion  $m_2$  has previously passed through a first recuperator Recup1 to thereby increase its temperature. In one embodiment, the second recuperator (Recup2) may be configured to preheat the separated portion  $m_2$  to a temperature within approximately 5 to 10°C of the exhaust working fluid  $m_1$  fluid at state 5. The separated portion  $m_2$  at state 45 may be subsequently

expanded through a second-stage power turbine PT2 and thereafter re-combine with the first portion  $m_1$  at point 504. The re-combined working fluid  $m_1 + m_2$  may then be directed to a loop including a first recuperator (Recup1), a condenser (e.g., state 6), and a working fluid pump P (e.g., state 1).

**[0034]** In all of the fluid circuit embodiments disclosed herein, and any equivalents thereof, an optional bypass loop can be included whereby all or some of the working fluid can be directed through the bypass loop and not into one or more of the recuperators RC1, RC2. By providing this flexibility to the system, the operator or control system can monitor and control operation according to the amount of heat available at one or more locations within the system, and thereby maximize efficiency.

**[0035]** As briefly mentioned above, the working fluid circulated in each of the exemplary cycles described herein may be carbon dioxide. Carbon dioxide is a greenhouse friendly and neutral working fluid that offers benefits such as non-toxicity, non-flammability, easy availability, low price, and no need of recycling. It should be noted that the use of the term "carbon dioxide" is not intended to be limited to a carbon dioxide of any particular type, purity, or grade. For example, in at least one embodiment industrial grade carbon dioxide may be used.

**[0036]** In other embodiments, the working fluid circulated in each of the exemplary cycles described herein may a binary, ternary, or other working fluid blend. The working fluid combination can be selected for the unique attributes possessed by the fluid combination within a heat recovery system, as described herein. For example, one such fluid combination includes a liquid absorbent and carbon dioxide mixture enabling the combined fluid to be pumped in a liquid state to high pressure with less energy input than required to compress CO<sub>2</sub>. In another embodiment, the working fluid may be a combination of carbon dioxide or supercritical carbon dioxide and one or more other miscible fluids or chemical compounds. In yet other embodiments, the working fluid may be a combination of carbon dioxide and propane, or carbon dioxide and ammonia, without departing from the scope of the disclosure.

**[0037]** In the exemplary fluid cycles described herein, the working fluid may be in a supercritical state over certain portions of the system (the "high pressure side"), and in a subcritical state over other portions of the system (the "low pressure side"). In other

embodiments, the entire fluid cycle may be operated such that the working fluid is in a supercritical or subcritical state during the entire execution of the cycle.

**[0038]** Using the term "working fluid" is not intended to limit the state or phase of matter that the working fluid is in. In other words, the working fluid may be in a fluid phase, a gas phase, a supercritical phase, a subcritical state, or any other phase or state at any one or more points within the fluid cycle. For example, in one embodiment the pressure at the inlet of the pump P exceeds the vapor pressure of the working fluid by a margin sufficient to prevent vaporization of the fluid at the local regions of the low pressure and/or high velocity. This is especially important with high speed pumps such as the turbopumps used in the various embodiments disclosed herein. Consequently, a traditional passive system, such as one that employs a surge tank which only provides the incremental pressure of gravity relative to the fluid vapor pressure, is insufficient for the embodiments disclosed herein.

**[0039]** The use of carbon dioxide in power cycles requires particular attention to minimize the suction pressure of the pump P due to several factors. One factor is carbon dioxide's near-ambient critical temperature which requires the suction pressure of the pump P to be controlled both above and below the critical pressure (e.g., subcritical and supercritical operation). Another factor to consider is carbon dioxide's relatively high compressibility which makes the volumetric and overall pump efficiency more sensitive to suction pressure margin than other working fluids. At least one more factor is carbon dioxide's low overall pressure ratio which makes the cycle efficiency more sensitive to suction pressure margin.

**[0040]** In order to minimize the suction pressure of the pump P, among other benefits, embodiments of the disclosure may further include the incorporation and use of a mass management system ("MMS") in connection with or integrated into the described thermodynamic fluid cycles. The MMS may be configured to control the inlet pressure at the pump P by adding and/or removing mass from the system, and this in turn makes the system more efficient by increasing the overall system pressure ratio to the maximum possible extent. In at least one embodiment, the MMS operates with the system semi-passively. For example, the MMS may use sensors to monitor pressures and temperatures within the high pressure side (from pump P outlet to turbine PT1 inlet) and low pressure side (from turbine PT1 outlet to pump P inlet) of the system. The MMS may also include

valves, tank heaters, pumps, or other equipment to facilitate the movement of the working fluid into and out of the system and a mass control tank for storage of working fluid.

**[0041]** Referring to Figure 10, illustrated is an exemplary embodiment of a waste heat recovery system that includes a MMS 100 having a plurality of valves 14, 15, 16, 17, 18, 21, 22, and 23, a mass control tank 7, and a control system 108. The MMS 100 is operatively connected to the waste heat recovery system at the valves or termination points 14, 15, 16, 17, 18, 21, 22, and 23. In one embodiment, the MMS 100 is adapted to remove higher pressure and denser working fluid (relative to the pressure, temperature, and density on the low pressure side of the system) from the thermodynamic cycle via valve 16. The MMS 100 may dispense working fluid into the waste heat recovery system via valve 15. The MMS 100 automatically pressurizes the mass control tank 7 by opening valve 14 until the pressure within mass control tank 7 is sufficient to inject fluid through valve 15. By controlling the operation of the valves 14, 15, 16, the MMS 100 adds and/or removes mass (*i.e.*, working fluid) to/from the waste heat recovery system without the need of a pump, thereby reducing system cost, complexity, and maintenance.

**[0042]** In the illustrated embodiment, the MMS 100 includes a mass control tank 7 that may be filled with working fluid. The tank 7 may be in fluid communication with valves 14, 16 such that opening either or both valves 14, 16 will deliver working fluid to the top of the mass control tank 7. The mass control tank 7 may also be in fluid communication with the valve 15 such that opening the valve 15 will remove working fluid from the bottom of the mass control tank 7 to be injected into the waste heat recovery system adjacent and preceding the pump 9. Within the mass control tank 7 the working fluid may be in liquid phase, vapor phase, or both, or in a supercritical state; if the working fluid is in both vapor phase and liquid phase, a phase boundary may separate the two phases whereby the denser working fluid settles at the bottom of the mass control tank 7. Consequently, the working fluid contained within the mass control tank 7 will tend to stratify with the higher density working fluid at the bottom of the tank 7 and the lower density working fluid at the top of the tank 7. In this way, the valve 15 will be able to deliver to the waste heat recovery system the densest working fluid from within the mass control tank 7.

**[0043]** A first set of sensors 102 may be arranged at the suction inlet of the pump 9 and be configured to measure and report the temperature, pressure, and mass flow rate of the working fluid at that point in the system. A second set of sensors 104 may be arranged at

or adjacent the outlet of the pump 9 and configured to measure and report the temperature, pressure, and mass flow rate of the working fluid at that point in the system. A third set of sensors 106 may communicate with the mass control tank 7 and be configured to measure and report the pressure and temperature of the working fluid within the tank 7. Each set of sensors 102, 104, 106 may be in communication (wired and/or wireless) with a control system 108 that is also in communication with each of the valves 14, 15, 16 via actuators, servos, or other devices capable of manipulating the general disposition (*i.e.*, open/closed) of each valve 14, 15, 16. Accordingly, the control system 108 may receive the measurement communications from each set of sensors 102, 104, 106 and adjust each valve 14, 15, 16 in order to maximize operation of the waste heat recovery system. Moreover, the first set of sensors 102 may correspond to location 1 in Figures 1-5, and the second set of sensors 104 may correspond to location 2 in Figures 1-5.

**[0044]** The exemplary MMS 100 may also include points 18 and 19 used to purge and/or fill working fluid to/from the waste heat recovery system. Point 17 may be used to vent working fluid from the MMS 100, and other illustrated equipment is used in a variety of operating conditions such as start up, charging, and shut-down of the waste heat recovery system. A more detailed description of the other illustrated equipment may be found in co-pending U.S. patent no. 8,096,128.

**[0045]** Operation of the exemplary MMS 100 follows. When the working fluid, such as CO<sub>2</sub>, in the mass storage tank 7 is at the fluid vapor pressure for a given ambient temperature, and the low side pressure in the waste heat recovery system is above the vapor pressure, the pressure in the mass control tank 7 must be increased to allow for the addition of mass into the waste heat recovery system. This can be controlled by opening valve 14 and thereby allowing higher pressure, higher temperature, lower density working fluid, such as supercritical CO<sub>2</sub>, to flow into the mass control tank 7. Valve 15 may be opened to allow higher density liquid working fluid at the bottom of the mass control tank 7 to flow into the waste heat recovery system and thereby increase the suction pressure of the pump 9.

**[0046]** The description of the foregoing MMS 100 may be equally applicable as a supplement to the various thermodynamic cascade cycles disclosed herein, and shown generally in Figures 1-5. For example, referring now to Figures 6 and 7, Figure 7

schematically illustrates a mass management system 700 substantially similar to the MMS 100 shown in Figure 10, and Figure 6 schematically illustrates another exemplary mass management system 600. System tie-in points A, B, and C as shown in Figures 6, 7 and 10 (only points A and C shown in Figure 6) correspond to the system tie-in points A, B, and C shown in Figures 1-5. Accordingly, MMS 600 and 700 may each be fluidly coupled to the cascade cycled of Figures 1-5 at the corresponding system tie-in points A, B, and C (if applicable). The MMS 600 stores a working fluid at low (sub-ambient) temperature and therefore low pressure, and MMS 700 stores a working fluid at or near ambient temperature. As discussed above, the working fluid may be CO<sub>2</sub>, but may also be other working fluids without departing from the scope of the disclosure.

**[0047]** Where a working fluid pump P is indicated in each of the described cascade cycles of Figures 1-5, working fluid is supplied as necessary from a mass control tank T (Figures 6 and 7) to an inlet of the pump P. In operation, the MMS 700 works by selectively adding working fluid to the main loop of the cascade cycle by pressurizing the working mass control tank T and then opening a valve at the bottom of the mass control tank T to flow into the rest of the cycle through interface or system tie-in C. For example, the mass control tank T in Figure 7 may be pressurized by opening the valve at or adjacent interface A, and liquid may be released from the mass control tank T by opening the valve at or adjacent interface C. This process raises the system pump inlet pressure at pump P in Figures 1-5. To extract fluid from the main system loop, and decrease the system pump inlet pressure, the valve at interface B (Figure 7) may be opened, thereby permitting cool, pressurized fluid to enter the mass control tank T.

**[0048]** In the embodiment of Figure 6, the MMS 600 uses only two system tie-ins or interface points A and C. The valve-controlled interface A is not used during the control phase, and is provided only to pre-pressurize the main fluid loop with vapor so that the temperature of the main fluid loop remains above a minimum threshold during fill. In operation, when the suction pressure of the pump P shown in Figures 1-5 needs to be increased, working fluid is selectively added to the main system loop by pumping it in with a transfer pump 602 provided at or proximate interface C. When the suction pressure of the pump P needs to be decreased, liquid is selectively extracted from the system at interface C and expanded through one or more valves down to the relatively low storage pressure. Under most conditions, the expanded fluid will be two-phase (i.e., vapor + liquid). To

prevent the pressure in the mass control tank T from exceeding its normal operating limits, a small vapor compression refrigeration cycle (vapor compressor VC) is provided to decrease the fluid temperature and sufficiently condense the vapor to maintain the pressure of the mass control tank T at its design condition. The vapor compression refrigeration cycle may be integrated within the CO<sub>2</sub> storage tank system, or may be a standalone vapor compression cycle with an independent refrigerant loop.

**[0049]** Although not necessary in every application, the MMS 700 may also include a transfer pump 704, substantially similar to the transfer pump 602 of Figure 6. The transfer pump 704 may be configured to remove working fluid from the tank T and inject it into the working fluid circuit.

**[0050]** All of the various described controls or changes to the working fluid environment and status throughout the cascade cycle, including temperature, pressure, flow direction and rate, and component operation such as pumps and turbines, may be monitored and/or controlled by a control system 108, as generally described above with reference to Figures 6, 7, and 10. In one embodiment, the control system 108 may include one or more proportional-integral-derivative (PID) controllers as control loop feedback systems. In another embodiment, the control system 108 may be any microprocessor-based system capable of storing a control program and executing the control program to receive sensor inputs and generate control signals in accordance with a predetermined algorithm or table. For example, the controller may be a microprocessor-based computer running a control software program stored on a compute readable medium. The software program may be configured to receive sensor inputs from various pressure, temperature, flow rate, etc. sensors positioned throughout the system and generate control signals therefrom, wherein the control signals are configured to optimize and/or selectively control the operation of the system.

**[0051]** Each MMS 600, 700 may be communicably coupled to such a control system 108 such that control of the various valves and other equipment is automated or semi-automated and reacts to system performance data obtained via the various sensors located throughout the system, and also reacts to ambient and environmental conditions. That is to say that the controller 108 may be in communication with each of the components of the MMS 600, 700 and be configured to control the operation thereof to accomplish the function of the system more efficiently. For example, the control system

108 may be in communication (via wires, RF signal, etc.) with each of the valves, pumps, sensors, etc. in the system and configured to control the operation of each of the components in accordance with a control software, algorithm, or other predetermined control mechanism. This may prove advantageous to control temperature and pressure of the working fluid at the inlet of the pump P, to actively increase the suction pressure of the pump P by decreasing compressibility of the working fluid. Doing so may avoid damage to the pump P as well as increase the overall pressure ratio of the cascade cycle, thereby improving the efficiency and power output.

**[0052]** In one or more embodiments, it may prove advantageous to maintain the suction pressure of the pump P above the boiling pressure of the working fluid at the inlet of the pump P. One method of controlling the pressure of the working fluid in the low side of the working fluid circuit is by controlling the temperature of the working fluid in the mass control tank T. This may be accomplished by maintaining the temperature of the mass control tank T at a higher level than the temperature at the inlet of the pump P. To accomplish this, the MMS 600, 700 may include the use of a heater and/or a coil 702 within the tank T (Figure 7). The heater/coil 702 may be configured to add or remove heat from the fluid/vapor within the tank T. In one embodiment, the temperature of the mass control tank T may be controlled using direct electric heat. In other embodiments, however, the temperature of the mass control tank T may be controlled using other devices, such as but not limited to, a heat exchanger coil with pump discharge fluid (which is at a higher temperature than at the pump inlet), a heat exchanger coil with spent cooling water from the cooler/condenser (also at a temperature higher than at the pump inlet), or combinations thereof.

**[0053]** Referring now to Figures 8 and 9, chilling systems 800 and 900, respectively, may also be employed in connection with any of the above-described cycles in order to provide cooling to other areas of an industrial process, including but not limited to pre-cooling of the inlet air of a gas-turbine or other air-breathing engines, thereby providing for a higher engine power output. System tie-in points B and D or C and D in Figures 8 and 9 may correspond to the system tie-in points B, C, and D in Figures 1-5. Accordingly, chilling systems 800, 900 may each be fluidly coupled to the cascade cycles of Figures 1-5 at the corresponding system tie-in points B, C, and/or D (where applicable). In the chilling system 900 of Figure 9, a portion of the working fluid may be extracted from the working fluid circuit at system tie-in C. The pressure of that portion of fluid is reduced through an expansion

device 902, which may be a valve, orifice, or fluid expander such as a turbine or positive displacement expander. This expansion process decreases the temperature of the working fluid. Heat is then added to the working fluid in an evaporator heat exchanger 904, which reduces the temperature of a process fluid (e.g., air, as shown in Figures 8 and 9). The fluid pressure is then increased through the use of a compressor 802, where it is reintroduced to the working fluid circuit at system tie-in D.

**[0054]** The compressor 802 shown in Figures 8 and 9 may be either motor-driven or turbine-driven off either a dedicated turbine or an additional wheel added to a primary turbine of the system. In other embodiments, the compressor 802 may be integrated with the main working fluid circuit. In other embodiments, the compressor 802 may take the form of a fluid ejector, with motive fluid supplied from system tie-in point A, and discharging to system tie-in point D, upstream from the condenser C. In the chilling system 800 of Figure 8, the compressor 802 may take the form of a fluid ejector, with motive fluid supplied from system tie-in point A (not shown, but corresponding to point A in Figures 1-5), and discharging to system tie-in point D. In another embodiment, the working fluid is extracted from system tie-in point B shown in Figure 1-5 and pre-cooled by a heat exchanger 804 prior to expansion in an expansion device 806, similar to the expansion device 902 described above. In one embodiment, the heat exchanger 804 may include a water, air, water-CO<sub>2</sub>, or air-CO<sub>2</sub> heat exchanger. As can be appreciated, the addition of the heat exchanger 804 may provide additional cooling capacity relative to the chilling system 900 shown in Figure 9.

**[0055]** Each of the described cascade cycles may be implemented in a variety of physical embodiments, including but not limited to fixed or integrated installations or as a self-contained device such as a portable waste heat engine or "skid" wherein the working fluid circuit and related components such as turbines, recuperators, condensers, pumps, valves, working fluid supply and control systems and mechanical and electronic controls are consolidated as a single unit, as further disclosed and described in the related applications.

**[0056]** The terms "upstream" and "downstream" as used herein are intended to more clearly describe various embodiments and configurations of the disclosure. For example, "upstream" generally means toward or against the direction of flow of the working fluid during normal operation, and "downstream" generally means with or in the direction of the flow of the working fluid during normal operation.

**[0057]** The foregoing has outlined features of several embodiments so that those skilled in the art may better understand the present disclosure. Those skilled in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein.

## CLAIMS

1. A working fluid circuit for waste heat recovery, comprising:
  - a pump operative to direct a working fluid within the working fluid circuit to a waste heat exchanger fluidly coupled to the pump;
  - a first expansion device fluidly coupled to the waste heat exchanger and configured to receive the working fluid from the waste heat exchanger;
  - a first recuperator fluidly coupled to the first expansion device and configured to receive the working fluid from the first expansion device and transfer heat from the working fluid to a downstream portion of the working fluid;
  - a second expansion device fluidly coupled to the pump downstream from the pump and configured to receive the downstream portion of the working fluid;
  - a second recuperator fluidly coupled to the second expansion device and configured to receive the downstream portion of the working fluid from the second expansion device;
  - a condenser fluidly coupled to the first recuperator and the second recuperator, wherein the working fluid discharged from both the first recuperator and the second recuperator are combined prior to entering the condenser; and
  - a mass management system having a first system tie-in fluidly coupled upstream from the first expansion device and a second system tie-in fluidly coupled upstream from the pump, the mass management system having a mass control tank configured to selectively receive the working fluid from the working fluid circuit via the first system tie-in and to selectively input the working fluid into the working fluid circuit via the second system tie-in.
2. The working fluid circuit of claim 1, wherein the second expansion device is configured to drive the pump.
3. The working fluid circuit of claim 2, further comprising a starter pump fluidly coupled to a downstream side of the condenser and a downstream side of the pump.

4. The working fluid circuit of claim 1, wherein the working fluid comprises carbon dioxide.
5. The working fluid circuit of claim 4, wherein the working fluid is in a supercritical state through a portion of the working fluid circuit.
6. The working fluid circuit of claim 1, wherein the first and second expansion devices are power turbines.
7. The working fluid circuit of claim 1, wherein the mass management system comprises a system controller configured to sense at least one of a temperature and a pressure in the working fluid circuit, and in response thereto, generate control signals for at least one of a plurality of selectively-actuated valves and/or pumps arranged in the working fluid circuit, the mass management system being configured to maintain a pressure at an inlet of the pump between a low pressure level greater than a saturation pressure of the working fluid and a high pressure level greater than the low pressure level.
8. A working fluid circuit for waste heat recovery, comprising:
  - a pump configured to direct a working fluid within the working fluid circuit to a waste heat exchanger fluidly coupled to the pump, the working fluid being separated into a first portion and a separated portion, wherein the first portion passes through the waste heat exchanger;
  - a first recuperator configured to receive the separated portion of the working fluid and to increase the temperature of the separated portion;
  - a first expansion device fluidly coupled to the waste heat exchanger and configured to receive the first portion of the working fluid from the waste heat exchanger;
  - a second recuperator fluidly coupled to the first expansion device and configured to receive the first portion of the working fluid from the first expansion device, the

second recuperator also configured to receive the separated portion of the working fluid following the first recuperator and to further increase the temperature of the separated portion;

a second expansion device configured to receive the separated portion of the working fluid from the second recuperator;

a condenser fluidly coupled to the first recuperator and the second recuperator, wherein the separated portion of the working fluid and the first portion of the working fluid are re-combined prior to entering the first recuperator and the condenser; and

a mass management system having a first system tie-in fluidly coupled upstream from the first expansion device and a second system tie-in fluidly coupled upstream from the pump, the mass management system having a mass control tank configured to selectively receive the working fluid from the working fluid circuit via the first system tie-in and selectively input the working fluid into the working fluid circuit via the second system tie-in.

9. The working fluid circuit of claim 8, wherein the first recuperator uses heat derived from a re-combined working fluid to increase the temperature of the separated portion of the working fluid.

10. The working fluid circuit of claim 8, further comprising a control system for controlling a flow of working fluid to the working fluid circuit and to the pump, the control system being configured to maintain a pressure at an inlet of the pump between a low pressure level greater than a saturation pressure of the working fluid and a high pressure level greater than the low pressure level.

11. The working fluid circuit of claim 8, wherein the working fluid comprises carbon dioxide.

12. The working fluid circuit of claim 11, wherein the working fluid is in a supercritical state through a portion of the working fluid circuit.

13. The working fluid circuit of claim 8, wherein the first and second expansion devices are power turbines.
14. A method of recovering waste heat in a working fluid circuit, comprising:
  - pumping a working fluid within the working fluid circuit by a pump, the working fluid being separated into a first portion and a separated portion downstream from the pump;
  - pumping the first portion of the working fluid by the pump to a waste heat exchanger fluidly coupled to the pump;
  - pumping the separated portion of the working fluid by the pump through a first recuperator;
  - transferring thermal energy from the first recuperator to the separated portion of the working fluid;
  - expanding the first portion of the working fluid in a first expansion device fluidly coupled to the waste heat exchanger;
  - transferring thermal energy from the first portion of the working fluid to the separated portion of the working fluid in a second recuperator fluidly coupled to the first expansion device, the second recuperator being configured to receive the separated portion of the working fluid following the first recuperator;
  - expanding the separated portion of the working fluid in a second expansion device configured to receive the separated portion from the second recuperator;
  - re-combining the first portion and the separated portion of the working fluid to pass through the first recuperator and a condenser, the condenser being fluidly coupled to the first recuperator; and
  - controlling an amount of working fluid mass in the working fluid circuit with a mass management system having a mass control tank fluidly coupled to a first system tie-in and a second system tie-in, the first system tie-in being fluidly coupled upstream from the first expansion device and the second system tie-in being fluidly coupled upstream from the pump.

15. The method of claim 14, further comprising:
  - receiving the working fluid from the working fluid circuit into the mass control tank via the first system tie-in; and
  - inputting the working fluid into the working fluid circuit via the second system tie-in.
16. The method of claim 15, further comprising controlling with a control system a flow of working fluid to the working fluid circuit and to the pump, the control system being configured to maintain a pressure at an inlet of the pump between a low pressure level greater than a saturation pressure of the working fluid and a high pressure level greater than the low pressure level.
17. The method of claim 14, wherein the working fluid comprises carbon dioxide.
18. The method of claim 17, wherein the working fluid is in a supercritical state through a portion of the working fluid circuit.
19. A working fluid circuit for waste heat recovery, comprising:
  - a pump operative to direct a working fluid within the working fluid circuit to a waste heat exchanger fluidly coupled to the pump;
  - a first expansion device fluidly coupled to the waste heat exchanger and configured to receive the working fluid from the waste heat exchanger;
  - a first recuperator fluidly coupled to the first expansion device and configured to receive the working fluid from the first expansion device and transfer heat from the working fluid to a downstream portion of the working fluid;
  - a second expansion device fluidly coupled to the pump downstream from the pump and configured to receive the downstream portion of the working fluid;
  - a second recuperator fluidly coupled to the second expansion device and configured to receive the downstream portion of the working fluid from the second expansion device;

a mass management system having a first system tie-in fluidly coupled upstream from the first expansion device and a second system tie-in fluidly coupled upstream from the pump, the mass management system having a mass control tank configured to selectively receive the working fluid from the working fluid circuit via the first system tie-in and selectively input the working fluid into the working fluid circuit via the second system tie-in;

a condenser fluidly coupled to the first and second recuperators on the upstream side fluidly coupled to the first recuperator and the second recuperator, wherein the working fluid discharged from both the first recuperator and the second recuperator are combined prior to entering the condenser; and

a starter pump fluidly coupled to a downstream side of the condenser and a downstream side of the pump, wherein the working fluid is comprises carbon dioxide and is in a supercritical state through a portion of the working fluid circuit.

20. A working fluid circuit for waste heat recovery, comprising:

a pump configured to direct a working fluid within the working fluid circuit to a waste heat exchanger fluidly coupled to the pump, the working fluid being separated into a first portion and a separated portion, wherein the first portion passes through the waste heat exchanger, wherein the working fluid is carbon dioxide, and achieves a supercritical state through a portion of the working fluid circuit;

a first recuperator configured to receive the separated portion of the working fluid and to increase the temperature of the separated portion;

a first expansion device fluidly coupled to the waste heat exchanger and configured to receive the first portion of the working fluid from the waste heat exchanger;

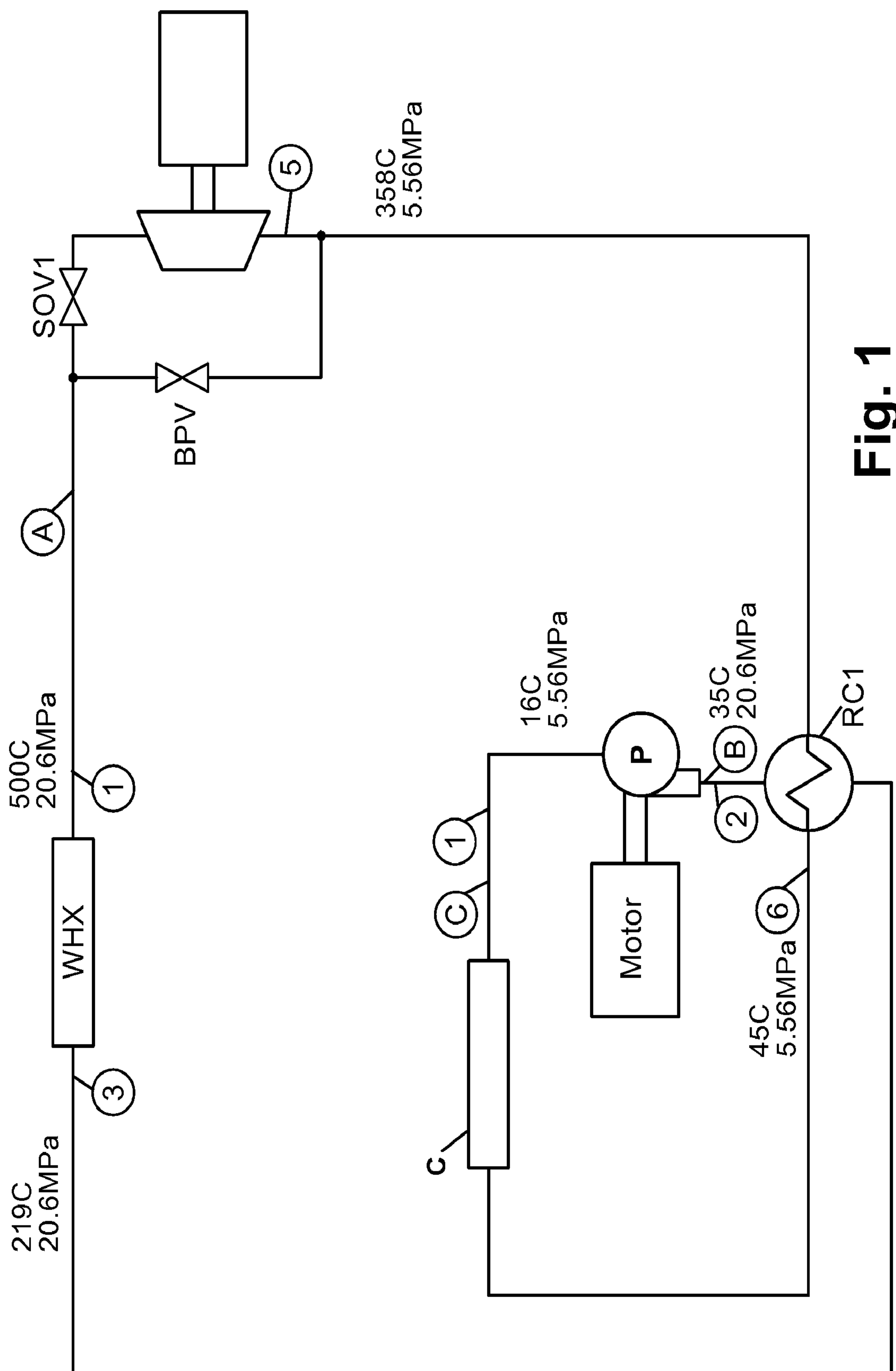
a second recuperator fluidly coupled to the first expansion device and configured to receive the first portion of the working fluid from the first expansion device, the second recuperator also configured to receive the separated portion of the working fluid following the first recuperator and to further increase the temperature of the separated portion;

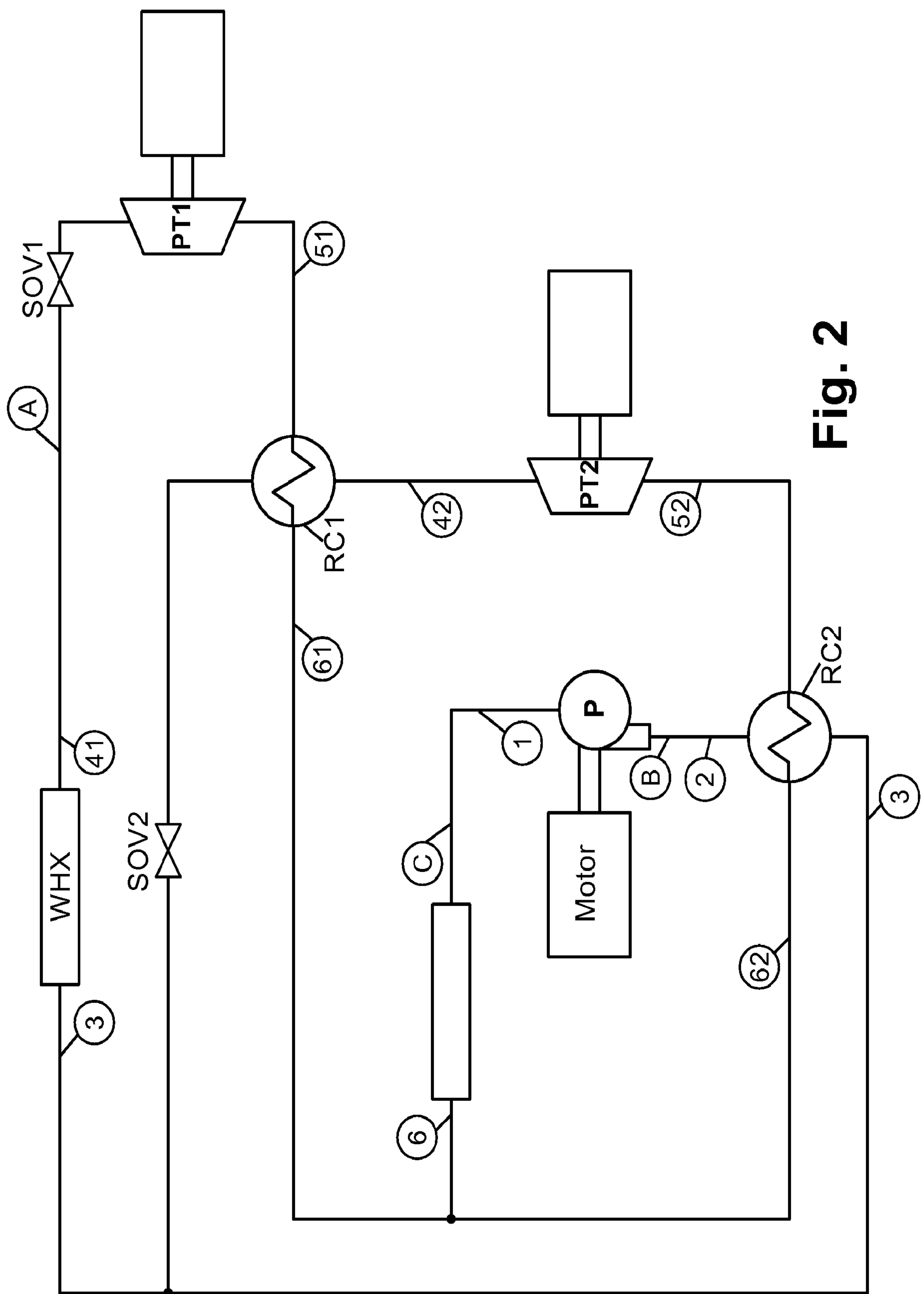
a second expansion device configured to receive the separated portion of the working fluid from the second recuperator;

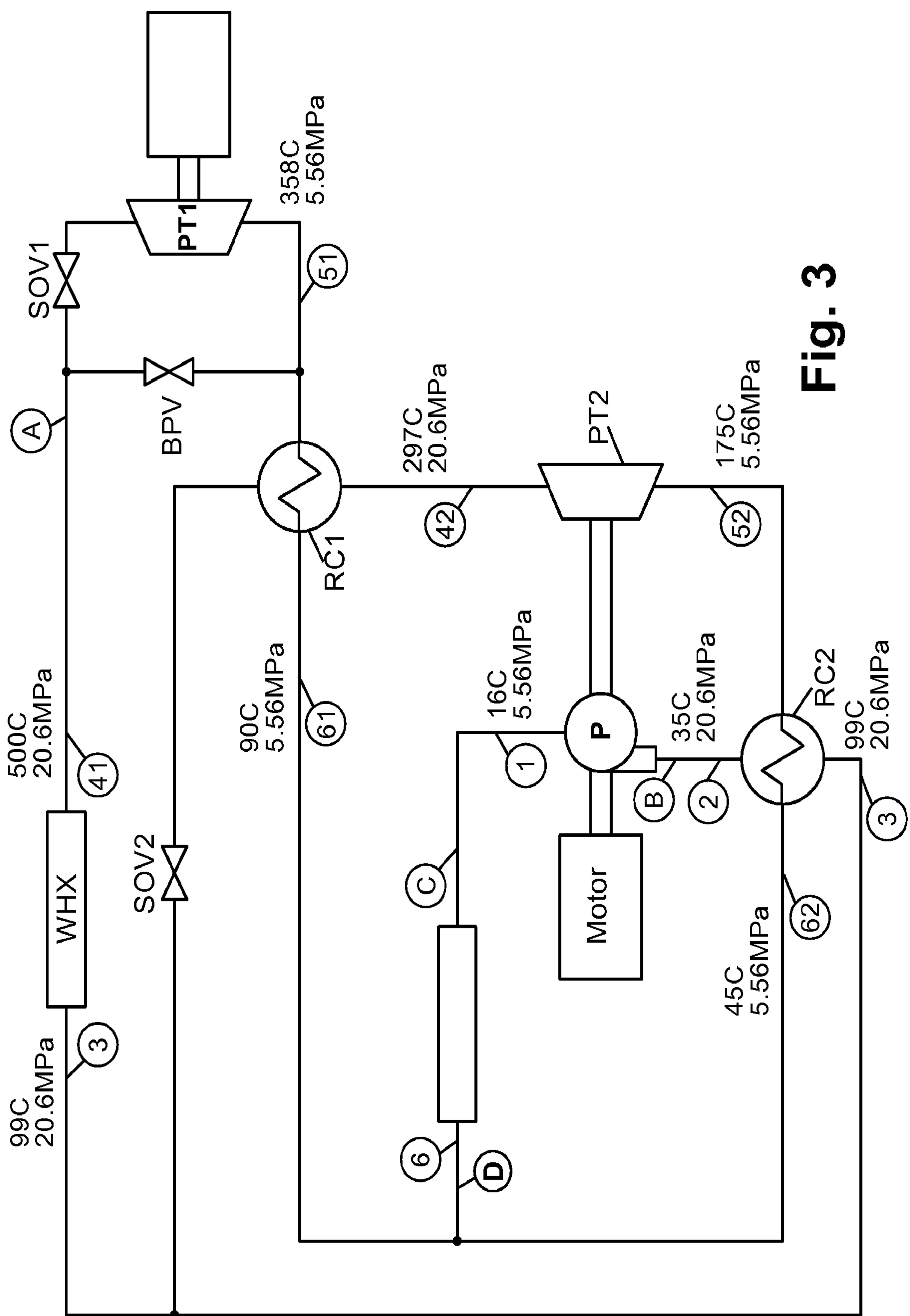
a condenser fluidly coupled to the first recuperator and the second recuperator, wherein the separated portion of the working fluid and the first portion of the working fluid are re-combined prior to entering the first recuperator and the condenser;

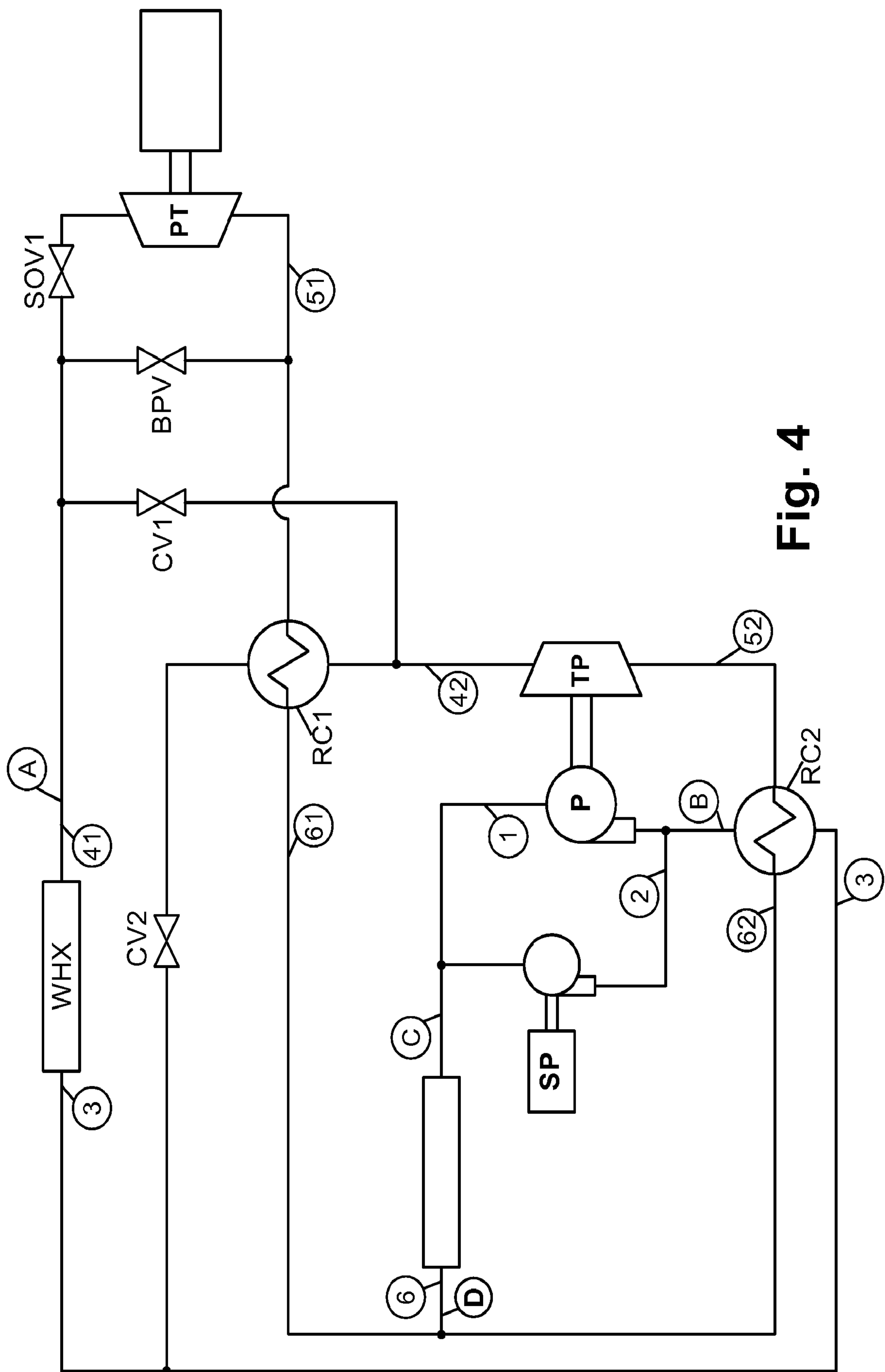
a mass management system having a first system tie-in fluidly coupled upstream from the first expansion device and a second system tie-in fluidly coupled upstream from the pump, the mass management system having a mass control tank configured to selectively receive the working fluid from the working fluid circuit via the first system tie-in and selectively input the working fluid into the working fluid circuit via the second system tie-in; and

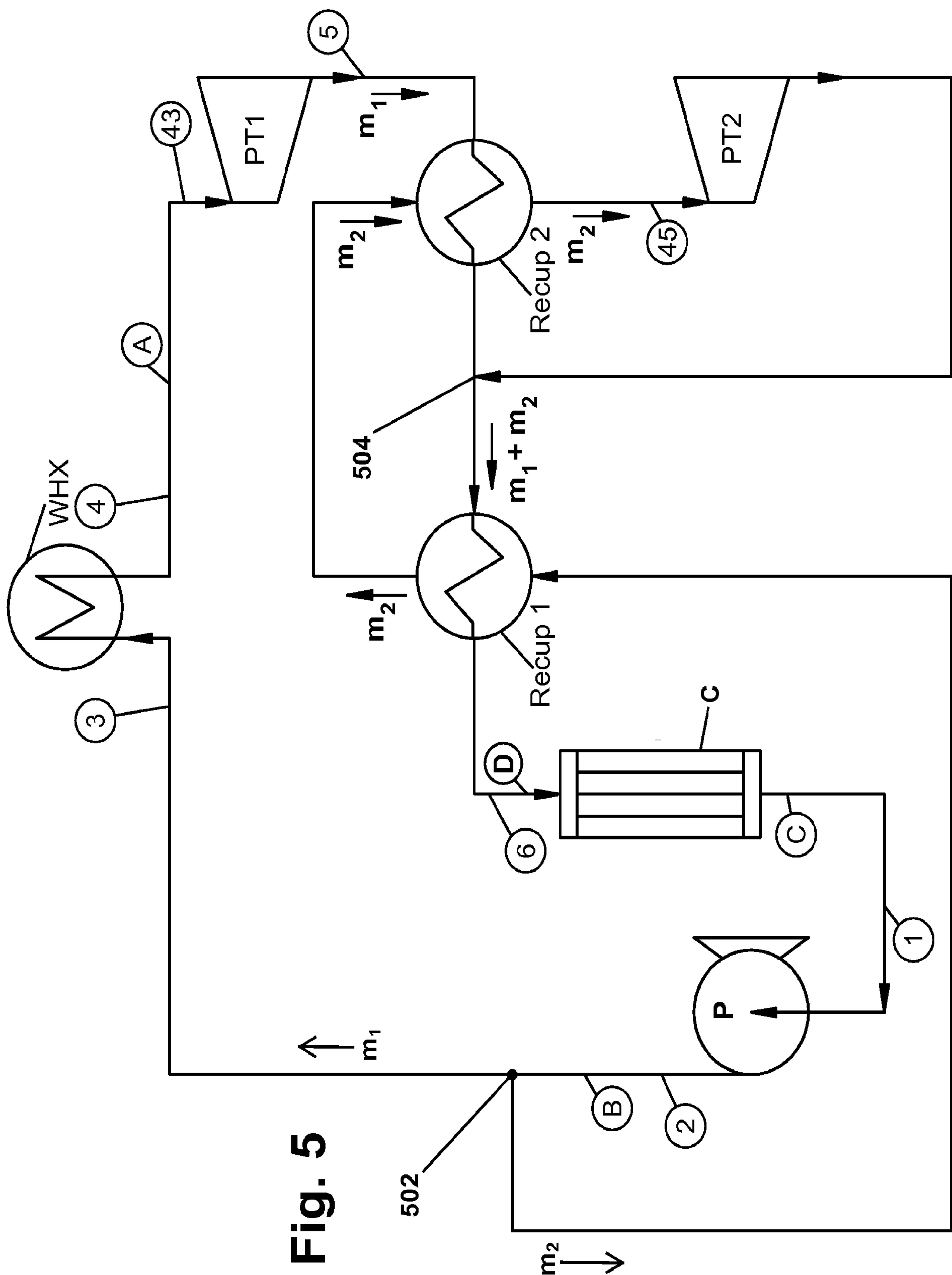
a control system for controlling a flow of working fluid to the working fluid circuit and to the pump, the control system being configured to maintain a pressure at an inlet of the pump between a low pressure level greater than a saturation pressure of the working fluid and a high pressure level greater than the low pressure level.

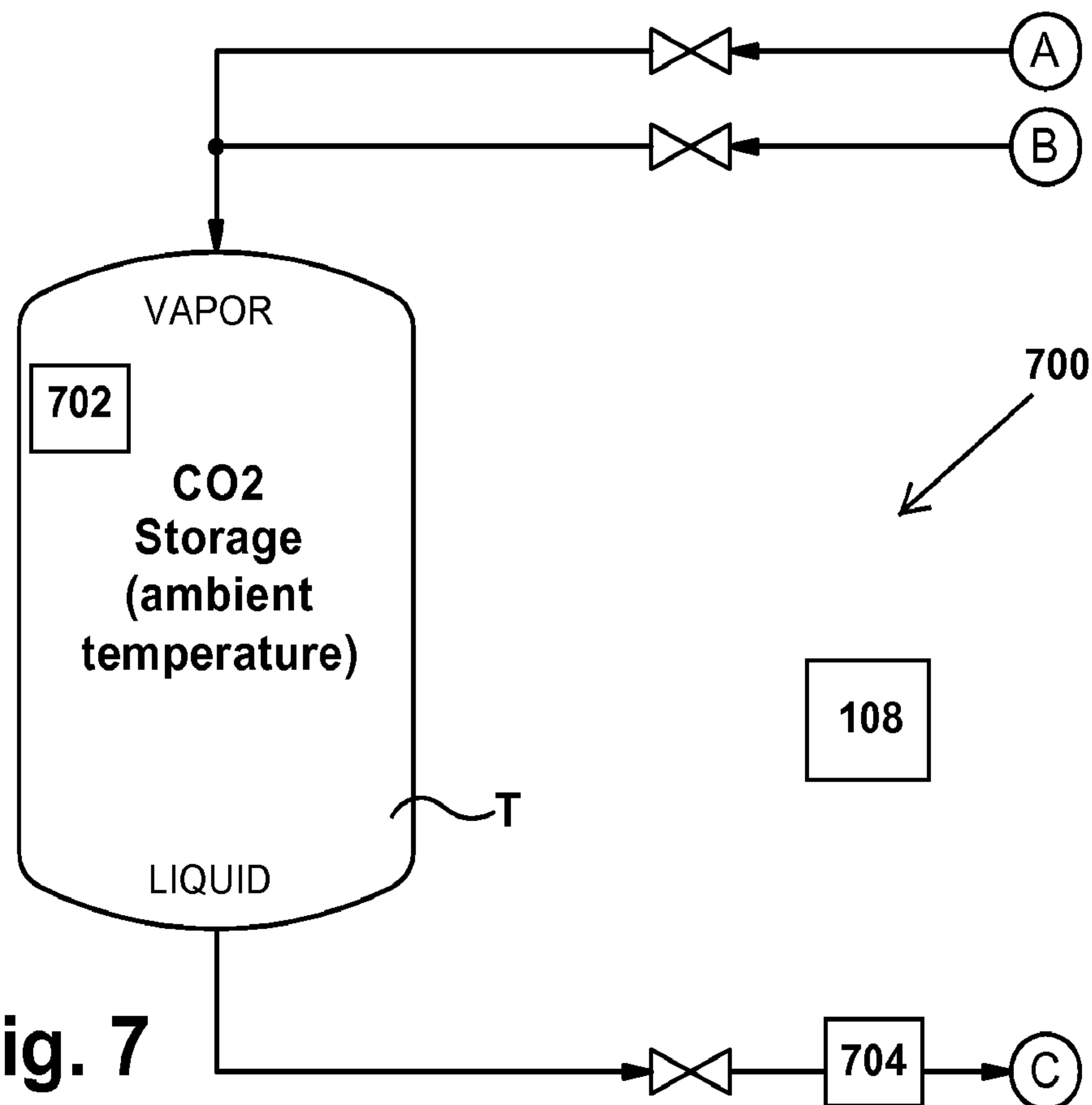
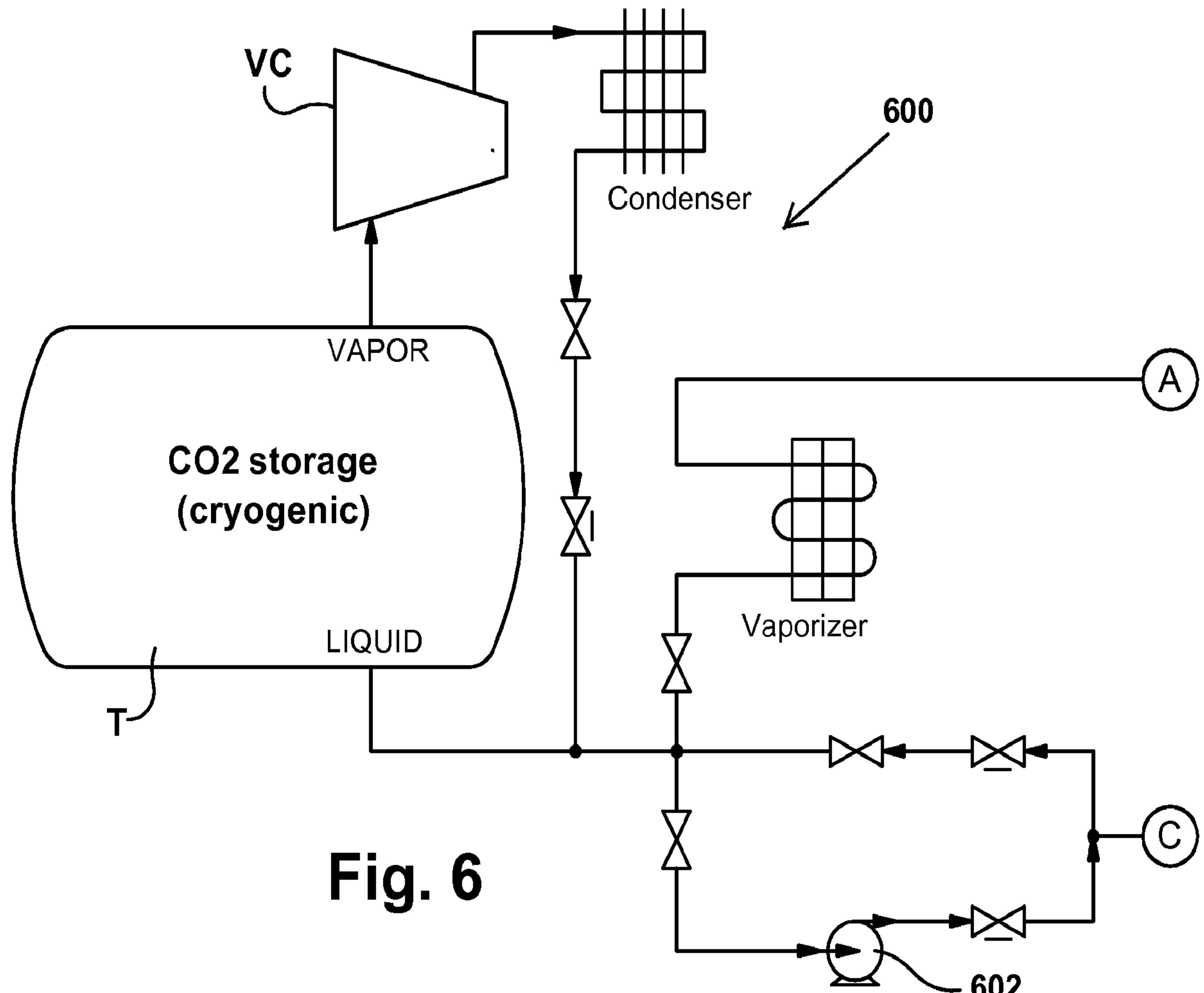
**Fig. 1**



**Fig. 3**

**Fig. 4**

**Fig. 5**



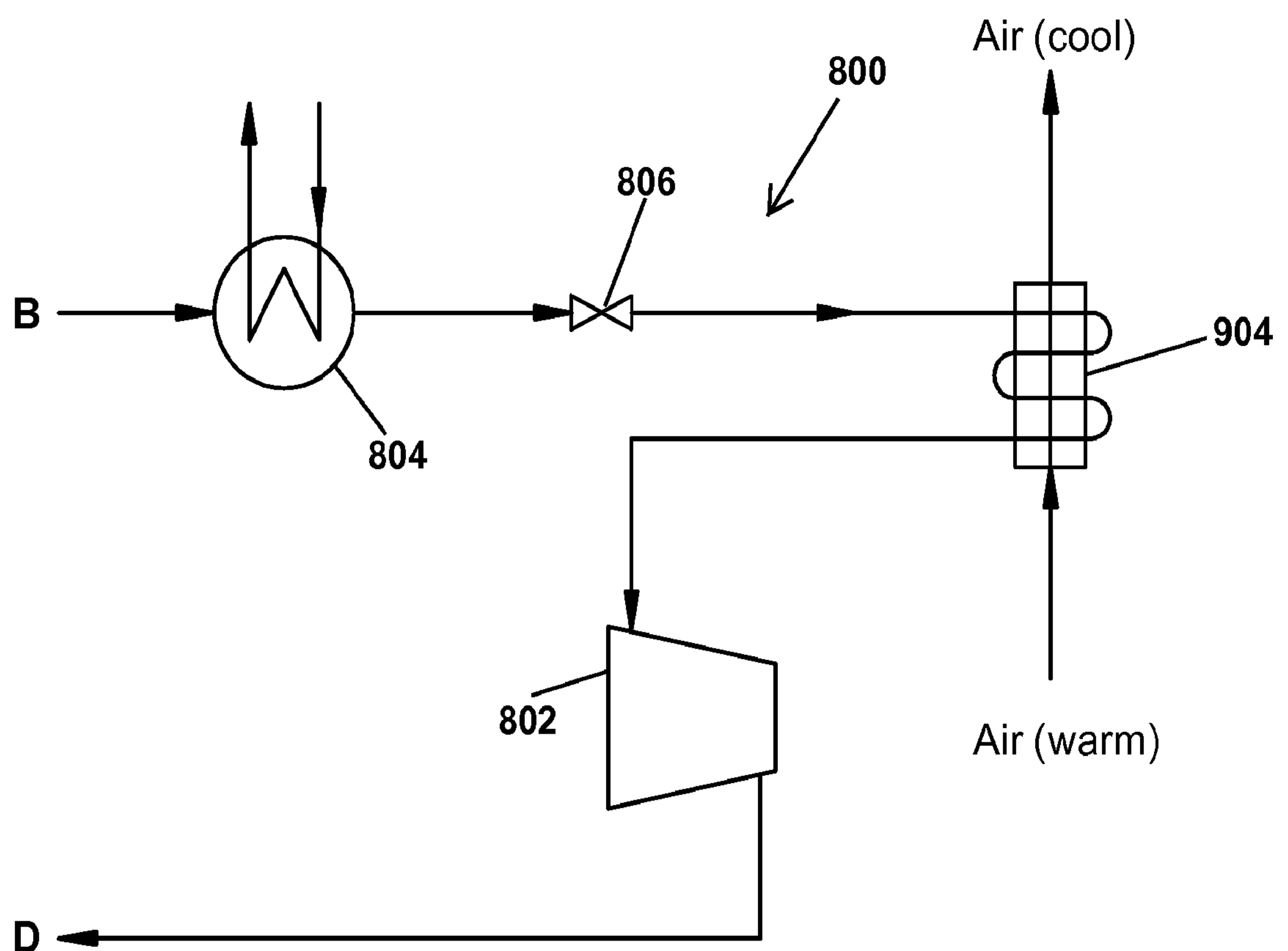


Fig. 8

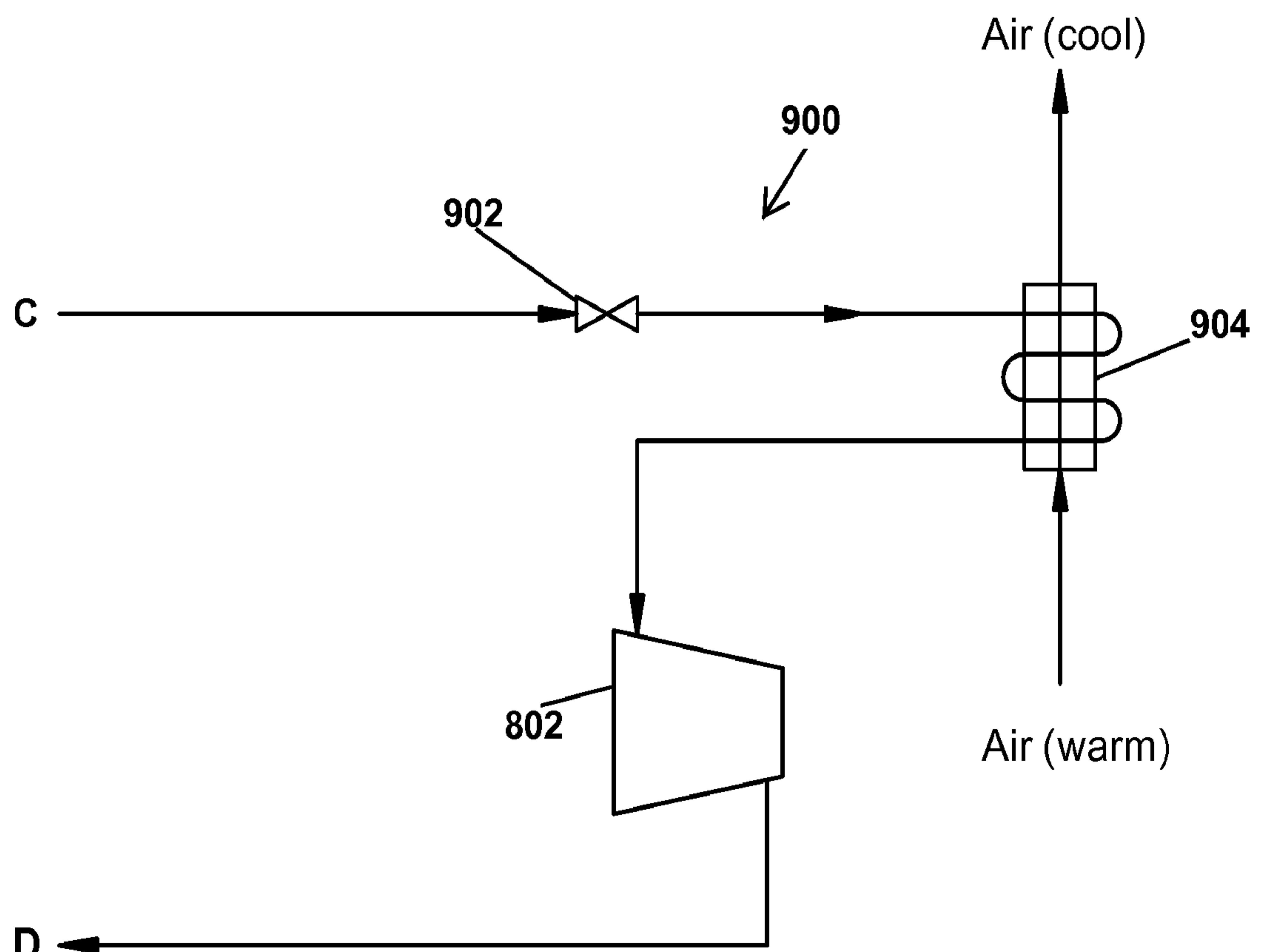


Fig. 9

10  
11  
12  
13  
14

