APPARATUS FOR RECIRCULATING A FLUID WITHIN A TURBOMACHINE AND METHOD FOR OPERATING THE SAME

ABSTRACT

A turbomachine for use with a high-temperature and high-pressure working fluid is provided. The turbomachine includes a rotatable shaft and a casing enclosing the rotatable shaft, which defines at least a first and second compartment fluidly coupled together. The first compartment at least partially encloses one of a compressor and an expander. The second compartment at least partially encloses a generator. Attached to opposite ends of the rotatable shaft is a compressor for compressing the working fluid and an expansion turbine for expanding the working fluid. A motor-generator is attached to the rotatable shaft between the compressor and expansion turbine. The turbomachine includes at least one sealing system positioned between the first and second compartments that includes a number of seals for regulating the flow rate of the working fluid between the first and second compartments and for suppressing the heat and pressure transfer between the first and second compartments.
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BACKGROUND

[0001] The subject matter described herein relates to turbomachines and, more particularly, to methods and apparatus for recirculating a fluid within turbomachines.

[0002] At least some known turbomachines operate in closed-loop systems and comprise an expansion turbine, a compressor, and a motor-generator, which are carried within expander, compressor, and motor-generator casings respectively, and are coupled to a common rotor shaft. These turbomachines may be referred to as turboexpanders. Often, some known closed-loop systems require the turbomachine enclosure to be hermetically-sealed, or canned, enclosure in order to retain the working fluid in the process loop. In at least some known canned enclosure turbomachines, substantially leak-free seals are positioned between the motor-generator casing and each of the expander and compressor casings.

[0003] Fluid leakage from the expander and compressor casings into the motor-generator casing may be recirculated into the process loop. At least some known turbomachine sealing system designs for regulating fluid leakage derive from gas turbines, which operate at temperatures up to 1,500 degrees Celsius (° C.) (2,732 degrees Fahrenheit (° F.)) and pressures up to 30 bars (3,000 kilo-Pascal (kPa), 435 pounds per square inch (psi)). In contrast, at least some known turbomachine sealing system designs for regulating fluid leakage derive from steam turbines, which operate at pressures up to approximately 310 bars (31,000 kPa, 4,500 psi) and temperatures up to 620° C. (1,148° F.). The sealing systems of these known turbomachines are capable of regulating and recirculating the working fluid under these conditions. However, the sealing systems of at least some known turbomachines will not operate as well under the high-temperature/high-pressure working conditions of high-density working fluids.

BRIEF DESCRIPTION

[0004] In one aspect, a turbomachine for use with a high-temperature and high-pressure working fluid is provided. The turbomachine includes a rotatable shaft that includes a first end portion and a second end portion. The turbomachine also includes a casing extending about and enclosing the rotatable shaft. The casing defines a number of compartments including a first compartment that at least partially encloses one of a compressor apparatus and an expander apparatus, and a second compartment coupled in flow communication with the first compartment and at least partially encloses a generator apparatus. The turbomachine further includes a compressor coupled to the first end portion of the rotatable shaft for compressing the working fluid. Additionally, the turbomachine includes an expansion turbine coupled to the second end portion of the rotatable shaft for expanding the working fluid. The turbomachine further includes a motor-generator coupled to the rotatable shaft and located between the first end portion and a second end portion of the rotatable shaft. Furthermore, the turbomachine includes at least one sealing system positioned between the first compartment and the second compartment. The sealing system includes a number of seals for regulating a predetermined flow rate of a working fluid between the first and second compartments. The first compartment contains the working fluid at a first pressure and a first temperature, and the second compartment contains the working fluid at a second pressure and a second temperature, wherein the first pressure is greater than the second pressure and the first temperature is greater than the second temperature.

[0005] In another aspect, a sealing system for a turbomachine is provided. The turbomachine includes a first compartment containing a working fluid at a first pressure and a first temperature, and a second compartment coupled in flow communication with the first compartment and containing the working fluid at a second pressure and a second temperature. The sealing system includes a first sealing device extending about a rotatable shaft and at least partially defining the first compartment of the turbomachine. The first sealing device is configured to maintain a temperature gradient across the first sealing device. The sealing system also includes a second sealing device extending about the rotatable shaft and at least partially defining the second compartment of the turbomachine. The second sealing device is configured to induce a pressure gradient across the second sealing device.

[0006] In another aspect, a method of recirculating a high-temperature and high-pressure working fluid within a turbomachine is provided. The turbomachine includes a casing enclosing a rotatable shaft. The method includes pressurizing a first compartment with a working fluid at a first temperature and a first pressure and rotating the rotatable shaft. The method also includes regulating a predetermined flow rate of the working fluid from the first compartment to a second compartment. The method further includes decreasing the first temperature and the first pressure to a second temperature and a second pressure by suppressing heat transfer from the first compartment to the second compartment with a first sealing device at least partially defining the first compartment and configured to maintain a temperature gradient across the first sealing device, and generating a decrease in pressure from the first compartment to the second compartment with a second sealing device at least partially defining the second compartment and configured to induce a pressure gradient across the second sealing device.

DRAWINGS

[0007] FIG. 1 is a schematic diagram of an exemplary power generation system that uses at least one turboexpander based process to convert thermal energy into electric power.

[0008] FIG. 2 is a longitudinal cross-sectional view of a turbomachine for use in a Brayton fluid power cycle.

[0009] Although specific features of various embodiments may be shown in some drawings and not in others, this is for convenience only. Any feature of any drawing may be referenced and/or claimed in combination with any feature of any other drawing.

DETAILED DESCRIPTION

[0010] Embodiments of the present disclosure are directed to turbomachines, and, more particularly, to methods and apparatus for recirculating a fluid within turbomachines. Specifically, embodiments of the present disclosure are directed to a hermetically-sealed supercritical carbon dioxide hot-gas turboexpander including a unique sealing system permitting operating on a closed-loop Brayton power cycle at high temperatures and high pressures. Furthermore, the sealing system includes a number of seals designed to regulate the flow of the
Brayton-cycle working fluid and provide temperature and pressure gradients across the seals. However, it should be understood that the sealing system of the present disclosure is not limited to the above example cycle configuration, but may be applicable to other cycle configurations, e.g., simple carbon dioxide ("\(\text{CO}_2\)) Brayton cycle and \(\text{CO}_2\) Rankine cycle, where \(\text{CO}_2\) is liquefied before compression.

[0011] The features, functions, and advantages described herein may be achieved independently in various embodiments of the present disclosure or may be combined in yet other embodiments, further details of which may be seen with reference to the following description and drawings. An element or step recited in the singular and preceded with the word “a,” “an,” or “the” should be understood as not excluding plural elements or steps unless such exclusion is explicitly recited. Moreover, references to “one embodiment” of the present invention and/or the “exemplary embodiment” are not intended to be interpreted as excluding the existence of additional embodiments that also incorporate the recited features.

[0012] Approximating language, as used in the following specification and claims, may be applied to modify any quantitative representation that could permissibly vary without resulting in a change in the basic function to which it is related. Accordingly, a value modified by a term or terms, such as “about” and “substantially,” are not to be limited to the precise value specified. In at least some instances, the approximating language may correspond to the precision of an instrument for measuring the value. In the following specification and the claims, range limitations may be combined or interchanged; such ranges are identified and include all the sub-ranges contained therein unless context or language indicates otherwise.

[0013] FIG. 1 is a simple schematic diagram of an exemplary power generation system 10 that uses at least one turboreexpander based process to convert thermal energy into electric power. In the exemplary embodiment, power generation system 10 is a concentrated solar power plant that uses a solar receiver 12 as a heat generation source, and a unique supercritical carbon dioxide ("\(\text{CO}_2\)") hot-gas turboreexpander 100 (a “turbomachine”) operating on a recompression closed-loop supercritical carbon dioxide Brayton power conversion cycle as a power generation source. In alternative embodiments, the methods and apparatus as described herein may be used with any conventional power generation system with a heat generation source in any suitable configuration including, but not limited to, geothermal, fossil fuel combustion, biofuel, nuclear heat, waste heat from gas turbine or internal combustion engines, and other industrial processes. Before describing the exemplary turbomachine 100 in detail, other parts of power generation system 10 are first described to provide context for this embodiment of turbomachine 100. Those skilled in the art will understand that power generation system 10 is an example of a power generation system and may include other components, for example, additional recuperators, additional precoolers, and/or one or more pumps, among other things.

[0014] In the exemplary embodiment, a Brayton-cycle working fluid, e.g., \(\text{CO}_2\), is used as both the heat transfer fluid in solar receiver 12 and the working fluid in turbomachine 100. Solar receiver 12 is used to provide thermal energy to the Brayton-cycle working fluid in turbomachine 100. In general, turbomachine 100 is intended to operate in high-temperature and high-pressure conditions, for example, that range between approximately 20° C. (68° F.) and 800° C. (1,472° F.) and approximately 65 bar (6,500 kPa, 943 psi) and 350 bar (35,000 kPa, 5,076 psi). Using solar receiver 12 in combination with turbomachine 100 allows for efficient use of turbomachine 100 and increases the thermal energy conversion efficiency of turbomachine 100 to greater than 50%. This increases the overall efficiency of power generation system 10, reducing the system’s capital costs and electricity production costs.

[0015] Power generation system 10 generally includes fluid flow system 16, solar receiver 12, turbomachine 100, high-temperature recuperator 20, low-temperature recuperator 24, and precooler 28. Turbomachine 100 generally includes compressor 102, recompressor 108, and expansion turbine 104. Additionally, turbomachine 100 includes an electric power component driven by expansion turbine 104, generally motor-generator 106 as described in the present embodiment, or alternatively, an alternator or pump. Motor-generator 106, expansion turbine 104, recompressor 108, and compressor 102 are coupled to rotatable shaft 110.

[0016] In operation, fluid flow system 16 guides a Brayton-cycle working fluid through power generation system 10. In one embodiment, \(\text{CO}_2\) is used as the Brayton-cycle working fluid. Compressor 102 and recompressor 108 compress the \(\text{CO}_2\) to a pressure that ranges between approximately 65 bar (6,500 kPa, 943 psi) and 120 bar (12,000 kPa, 1,740 psi) and circulate it through fluid flow system 16. Concentrated solar energy heats the \(\text{CO}_2\) as it flows through solar receiver 12 to a temperature that ranges between approximately 300° C. (572° F.) and 800° C. (1,472° F.). The \(\text{CO}_2\) leaves solar receiver 12 and is guided to expansion turbine 104 by fluid flow system 16. The \(\text{CO}_2\) enters expansion turbine 104 at a temperature that ranges between approximately 300° C. (572° F.) and 800° C. (1,472° F.), and a pressure that ranges between approximately 140 bar (14,000 kPa, 2,031 psi) and 350 bar (35,000 kPa, 5,076 psi).

[0017] As the \(\text{CO}_2\) flows through expansion turbine 104, it expands and releases energy, reducing the temperature of the \(\text{CO}_2\) to a range between approximately 200° C. (392° F.) and 650° C. (1,202° F.), and the pressure of the \(\text{CO}_2\) to a range between approximately 65 bar (6,500 kPa, 943 psi) and 120 bar (12,000 kPa, 1,740 psi). The release of the energy during the expansion process causes expansion turbine 104 to rotate, thus converting the energy to shaft work by rotating rotatable shaft 110, compressor 102, recompressor 108, and the rotor component of motor-generator 106. Motor-generator 106 converts the mechanical energy of the rotatable shaft to electrical energy by the relative rotation between the rotor and stator of motor-generator 106. This electrical energy may be directed to a power converter (not shown) and used for various purposes, including, e.g., providing electrical power to commercial and residential facilities, power storage units, etc.

[0018] After releasing energy in expansion turbine 104, the \(\text{CO}_2\) is guided by fluid flow system 16 through high-temperature recuperator 20 and low-temperature recuperator 24. High-temperature recuperator 20 and low-temperature recuperator 24 function as heat exchangers for transferring heat from the \(\text{CO}_2\) leaving expansion turbine 104 to the \(\text{CO}_2\) entering solar receiver 12, thus facilitating increasing the efficiency of power generation system 10. The \(\text{CO}_2\) exits low-temperature recuperator 24 with a temperature that ranges between approximately 50° C. (122° F.) and 150° C.
(302°F) and a pressure that ranges between approximately 65 bar (6,500 kPa, 943 psi) and 120 bar (12,000 kPa, 1,740 psi).

After passing through high-temperature recuperator 20 and low-temperature recuperator 24, in one embodiment, a first portion of the sCO₂ is guided by fluid flow system 16 through precooler 28. Precooler 28 functions as a heat exchanger for removing heat from the sCO₂ and transferring it to a cooling fluid. Precooler 28 may use air as its cooling fluid and rejecting the heat from the sCO₂ to the atmosphere. In another embodiment, precooler 28 may use water as its cooling fluid. The sCO₂ exits precooler 28 with a temperature that ranges between approximately 20°C (68°F) and 100°C (212°F) and a pressure that ranges between approximately 65 bar (6,500 kPa, 943 psi) and 120 bar (12,000 kPa, 1,740 psi). Fluid flow system 16 guides the portion of sCO₂ cooled by precooler 28 to compressor 102. Compressor 102 compresses the cooled portion of sCO₂ to a pressure that ranges between 65 bar (6,500 kPa, 943 psi) and 120 bar (12,000 kPa, 1,740 psi), which also increases the temperature to a range between approximately 20°C (68°F) and 150°C (302°F). Fluid flow system 16 then guides the compressed portion of sCO₂ through high-temperature recuperator 24 where it is recombined with the second portion of sCO₂.

After passing through high-temperature recuperator 20 and low-temperature recuperator 24, the second portion of the sCO₂ is guided by fluid flow system 16 through recompressor 108. Recompressor 108 compresses the second portion of sCO₂ to a pressure that ranges between 65 bar (6,500 kPa, 943 psi) and 120 bar (12,000 kPa, 1,740 psi). The second portion of sCO₂ is then recombined with the first portion of the sCO₂ after the first portion of the sCO₂ exits low-temperature recuperator 24 but before the sCO₂ enters high-temperature recuperator 20. The recombined sCO₂ is guided through high-temperature recuperator 20 and exits with a temperature that ranges between approximately 20°C (68°F) and 800°C (1,472°F) and a pressure that ranges between approximately 65 bar (6,500 kPa, 943 psi) and 140 bar (14,000 kPa, 2,031 psi). The sCO₂ is then guided through solar receiver 12 to repeat the power cycle.

FIG. 2 is a longitudinal cross-sectional view of a turbomachine for use in a Brayton fluid power cycle. Turbomachine 100, as shown and described hereinafter, may be a turbine-driven generator. However, turbomachine 100 may be used as a turbine-driven alternator or a turbine-driven pump without affecting the operation of the turbomachine. Alternatively, turbomachine 100 is adaptable to be a motor-driven compressor or motor-driven pump without departing from the spirit and principles of the present disclosure.

In one embodiment, turbomachine 100 includes a common rotatable shaft 110 rotationally supported by a pair of main bearings 30 and 32. Main bearings 30 and 32 are located within motor-generator compartment 38. Bearings suitable for use as main bearings 30 and 32 may include, for example, one or more of magnetic bearings, foil gas bearings, or hydrodynamic journal bearings. In another embodiment, main bearings 30 and 32, may be any suitable bearing for use in turbomachine 100, and therefore are not limited to a specific type of bearing. In addition to main bearings 30 and 32, a thrust bearing, located at one of 34 and 36, may be included for axially positioning rotatable shaft 110. Thrust bearing 34, 36 may include, for example, a magnetic thrust bearing. In another embodiment, thrust bearing 34, 36, may be any suitable bearing for use in turbomachine 100, e.g., a hydrostatic or hydrodynamic thrust bearing, and therefore is not limited to a specific type of bearing. Thrust bearing 34, 36 may be located within motor-generator compartment 38.

As shown in FIG. 2, compressor 102 is a single-stage radial inflow turbine. In other embodiments, compressor 102 may be a multistage radial inflow turbine or a mixed flow type of turbine with or without variable inlet guide vanes, as may be needed for a particular design. Variable inlet guide vanes facilitate high efficiency compression of the Brayton-cycle working fluid over a wide operating range. The turbine of compressor 102 is coupled to rotatable shaft 110 in any appropriate manner, such as being attached using a suitable mechanical attachment means including, but not limited to, fusion welding, friction welding, interference fitting, mechanical fastener, and splined shaft connection. Compressor 102 is enclosed within compressor compartment 40. In other embodiments, there may be additional compressor compartments enclosing additional compressor stages. In one embodiment, compressor compartment 40 includes a working fluid inlet 42 and a working fluid outlet 44 that at least partially define fluid flow system 16 (shown in FIG. 1). Compressor compartment 40 can be formed integrally with motor-generator compartment 38 or can be coupled, in a sealed manner, to motor-generator compartment 38 at an end of turbomachine 100 to provide at least a portion of sealed casing 68.

In the exemplary embodiment, expansion turbine 104 is a single-stage radial turbine. In other embodiments, expansion turbine 104 may be a multistage axial turbine, with or without variable outlet guide vanes, as may be necessitated by a particular design. Variable outlet guide vanes facilitate high efficiency expansion of the Brayton-cycle working fluid over a wide operating range. Expansion turbine 104 is coupled to rotatable shaft 110 in any appropriate manner, such as being attached using a suitable mechanical attachment means including, but not limited to, fusion welding, friction welding, interference fitting, mechanical fastener, and splined shaft connection. Expansion turbine 104 is enclosed within expander compartment 46. Expander compartment 46 includes a working fluid inlet 48 and a working fluid outlet 50 that at least partially define fluid flow system 16 (shown in FIG. 1). Expander compartment 46 can be formed integrally with motor-generator compartment 38 or can be coupled, in a sealed manner, to motor-generator compartment 38 at an end of turbomachine 100 to provide at least a portion of sealed casing 68.

In one embodiment, motor-generator 106 is coupled to rotatable shaft 110 and is located entirely within motor-generator compartment 38, between main bearings 30 and 32. Motor-generator 106 is coupled to rotatable shaft 110 in any suitable manner, including, but not limited to, mechanical fastening. Motor-generator 106 may be of any suitable type for converting rotational energy into electrical energy. Motor-generator 106 may be connected to an electrical power grid such that electrical energy produced by motor-generator 106 is provided to the grid.

In one embodiment, sealed casing 68 includes compressor compartment 40, motor-generator compartment 38, and expander compartment 46, formed or coupled together in a sealed manner. Working fluid outlet 44 of compressor compartment 40 is coupled in a sealed manner and in flow communication with working fluid inlet 48 of expander compartment 46 by fluid flow system 16 (shown in FIG. 1) to form a portion of a closed-loop power generation system. One or
more components of power generation system 10 may be coupled in a sealing manner and in flow communication between working fluid outlet 44 and working fluid inlet 48, as illustrated in FIG. 1. Additionally, working fluid outlet 50 of expander compartment 46 is coupled in a sealed manner and in flow communication with working fluid inlet 42 of compressor compartment 40 by fluid flow system 16 (shown in FIG. 1) to form another portion of the closed-loop power generation system. Also, one or more components of power generation system 10 may be coupled in a sealed manner and in flow communication between working fluid outlet 50 and working fluid inlet 42, as illustrated in FIG. 1. Furthermore, rotatable shaft 110 is entirely enclosed within sealed casing 68 of turbomachine 100. Significantly, the entire space within turbomachine 100 is exposed only to the Brayton-cycle working fluid, e.g., $\text{scCO}_2$, during operation of turbomachine 100.

As shown in FIG. 2 and discussed above in detail, in one embodiment, turbomachine 100 includes a plurality of compartments, 38, 40, and 46, each compartment enclosing a part 102, 104, and 106, operably coupled to rotatable shaft 110 and operable at a pressure greater than atmospheric pressure, i.e., approximately 1.01 bar (101 kPa, 14.7 psi), and a temperature greater than 20°C (68°F). In one example, compressor 102 is a high-pressure turbine that may operate, for example, at a pressure P1 ranging between approximately 65 bar (6,500 kPa, 943 psi) and 120 bar (12,000 kPa, 1,740 psi), and a temperature T1 ranging between approximately 20°C (68°F) and 150°C (302°F). Compressor compartment 40 also includes a seal 52 for partially sealing the compartment with rotatable shaft 110. As understood, other turbine(s) in additional compartments, such as additional compressor turbines, not shown, may also be provided.

Turbomachine 100 also includes a motor-generator compartment 38 including a motor-generator 106 operably coupled to rotatable shaft 110. Motor-generator 106 is operable at a second pressure greater than atmospheric pressure and a second temperature greater than 20°C (68°F). In one example, motor-generator 106 is an induction generator that may operate, for example, at a pressure P2 ranging from approximately 1.01 bar (101 kPa, 14.7 psi) to approximately 15 bar (1,500 kPa, 218 psi), and a temperature T2 ranging from approximately 20°C (68°F) to approximately 100°C (212°F). Consequently, pressure P1 in compressor compartment 40 is greater than pressure P2 in motor-generator compartment 38. In addition, temperature T1 in compressor compartment 40 may be greater than temperature T2 in motor-generator compartment 38. These differences result in the Brayton-cycle working fluid, e.g., $\text{scCO}_2$, flowing from compressor compartment 40 to motor-generator compartment 38 thus increasing the pressure and the temperature within motor-generator compartment 38. Motor-generator compartment 38 includes a seal 56 for partially sealing the compartment with rotatable shaft 110 to facilitate reducing the flow of the $\text{scCO}_2$ into the compartment.

Due to the high pressures and high temperatures intended for operating turbomachine 100, motor-generator compartment 38 must be kept cool and at a low pressure to maintain efficient levels of performance. Accordingly, the sealing system of turbomachine 100 is designed to control, or suppress, the transfer of mass, heat, and pressure from compressor compartment 40 and expander compartment 46 to motor-generator compartment 38. This is accomplished by a sealing system design, as described more fully below.

Seals 52 and 56 include a number of non-contacting seals such as labyrinth seals, dry-gas seals, etc., that partially seal against rotatable shaft 110 of turbomachine 100. Seals 52 and 56, however, do not completely seal compartments 38 and 40 with rotatable shaft 110, but regulate the flow of the high-temperature and high-pressure $\text{scCO}_2$. To regulate the flow from, and provide a thermal barrier between, compressor compartment 40 and motor-generator compartment 38, in one embodiment, seal 52 is a labyrinth seal fabricated to provide a significant temperature gradient thereacross. Seal 52 is constructed in one embodiment, from a steel alloy, such as a stainless steel. In alternative embodiments, seal 52 is constructed of a high nickel alloy. Seal 52 includes a series of parallel seal teeth that form a tortuous flow path and facilitate minimizing clearance between rotatable shaft 110 and compressor compartment 40. Seal 52 has a radial clearance in the range of 2.5 mils to 15 mils. In alternative embodiments, seal 52 is constructed with any suitable material and configuration to form a thermal barrier and provide a significant temperature gradient thereacross. The structure of seal 52 determines its heat suppression operation. In one embodiment, seal 56 is a dry-gas seal and is constructed to provide a significant pressure gradient thereacross. Dry-gas seal 56 includes a rotating ring coupled to rotatable shaft 110 and positioned in a face-to-face relationship with a fixed ring coupled to motor-generator compartment 38. One seal ring is configured with spiral grooves that, when rotating, directs gas towards the other seal ring generating a pressure sufficient to maintain a gap between the seal rings. In one embodiment, dry-gas seal 56 operates with a gap in the range of 2.5 microns to 30 microns. Seal 56, however, may be constructed with any suitable material and configuration to form a pressure barrier and provide a significant pressure gradient across the seal. The structure of seal 56 determines its pressure suppression operation.

In the exemplary embodiment, seal 52 is axially spaced from seal 56 to provide a sealed cavity 60 fluidly coupling compressor compartment 40 and motor-generator compartment 38. In one embodiment, seal 52 may be inset a distance from an end face of compressor compartment 40 and seal 56 may be inset a distance from an end face of motor-generator compartment 38 resulting in seal 52 being axially spaced from seal 56 when coupling compressor compartment 40 to motor-generator compartment 38 in a sealed manner. In another embodiment, seal 52 and seal 56 are positioned in any manner that enables sealed cavity 60 to be provided as described herein.

Sealed cavity 60 includes a cooling circuit 64 for cooling the high-temperature and high-pressure $\text{scCO}_2$ that flows from compressor compartment 40 through seal 52. In one embodiment, cooling circuit 64 includes a conduit coupled in flow communication with sealed cavity 60 and an external heat transfer fluid source (not shown). Cooling circuit 64 channels a cooling fluid from the external heat transfer fluid source and injects it into sealed cavity 60. The cooling fluid is injected into sealed cavity 60 at a temperature below the temperature of the $\text{scCO}_2$ flowing into sealed cavity 60 from compressor compartment 40. In one embodiment, the cooling fluid reduces the temperature of the $\text{scCO}_2$ in sealed cavity 60.
to less than 300°C (572°F). In other embodiments, the cooling fluid may reduce the temperature of the sCO2 in sealed cavity 60 to less than 200°C (392°F), or to less than 100°C (212°F). In an alternative embodiment, the cooling fluid may not reduce the temperature of the sCO2 in sealed cavity 60. In another embodiment, cooling circuit 64 includes a conduit in flow communication with fluid flow system 16 for channeling a small portion of the sCO2 to a heat exchanger (not shown) for cooling the sCO2. Additionally, cooling circuit 64 includes a metering device coupled to the conduit for injecting the cooled sCO2 into sealed cavity 60. After the sCO2 is cooled, it is channeled by the conduit to the metering device where it is injected into sealed cavity 60 to facilitate cooling the high-temperature and high-pressure sCO2 that flowed into sealed cavity 60 from compressor compartment 40. In other embodiments, cooling circuit 64 includes a heat exchanger positioned in sealed cavity 60 and coupled in thermal communication with an external heat exchanger (not shown). A heat transfer fluid is circulated through cooling circuit 64 for removing heat from the high-temperature and high-pressure sCO2 and releasing it through the external heat exchanger, for example, by being cooled by water or any fluid at a lower temperature than the cooling circuit fluid flow.

[0034] Turbo Machinery 100, in some embodiments, also includes an expander compartment 46 including an expansion turbine 104 operably coupled to rotatable shaft 110. Expansion turbine 104 is operable at a pressure greater than 65 bar (6,500 kPa, 943 psi), and a temperature greater than 20°C (68°F). In one example, expansion turbine 104 is a high-pressure turbine that may operate, for example, at a pressure P3 ranging between approximately 65 bar (6,500 kPa, 943 psi) and 350 bar (35,000 kPa, 5,076 psi), and a temperature T3 ranging between approximately 200°C (392°F) and 800°C (1,472°F). Expander compartment 46 also includes a seal 54 for partially sealing the compartment with rotatable shaft 110. As discussed above, expander compartment 46 is coupled to motor-generator compartment 38 in a sealed manner. Motor-generator 106 is operable at a second pressure greater than atmospheric pressure and a second temperature greater than 20°C (68°F). In one example, motor-generator 106 is an induction generator that may operate, for example, at a pressure P2 ranging from approximately 1.01 bar (101 kPa, 14.7 psi) to approximately 15 bar (1,500 kPa, 218 psi), and a temperature T2 ranging from approximately 20°C (68°F) to approximately 100°C (212°F). Consequently, pressure P3 in expander compartment 46 is greater than pressure P2 in motor-generator compartment 38. In addition, temperature T3 in expander compartment 46 is greater than temperature T2 in motor-generator compartment 38. These differences result in the sCO2 flowing from expander compartment 46 to motor-generator compartment 38 thus increasing the pressure and the temperature within motor-generator compartment 38. Motor-generator compartment 38 includes a seal 58 for partially sealing the compartment with rotatable shaft 110 to facilitate reducing the flow of the sCO2 into the compartment.

[0035] Seals 54 and 58 include a number of non-contacting seals such as labyrinth seals, dry-gas seals, etc., that partially seal against rotatable shaft 110 of Turbo Machinery 100. Seals 54 and 58, however, do not completely seal compartments 38 and 46 with rotatable shaft 110, but regulate the flow of the high-temperature and high-pressure sCO2. To regulate the flow from, and provide a thermal barrier between, expander compartment 46 and motor-generator compartment 38, in one embodiment, seal 54 is a labyrinth seal fabricated to provide a significant temperature gradient thereacross. Seal 54 is constructed, in one embodiment, from a steel alloy, such as a stainless steel. In alternative embodiments, seal 54 is constructed of a high nickel alloy. Seal 54 includes a series of parallel seal teeth that form a tortuous flow path and facilitate minimizing clearance between rotatable shaft 110 and expander compartment 46. Seal 54 has a radial clearance in the range of 2.5 mils to 15 mils. In alternative embodiments, seal 54 is constructed with any suitable material and configuration to form a thermal barrier and provide a significant temperature gradient thereacross. In one embodiment, seal 58 is a dry-gas seal and is constructed to provide a significant pressure gradient thereacross. Dry-gas seal 58 includes a rotating ring coupled to rotatable shaft 110 and positioned in a face-to-face relationship with a fixed ring coupled to motor-generator compartment 38. One seal ring is configured with spiral grooves that, when rotating, directs gas towards the other seal ring generating a pressure sufficient to maintain a gap between the seal rings. In one embodiment, the dry-gas seal 58 operates with a gap in the range of 2.5 microns to 30 microns. Seal 58, however, may also be constructed with any suitable material and configuration to form a pressure barrier and provide a significant pressure gradient across the seal.

[0036] In the exemplary embodiment, seal 54 is axially spaced from seal 58 to provide a sealed cavity 62 fluidly coupling expander compartment 46 and motor-generator compartment 38. In one embodiment, seal 54 may be set a distance from an end face of expander compartment 46 and seal 58 may be set a distance from an end face of motor-generator compartment 38 resulting in seal 54 being axially spaced from seal 58 when coupling expander compartment 46 to motor-generator compartment 38 in a sealed manner. In another embodiment, seal 54 and seal 58 are positioned in any manner that enables sealed cavity 62 to be provided as described herein.

[0037] As discussed above with sealed cavity 60, sealed cavity 62 includes a cooling circuit 66 for cooling the high-temperature and high-pressure sCO2 that flows from expander compartment 46 through sealed cavity 62. In one embodiment, cooling circuit 66 includes a conduit coupled in flow communication with sealed cavity 62 and an external heat transfer fluid source. In one embodiment, cooling circuit 66 channels a cooling fluid from the external heat transfer fluid source and injects it into sealed cavity 62. The cooling fluid is injected into sealed cavity 62 at a temperature below the temperature of the sCO2 flowing into sealed cavity 62 from expander compartment 46. In one embodiment, the cooling fluid reduces the temperature of the sCO2 in sealed cavity 62 to less than 300°C (572°F). In other embodiments, the cooling fluid may reduce the temperature of the sCO2 in sealed cavity 62 to less than 200°C (392°F), or to less than 100°C (212°F). In an alternative embodiment, the cooling fluid may not reduce the temperature of the sCO2 in sealed cavity 62. In another embodiment, cooling circuit 66 includes a conduit in flow communication with fluid flow system 16 for channeling a small portion of the sCO2 to a heat exchanger (not shown) for cooling the sCO2. Additionally, cooling circuit 66 includes a metering device coupled to the conduit for injecting the cooled sCO2 into sealed cavity 62. After the sCO2 is cooled, it is channeled by the conduit to the metering device where it is injected into sealed cavity 62 to facilitate cooling the high-temperature and high-pressure sCO2 that flowed into sealed cavity 62 from expander compartment 46. In other
embodiments, cooling circuit 66 includes a heat exchanger positioned in sealed cavity 62 and coupled in thermal communication with an external heat exchanger (not shown). A heat transfer fluid is circulated through cooling circuit 66 for removing heat from the high-temperature and high-pressure scCO₂ and releasing it through the external heat exchanger, for example, by being cooled by water or any fluid at a lower temperature than the cooling circuit fluid flow.

[0038] High temperature and high pressure operation is one of the central technical challenges of turbomachine design for use with super critical carbon dioxide, as described in the present embodiment. The sealing system design described above facilitates maintaining motor-generator compartment 38 at favorable heat and pressure levels for efficient operation of motor-generator 106. Materials chosen for manufacture of turbomachine 100 described herein are widely recognized materials for high-temperature applications, such as stainless steels and high nickel alloys. These materials may be required for the casings and internal components because of the high temperatures and high pressures required for operation of the turbomachine. These materials facilitate even thermal expansion in the power generation system due to the high heat. The materials used are also corrosion and creep resistant at such elevated temperatures. This permits any Brayton-cycle working fluid to be used with the turbomachine configurations described herein.

[0039] Exemplary embodiments of turbomachines operating at high temperatures and high pressures are described above in detail. The methods and systems are not limited to the specific embodiments described herein, but rather, components of systems and/or steps of the methods may be utilized independently and separately from other components and/or steps described herein. For example, the methods may also be used in combination with other high-temperature and high-pressure turbomachine systems and methods, and are not limited to practice with only the components, materials, and methods as described herein.

[0040] Although specific features of various embodiments of the invention may be shown in some drawings and not in others, this is for convenience only. In accordance with the principles of the invention, any feature of a drawing may be referenced and/or claimed in combination with any feature of any other drawing.

[0041] This written description uses examples to disclose the invention, including the best mode, and also to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of the claims.

What is claimed is:

1. A turbomachine for use with a high-temperature and high-pressure working fluid comprising:
   a rotatable shaft defining an axis of rotation, said rotatable shaft having a first end portion and a second end portion;
   a casing enclosing said rotatable shaft, said casing defining at least a first compartment at least partially enclosing one of a compressor apparatus and an expander apparatus, and a second compartment in flow communication with said first compartment and at least partially enclosing a generator apparatus;
   a compressor coupled to the first end portion of said rotatable shaft for rotation therewith, said compressor configured to compress the working fluid;
   an expansion turbine coupled to the second end portion of said rotatable shaft for rotation therewith, said expansion turbine configured to expand the working fluid;
   a motor-generator coupled to said rotatable shaft between the first end portion and a second end portion; and
   at least one sealing system positioned between said first compartment and said second compartment, said sealing system comprising a plurality of seals for regulating a predetermined flow rate of the working fluid between said first compartment containing the working fluid at a first pressure and a first temperature, and said second compartment containing the working fluid at a second pressure and a second temperature, wherein the first pressure is greater than the second pressure and the first temperature is greater than the second temperature.

2. A turbomachine in accordance with claim 1, wherein plurality of seals comprises:
   a first sealing device at least partially defining said first compartment; and
   a second sealing device at least partially defining said second compartment.

3. The turbomachine in accordance with claim 2, wherein said first sealing device is a labyrinth seal configured to maintain a temperature gradient across said first sealing device.

4. The turbomachine in accordance with claim 2, wherein said second sealing device is a dry-gas seal configured to induce pressure gradient across said second sealing device.

5. The turbomachine in accordance with claim 2, wherein said sealing system defines an intermediate sealing cavity in flow communication with said first sealing device and said second sealing device.

6. The turbomachine in accordance with claim 5, further comprising a sealing system cooling circuit in thermal communication with said intermediate sealing cavity.

7. The turbomachine in accordance with claim 6, wherein said sealing system cooling circuit comprises at least one conduit coupled in flow communication with said intermediate sealing cavity, said at least one conduit configured to introduce a cooling fluid into said intermediate sealing cavity.

8. The turbomachine in accordance with claim 7, wherein the cooling fluid is at a third temperature that is less than the second temperature.

9. The turbomachine in accordance with claim 7, wherein said at least one conduit is coupled in flow communication with said casing, said at least one conduit configured to introduce the working fluid into said intermediate sealing cavity.

10. The turbomachine in accordance with claim 5, further comprising at least one heat exchanger positioned within said intermediate sealing cavity, said at least one heat exchanger coupled in flow communication with an external heat transfer source.

11. A sealing system for a turbomachine that includes a first compartment containing a working fluid at a first pressure and a first temperature, and a second compartment coupled in flow communication with said first compartment, the second compartment containing the working fluid at a second pressure and a second temperature, said sealing system comprising:
a first sealing device extending about a rotatable shaft and at least partially defining the first compartment; said first sealing device configured to maintain a temperature gradient across said first sealing device; and

a second sealing device extending about the rotatable shaft and at least partially defining the second compartment; said second sealing device configured to induce a pressure gradient across said second sealing device.

12. The sealing system in accordance with claim 11, wherein said first sealing device and said second sealing device are disposed at an axial distance from each other, wherein said first sealing device and said second sealing device define an intermediate sealing cavity in flow communication with said first compartment and said second compartment.

13. The sealing system in accordance with claim 11, further comprising a sealing system cooling circuit in thermal communication with said intermediate sealing cavity.

14. The sealing system in accordance with claim 13, wherein said sealing system cooling circuit comprises at least one conduit coupled in flow communication with said intermediate sealing cavity, said at least one conduit configured to introduce a cooling fluid into said intermediate sealing cavity.

15. The sealing system in accordance with claim 14, wherein said at least one conduit is in flow communication with said first compartment, said at least one conduit configured to introduce the working fluid into said intermediate sealing cavity.

16. The sealing system in accordance with claim 11, further comprising at least one heat exchanger positioned within said intermediate sealing cavity, said at least one heat exchanger in flow communication with an external heat transfer source.

17. A method of recirculating a high-temperature and high-pressure working fluid within a turbomachine that includes a casing enclosing a rotatable shaft, said method comprising: pressurizing a first compartment with a working fluid at a first temperature and a first pressure; rotating the rotatable shaft;

regulating a predetermined flow rate of the working fluid from the first compartment to a second compartment; decreasing the first temperature and the first pressure to a second temperature and a second pressure, including: suppressing heat and mass transfer from the first compartment to the second compartment with a first sealing device at least partially defining the first compartment and configured to maintain a temperature gradient across the first sealing device; and generating a decrease in pressure from the first compartment to the second compartment with a second sealing device at least partially defining the second compartment and configured to induce a pressure gradient across the second sealing device; and

pressurizing the second compartment with the working fluid at the second temperature and the second pressure.

18. A method in accordance with claim 17, wherein decreasing the first temperature and the first pressure to a second temperature and a second pressure further includes introducing a cooling fluid at a third temperature into an intermediate sealing cavity through a sealing system cooling circuit that includes at least one conduit coupled in flow communication with the intermediate sealing cavity, wherein the third temperature is lower than the second temperature.

19. A method in accordance with claim 17, wherein decreasing the first temperature and the first pressure to a second temperature and a second pressure further includes introducing a portion of the working fluid into the intermediate sealing cavity using a flow metering device, wherein the portion of working fluid is channeled through a sealing system cooling circuit that includes at least one conduit coupled in flow communication with the casing and the flow metering device.

20. A method in accordance with claim 17, wherein decreasing the first temperature and the first pressure to a second temperature and a second pressure further includes channeling a cooling fluid through at least one heat exchanger positioned within and intermediate sealing cavity.