CONTROLLING TURBOPUMP THRUST IN A HEAT ENGINE SYSTEM

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ABSTRACT

A heat engine system and a method are provided for generating energy by transforming thermal energy into mechanical and/or electrical energy, and for controlling a thrust load applied to a turbopump of the heat engine system. The generation of energy may be optimized by controlling a thrust or net thrust load applied to a turbopump of the heat engine system. The heat engine system may include one or more valves, such as a turbopump throttle valve and/or a bearing drain valve, which may be modulated to control the thrust load applied to the turbopump during one or more modes of operating the heat engine system.
Circulating a working fluid through a high pressure side and a low pressure side of a working fluid circuit with a turbopump, wherein at least a portion of the working fluid is in a supercritical state.

Transferring thermal energy from a heat source to the working fluid by a heat exchanger fluidly coupled to and in thermal communication with the heat source and the high pressure side of the working fluid circuit.

Flowing the working fluid into an expander and converting the thermal energy from the working fluid to mechanical energy of the expander.

Flowing a portion of the working fluid from the working fluid circuit through a charging pump to an inlet of a bearing housing substantially encompassing bearings of the turbopump.

Modulating a turbopump throttle valve to control a flow of the working fluid to a drive turbine of the turbopump, thereby at least partially controlling a thrust load applied to the turbopump.

Modulating a bearing drain valve to control a flow of the working fluid through a bearing drain line fluidly coupled to an outlet of the bearing housing, thereby at least partially controlling the thrust load applied to the turbopump.

Fig. 2
CONTROLLING TURBOPUMP THRUST IN A HEAT ENGINE SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims benefit of U.S. Prov. Appl. No. 61/782,578, filed on Mar. 14, 2013, the contents of which are hereby incorporated by reference to the extent not inconsistent with the present disclosure.

BACKGROUND

[0002] Waste heat is often created as a byproduct of industrial processes where flowing streams of high-temperature liquids, gases, or fluids must be exhausted into the environment or removed in some way in an effort to maintain the operating temperatures of the industrial process equipment. Some industrial processes utilize heat exchanger devices to capture and recycle the waste heat back into the process streams. The waste heat can be converted into useful energy by a variety of turbine generator or heat engine systems that employ thermodynamic methods, such as Rankine cycles. Rankine cycles and similar thermodynamic methods are typically steam-based processes that recover and utilize the waste heat to generate steam to drive turbines, turbos, or other expanders coupled with electric generators, pumps, or other devices.

[0003] An organic Rankine cycle utilizes a lower boiling-point working fluid in substitution of water, which is often used during a traditional Rankine cycle. Exemplary lower boiling-point working fluids include hydrocarbons, such as light hydrocarbons (e.g., propane or butane) and halogenated hydrocarbons, such as hydrochlorofluorocarbons (HCFCs) or hydrofluorocarbons (HFCs) (e.g., R245fa). More recently, in view of issues such as thermal instability, toxicity, flammability, and production cost of the lower boiling-point working fluids, some thermodynamic cycles have been modified to circulate non-hydrocarbon working fluids, such as ammonia.

[0004] The heat engine systems may often utilize a turbopump to circulate the working fluid to capture the waste heat. The turbopumps utilized in the heat engine systems may have operational limitations set or determined by a maximum thrust load that may be applied thereto before damaging the turbopump and/or components thereof. Further, the thrust load applied to the turbopump may depend upon one or more operating conditions of the heat engine system and/or components thereof. The operating conditions of the heat engine system may vary over a broad range and may be determined by the mode (e.g., startup, steady operation, and/or shutdown) in which the heat engine system is operating. Accordingly, the thrust load applied to the turbopump may correspondingly vary with these operating conditions, thereby increasing the difficulty of maintaining the thrust load within a safe operational range when operating the heat engine system in the various modes.

[0005] What is needed, then, is a heat engine system and method of operating thereof, including one or more valves capable of actively controlling the thrust load applied to the turbopump in varying operating conditions.

SUMMARY

[0006] Embodiments of the disclosure may provide a heat engine system. The heat engine system may include a working fluid circuit having a high pressure side and a low pressure side. The working fluid circuit may contain a working fluid at least partially in a supercritical state. The working fluid may include carbon dioxide. A heat exchanger may be fluidly coupled to and in thermal communication with the high pressure side of the working fluid circuit. The heat exchanger may also be fluidly coupled to and in thermal communication with a heat source. The heat exchanger may be configured to transfer thermal energy from the heat source to the working fluid within the high pressure side of the working fluid circuit. The heat engine system may further include an expander fluidly coupled to and disposed between the high pressure side and the low pressure side of the working fluid circuit. The expander may be configured to convert a pressure drop in the working fluid to mechanical energy. A recuperator may be fluidly coupled to the working fluid circuit. A recuperator may be operative to transfer thermal energy between the high pressure side and the low pressure side of the working fluid circuit. A cooler may be in thermal communication with the working fluid in the low pressure side of the working fluid circuit. The cooler may be configured to remove thermal energy from the working fluid circuit. The cooler may be configured to control the working fluid in the low pressure side of the working fluid circuit. The turbopump may be configured to circulate the working fluid through the working fluid circuit. A turbopump throttle valve may be coupled to the high pressure side of the working fluid circuit. The turbopump throttle valve may be configured to control a flow of the working fluid to the turbopump, thereby at least partially controlling the thrust load applied to the turbopump. A bearing housing may substantially encompass one or more bearings contained within the turbopump. A charging pump may be fluidly coupled with the working fluid circuit. The charging pump may be configured to transfer the working fluid to an inlet of the bearing housing. The heat engine system may further include a bearing drain line fluidly coupled to an outlet of the bearing housing. The bearing drain line may include a bearing drain valve coupled thereto. The bearing drain valve may be configured to control a flow of the working fluid through the bearing drain line, thereby at least partially controlling the thrust load applied to the turbopump.

[0007] Embodiments of the disclosure may further provide another heat engine system. The heat engine system may include a working fluid circuit having a high pressure side and a low pressure side. A working fluid at least partially in a supercritical state may be contained in the working fluid circuit. The working fluid may include carbon dioxide. A heat exchanger may be fluidly coupled to and in thermal communication with the high pressure side of the working fluid circuit. The heat exchanger may also be fluidly coupled to and in thermal communication with a heat source. The heat exchanger may be configured to transfer thermal energy from the heat source to the working fluid within the high pressure side of the working fluid circuit. An expander may be fluidly coupled to and disposed between the high pressure side and the low pressure side of the working fluid circuit. The expander may be configured to convert a pressure drop in the working fluid to mechanical energy. A recuperator may be fluidly coupled to the working fluid circuit and may be operative to transfer thermal energy between the high pressure side and the low pressure side of the working fluid circuit. A cooler may be in thermal communication with the working fluid in the low pressure side of the working fluid circuit. The cooler may be configured to remove thermal energy from the work-
ing fluid in the low pressure side of the working fluid circuit. The heat engine system may also include a turbopump coupled to the working fluid circuit. The turbopump may include a pump portion coupled with a drive portion via a driveshaft. The pump portion may be coupled between the low pressure side and the high pressure side of the working fluid circuit. The pump portion may be configured to be driven by the drive turbine and to circulate the working fluid through the working fluid circuit. The drive portion of the turbopump may be fluidly coupled between the low pressure side and the high pressure side of the working fluid circuit. The drive portion may be configured to drive the pump portion by mechanical energy generated by the expansion of the working fluid flowing there through. A turbopump throttle valve may be coupled to the high pressure side of the working fluid circuit. The turbopump throttle valve may be configured to control a flow of the working fluid to an inlet of the drive turbine, thereby at least partially controlling the thrust load applied to the turbopump. A bearing housing may substantially encompass one or more bearings of the turbopump. A charging pump may be fluidly coupled with the working fluid circuit. The charging pump may be configured to transfer the working fluid to an inlet of the bearing housing. A bearing drain line may be fluidly coupled to an inlet of the bearing housing. The bearing drain line may include a bearing drain valve coupled thereto. The bearing drain valve may be configured to at least partially control the thrust load applied to the turbopump.

[0008] Embodiments of the disclosure may further provide a method for controlling a thrust load applied to a turbopump of a heat engine system. The method may include circulating a working fluid through a high pressure side and a low pressure side of a working fluid circuit with a turbopump. At least a portion of the working fluid in the working fluid circuit may be in a supercritical state. The method may also include transferring thermal energy from a heat source to the working fluid by a heat exchanger fluidly coupled to and in thermal communication with the heat source and the high pressure side of the working fluid circuit. The method may further include flowing the working fluid into an expander and converting the thermal energy from the working fluid to mechanical energy of the expander. The method may also include flowing a portion of the working fluid from the working fluid circuit through a charging pump to an inlet of a bearing housing substantially encompassing bearings of the turbopump. The method may also include modulating a turbopump throttle valve to control a flow of the working fluid to a drive turbine of the turbopump to at least partially control the thrust load applied to the turbopump. The method may further include modulating a bearing drain valve to control a flow of the working fluid through a bearing drain line fluidly coupled to an outlet of the bearing housing to at least partially control the thrust load applied to the turbopump.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] 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.

[010] FIG. 1 illustrates a schematic of an exemplary heat engine system including a turbopump throttle valve and a bearing drain valve, according to one or more embodiments disclosed herein.

[011] FIG. 2 is a flowchart illustrating a method for controlling a thrust load applied to a turbopump of an exemplary heat engine system, according to one or more embodiments disclosed herein.

DETAILED DESCRIPTION

[012] 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.

[013] 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.

[014] An exemplary heat engine system and method is provided for generating energy by transforming thermal energy into mechanical and/or electrical energy, and controlling a thrust load applied to a turbopump of the heat engine system. The generation of energy may be optimized by controlling a thrust or net thrust load applied to a turbopump of the heat engine system. The heat engine system may include
one or more valves, such as a turbopump throttle valve and/or a bearing drain valve, which may be modulated to control the thrust load applied to the turbopump during one or more modes of operation of the heat engine system.

[0015] The heat engine system may include a charging pump for efficiently implementing at least two independent tasks. In one aspect, the charging pump may be utilized to conduct inventory control by removing working fluid (e.g., CO₂) from and/or adding working fluid into a working fluid circuit of the heat engine system. In another aspect, the charging pump may be utilized to transfer or otherwise deliver the working fluid to bearings contained within a bearing housing of a system component. For example, the bearing housing containing the bearings may be a part of a turbopump including a drive turbine coupled with a pump portion via a drive shaft.

[0016] A mass control tank (e.g., cryogenic storage vessel) may be utilized for storing or otherwise containing the working fluid removed from the working fluid circuit, charged into the working fluid circuit, and/or delivered to the bearing housing. A fluid line may be fluidly coupled between the mass control tank and the charging pump. One or more bearing gas supply lines may be fluidly coupled with and disposed between the charging pump and the bearing housing of the turbopump. Additionally, one or more bearing gas discharge lines may be fluidly coupled with the bearing housing and may include a bearing drain valve coupled therewith. During one or more modes of operating the heat engine system, the working fluid may flow from the charging pump to the bearing housing of the turbopump via the bearing gas supply lines and from the bearing housing to an exhaust via the bearing gas discharge lines. The bearing drain valve may regulate or control the pressure of the working fluid within the turbopump and/or components thereof, including the bearing housing. In at least one embodiment, the pressure of the working fluid contained in the bearing housing may determine, at least in part, the net thrust applied to the turbopump. During one or more modes of operating the heat engine system, the working fluid may also flow through the turbopump via one or more lines of the working fluid circuit, thereby exerting a thrust load thereon. A drive turbine throttle valve may be coupled with the lines of the working fluid circuit to control the flow of the working fluid therethrough, thereby at least partially controlling the thrust load applied to the turbopump. Accordingly, the bearing drain valve and/or the drive turbine throttle valve may be modulated alone or in concert to control the thrust load exerted upon the turbopump.

[0017] FIG. 1 depicts an exemplary heat engine system 90, which may also be referred to as a thermal engine system, an electrical generation system, a waste heat or other heat recovery system, and/or a thermal to electrical energy system, according to one or more embodiments disclosed herein. The heat engine system 90 may include one or more elements of a Rankine cycle, a derivative of a Rankine cycle, or another thermodynamic cycle for the generation of electrical energy from a wide range of thermal sources. The heat engine system 90 may include a waste heat system 100 and a power generation system 220. The waste heat system 100 may be coupled with and/or in thermal communication with the power generation system 220 via a working fluid circuit 202.

[0018] The working fluid circuit 202 may include a high pressure side and a low pressure side. A working fluid may be contained in the working fluid circuit 202 and may flow therethrough. Use of the term “working fluid” is not intended to limit the state or phase of matter of the working fluid. For example, the working fluid or portions thereof may be in a fluid phase, a gas phase, a supercritical state, a subcritical state, or any other phase or state at any one or more points within the heat engine system 90. FIG. 1 depicts the high pressure side and the low pressure side of the working fluid circuit 202 by representing the high pressure side with “— — — — — —” and the low pressure side with “— — — — — —” as described in one or more embodiments. In at least one embodiment, the working fluid may be in a supercritical state over certain portions of the working fluid circuit 202 (e.g., a high pressure side) and in a subcritical state over other portions of the working fluid circuit 202 (e.g., a low pressure side). In another embodiment, the heat engine system 90 may be operated such that the working fluid may be maintained in either a supercritical or subcritical state throughout the entire working fluid circuit 202. During one or more modes of operating the heat engine system 90 (e.g., steady operation), the high pressure side of the working fluid circuit 202 may contain the working fluid in a supercritical state and the low pressure side of the working fluid circuit 202 may contain the working fluid in a subcritical state.

[0019] The high pressure side of the working fluid circuit 202 may contain the working fluid (e.g., sc-CO₂) at a pressure of about 15 MPa or greater, about 17 MPa or greater, or about 20 MPa or greater. For example, the working fluid in the high pressure side of the working fluid circuit 202 may have a pressure from about 15 MPa to about 30 MPa, about 16 MPa to about 26 MPa, about 17 MPa to about 25 MPa, about 17 MPa to about 24 MPa, about 17 MPa to about 23.5 MPa, or about 23 MPa to about 23.3 MPa. In at least one embodiment, the working fluid in the high pressure side of the working fluid circuit 202 may have a pressure of about 23 MPa or about 23.3 MPa. For example, the high pressure side of the working fluid circuit 202 may have a pressure from about 20 MPa to about 30 MPa, about 21 MPa to about 25 MPa, or about 22 MPa to about 24 MPa.

[0020] The low pressure side of the working fluid circuit 202 may contain the working fluid (e.g., CO₂ or sub-CO₂) at a pressure of less than 15 MPa. For example, the low pressure side of the working fluid circuit 202 may have a pressure of about 14 MPa or less, about 12 MPa or less, about 10 MPa or less, or about 8 MPa or less. In another example, the low pressure side of the working fluid circuit 202 may have a pressure from about 4 MPa to about 14 MPa, about 6 MPa to about 13 MPa, about 8 MPa to about 12 MPa, or about 10 MPa to about 11 MPa. In at least one embodiment, the low pressure side may have a pressure of about 6 MPa, about 7 MPa, or about 10.3 MPa. In another embodiment, the low pressure side of the working fluid circuit 202 may have a pressure from about 2 MPa to about 10 MPa, about 4 MPa to about 8 MPa, about 5 MPa to about 7 MPa, about 8 MPa to about 11 MPa, or about 10.3 MPa to about 11 MPa.

[0021] The types of working fluids that may be circulated, flowed, or otherwise utilized in the working fluid circuit 202 may include, but are not limited to, carbon oxides, hydrocarbons, alcohols, ketones, halogenated hydrocarbons, ammonia, amines, or any combination thereof. Illustrative working fluids that may be utilized in the heat engine system 90 may include, but are not limited to, carbon dioxide, ammonia, methane, ethane, propane, butane, ethylene, propylene, butylene, acetylene, methanol, ethanol, acetone, methyl ethyl ketone, water, derivatives thereof, or any combination thereof. Halogenated hydrocarbons may include, but are not
limited to, hydrochlorofluorocarbons (HCFCs), hydrofluoro- 
carbons (HFCs) (e.g., 1,1,1,3,3-pentfluoropropane 
(R245fa)), fluorocarbons, derivatives thereof, or any combi-
nation thereof.

[0022] In at least one embodiment, the working fluid circu-
lated, flowed, contained, or otherwise utilized in the working 
fluid circuit 202, including any other exemplary circuits 
disclosed herein, may be or include carbon dioxide (CO₂) 
or mixtures containing carbon dioxide. At least a portion of the 
working fluid circuit 202 may contain the carbon dioxide in a 
supercritical state (e.g., sc-CO₂). Utilizing carbon dioxide as 
the working fluid or as part of a mixture of the working fluid 
during one or more modes of operating the heat engine system 
90 (e.g., power generation cycle) may provide one or more 
advantages over other compounds that may typically be used 
as the working fluid. For example, carbon dioxide may pro-
vide a readily available, inexpensive, non-toxic, and non-
flammable working fluid. Due in part to a relatively high 
working pressure of carbon dioxide, the heat engine system 
90 incorporating carbon dioxide may be more compact than 
other heat engine systems incorporating other types of work-
ing fluids. The high density and heat capacity or volumetric 
heat capacity of carbon dioxide with respect to other working 
fluids may make carbon dioxide more “energy dense,” mean-
ning that a size of one or more system components may be 
reduced without reducing performance. It should be noted 
that use of the terms carbon dioxide (CO₂), supercritical 
carbon dioxide (sc-CO₂), or subcritical carbon dioxide (sub-
CO₂) is not intended to be limited to carbon dioxide of any 
particular type, source, purity, or grade. For example, indus-
trial grade carbon dioxide may be contained in and/or used 
as the working fluid without departing from the scope of 
the disclosure.

[0023] The working fluid in the working fluid circuit 202 
may be a working fluid mixture. The working fluid mixture 
may be selected for the unique attributes possessed by the 
mixture within the heat engine system 90. For example, the 
working fluid mixture may include a liquid absorbent and 
carbon dioxide, or a mixture containing carbon dioxide, 
enabling the mixture to be pumped in a liquid state to high 
pressure with less energy input than required to compress 
carbon dioxide, or a mixture containing carbon dioxide, 
and another compound. In another embodiment, the working fluid may be 
a mixture of supercritical carbon dioxide (sc-CO₂), subcriti-
cal carbon dioxide (sub-CO₂), and/or one or more other mis-
cible fluids or chemical compounds. In another embodiment, 
the working fluid may be a mixture of carbon dioxide and 
another suitable fluid including, but not limited to, propane, 
ammonia, or any combination thereof.

[0024] A heat source stream 110 may flow through one or 
more heat exchangers 120, 122, 124 of the waste heat system 
100. Each of the heat exchangers 120, 122, 124 may be 
independently fluidly coupled with and in thermal commu-
nication with the high pressure side of the working fluid circuit 
202 and the heat source stream 110. The heat exchangers 
120, 122, 124 may be configured to transfer thermal energy 
between the heat source stream 110 and the working fluid 
in the high pressure side of the working fluid circuit 202. 
Thermal energy may be absorbed by the working fluid within 
the working fluid circuit 202 and converted to mechanical 
energy by flowing the heated working fluid through one or 
more expanders or turbines, as further described herein.

[0025] The heat source stream 110 may be a waste heat 
stream including, but not limited to, a gas turbine exhaust 
stream, industrial process exhaust stream, or any other combi-
nation product exhaust stream, such as a furnace or a boiler 
exhaust stream. In at least one embodiment, the heat source 
stream 110 may derive thermal energy from renewable 
Sources, such as solar or geothermal sources. The heat source 
stream 110 may be at a temperature ranging from about 100° 
C. to about 1,000° C. or more. For example, the temperature 
of the heat source stream 110 may be from a low of about 100° 
C. , about 200° C., or about 400° C. to a high of about 600° C., 
about 800° C., about 1,000° C., about 1,200° C., or greater. 
In another example, the temperature of the heat source stream 
110 may be from about 100° C. to about 1,200° C., about 200° 
C. to about 1,000° C., about 400° C. to about 800° C., or about 
400° C. to about 600° C. The heat source stream 110 may 
contain air, carbon dioxide, carbon monoxide, water or steam, 
nitrogen, oxygen, argon, derivatives thereof, or any combi-
nation or mixture thereof.

[0026] The heat engine system 90 may contain one or more 
pumps, such as a turbopump 260 and a start pump 280, 
disposed within the working fluid circuit 202 and fluidly 
coupled between the low pressure side and the high pressure 
side of the working fluid circuit 202. The working fluid may 
be introduced to the turbopump 260 and/or the start pump 280 
from the low pressure side of the working fluid circuit 202 
and may subsequently be flowed through the turbopump 260 and/or 
the start pump 280 to the high pressure side of the working 
fluid circuit 202. The turbopump 260 and the start pump 280 
may be configured to circulate and/or pressurize the working 
fluid throughout the working fluid circuit 202. The start pump 
280 may be utilized to initially circulate and/or pressurize the 
working fluid in the working fluid circuit 202. Once a pro-
determined pressure, temperature, and/or flowrate of the work-
ning fluid is obtained within the working fluid circuit 202, the 
start pump 280 may be taken off-line, idled, or turned off, and 
the turbopump 260 may be utilized to circulate the working 
fluid during one or more modes of operating the heat engine 
system 90 (e.g., power generation cycle).

[0027] The start pump 280 may be a motorized pump, such 
as an electric-motorized pump, a mechanical-motorized 
pump, or other type of pump. For example, as illustrated in 
FIG. 1, the start pump 280 may be a variable frequency 
motorized drive pump including a pump portion 282 and a 
motor-drive portion 284. The motor-drive portion 284 may 
include a motor and a drive having a driveshaft and gears. In 
least one embodiment, the motor-drive portion 284 may 
include a variable frequency drive configured to regulate the 
speed of the motor. The pump portion 282 may be driven by 
the motor-drive portion 284 coupled therewith. The pump 
portion 282 may include an inlet configured to receive the 
working fluid from the low pressure side of the working fluid 
circuit 202. The pump portion 282 may also include an outlet 
configured to release or discharge the working fluid to the 
high pressure side of the working fluid circuit 202.

[0028] The heat engine system 90 may include one or more 
valves 283 and 285 coupled with the working fluid circuit 202 
to control the flow of the working fluid through the start pump 
280. For example, a valve 283 may be fluidly coupled with 
the high pressure side of the working fluid circuit 202 down-
stream from the pump portion 282 of the start pump 280. The 
valve 283 may control the flowrate of the working fluid exit-
ing the outlet of the pump portion 282. A valve 285 may also 
be fluidly coupled with the low pressure side of the working 
fluid circuit 202 upstream of the pump portion 282 of the start
pump 280. The valve 285 may control the flowrate of the working fluid entering the inlet of the pump portion 282.

[0029] The turbopump 260 may be a turbo-drive pump or a turbine-drive pump configured to pressurize and circulate the working fluid throughout the working fluid circuit 202. The turbopump 260 may contain a pump portion 262 coupled with a drive turbine 264. The drive turbine 264 may be configured to rotate the pump portion 262 and the pump portion 262 may be configured to circulate the working fluid within the working fluid circuit 202. The drive turbine 264 may be coupled with the pump portion 262 via a gearbox (not shown) and/or a driveshaft 267. The driveshaft 267 may be a single segment or multiple segments coupled with one another. The gearbox may include one or more gears configured to couple the multiple segments of the driveshaft 267 with one another. For example, a first segment of the driveshaft 267 may extend from the drive turbine 264 to the gearbox, a second segment of the driveshaft 230 may extend from the pump portion 262 to the gearbox, and the one or more gears of the gearbox may couple the first and second segments of the driveshaft 267 with one another.

[0030] The pump portion 262 may be fluidly coupled with the low pressure side of the working fluid circuit 202 via an inlet 141. The inlet 141 of the pump portion 262 may be configured to receive the working fluid via fluid line 142 of the low pressure side of the working fluid circuit 202. The pump portion 262 of the turbopump 260 may also be fluidly coupled with the high pressure side of the working fluid circuit 202 upstream of the heat exchangers 120 and 122. For example, the pump portion 262 may be fluidly coupled with a fluid line 144 of the high pressure side of the working fluid circuit 202 via an outlet 143 configured to release the working fluid into the fluid line 144. The pump portion 262 may be configured to circulate the working fluid within the working fluid circuit 202. For example, the pump portion 262 may be driven or rotated by the drive turbine 264 coupled therewith, thereby circulating the working fluid through the working fluid circuit 202. The flow and/or fluid density of the working fluid via the pump portion 262 may be measured at the inlet 141, the outlet 143, or any combination thereof. For example, as further described herein, the pump portion 262 may include one or more sensors configured to measure one or more properties of the working fluid at the inlet 141 and/or outlet 143 thereof.

[0031] An inlet 131 of the drive turbine 264 of the turbopump 260 may be fluidly coupled with the high pressure side of the working fluid circuit 202 downstream from the heat exchanger 124 via fluid line 132. An outlet 133 of the drive turbine 264 may be fluidly coupled with the low pressure side of the working fluid circuit 202 and may be configured to release the working fluid from the turbopump 260 to the low pressure side via fluid line 134. The drive turbine 264 may receive and be powered by the heated working fluid flowing from the heat exchanger 124 via the fluid line 132 and release the working fluid into the low pressure side of the working fluid circuit 202 via the fluid line 134, thereby rotating the pump portion 262 of the turbopump 260. The flow and/or fluid density of the working fluid via the drive turbine 264 may be measured at the inlet 131 and/or the outlet 133. For example, as further described herein, the drive turbine 264 may include one or more sensors configured to measure one or more properties of the working fluid at the inlet 131 and/or outlet 133 thereof.

[0032] A turbopump throttle valve 263 may be fluidly coupled with the fluid line 132 of the working fluid circuit 202 downstream from the heat exchanger 124 and upstream of the inlet 131 of the drive turbine 264. The turbopump throttle valve 263 may be configured to control a flow or flowrate of the working fluid flowing into and through the drive turbine 264. The turbopump throttle valve 263 may be configured to modulate the flow of the heated working fluid into the drive turbine 264 which in turn—may be utilized to adjust the flow of the working fluid throughout the working fluid circuit 202 via the pump portion 262. For example, the turbopump throttle valve 263 may control the flowrate of the heated working fluid flowing from the heat exchanger 124 to the drive turbine 264 of the turbopump 260. The fluid containing absorbed thermal energy from the waste heat system 100 may power the drive turbine 264 via the turbopump throttle valve 263, thereby rotating the pump portion 262 of the turbopump 260.

[0033] The turbopump throttle valve 263 may also control the flow and/or fluid density (p) of the working fluid through the drive turbine 264 to control or manage a thrust or net thrust load on to the turbopump 260. The flow and/or the fluid density of the working fluid at the inlet 131 of the drive turbine 264 may determine, at least in part, the thrust applied to the turbopump 260. For example, the flow and/or the fluid density of the working fluid at the inlet 131 may be related to or correlated with the thrust applied to the turbopump 260. Accordingly, modulating the turbopump throttle valve 263 may increase and/or decrease the flow and/or the fluid density of the working fluid at the inlet 131 may correspondingly increase and/or decrease the thrust applied to the turbopump 260.

[0034] A bypass valve 265 may be coupled between and in fluid communication with the fluid line 132 extending from the inlet 131 of the drive turbine 264 and the fluid line 134 extending from the outlet 133 of the drive turbine 264. The bypass valve 265 may be actuated to selectively bypass the turbopump 260 during one or more modes of operating the heat engine system 90. For example, the bypass valve 265 may be actuated to bypass the turbopump 260 during the initial stages of generating electricity or mechanical power with the heat engine system 90, when the start pump 280 circulates the working fluid through the working fluid circuit 202. Once a predetermined pressure and/or temperature of the working fluid is obtained within the working fluid circuit 202, the bypass valve 265 may be actuated to direct the working fluid through the drive turbine 264 to operate or start the turbopump 260.

[0035] A control valve 261 may be disposed downstream from the outlet 143 of the turbopump 260 and a control valve 281 may be disposed downstream from an outlet of the pump portion 282 of the start pump 280. The control valves 261 and 281 may be flow control safety valves and may be configured to control the directional flow or to prevent backflow of the working fluid within the working fluid circuit 202. The control valve 261 may be configured to prevent the working fluid from flowing upstream towards or into the outlet 143 of the pump portion 262 of the turbopump 260. Similarly, the control valve 281 may be configured to prevent the working fluid from flowing upstream towards or into the outlet of the pump portion 282 of the start pump 280.

[0036] In at least one embodiment, the working fluid circuit 202 may provide a bypass flowpath for the turbopump 260 via
fluid line 226 and bypass valve 256. The bypass valve 256 may be fluidly coupled with the fluid line 226 between the low pressure side and the high pressure side of the working fluid circuit 202 when in a closed position. The fluid line 226 may be fluidly coupled with the outlet 143 of the pump portion 262 via fluid line 144.

A valve 293 may be fluidly coupled with the fluid line 144 between the outlet 143 of the pump portion 262 and the heat exchanger 124. The valve 293 may be configured to provide a back pressure for the pump portion 262 during one or more modes of operating the heat engine system 90. In at least one embodiment, the valve 293 and/or the bypass valve 256 may be actuated to provide a back pressure for the pump portion 262 of the turbopump 260 by controlling the flow or fluid density of the working fluid at the outlet 143 of the pump portion 262. [0038]

The power generation system 220 of the heat engine system 90 may include a power turbine 228 disposed between the high pressure side and the low pressure side of the working fluid circuit 202. The power turbine 228 may be fluidly coupled with and in thermal communication with the working fluid, and configured to convert thermal energy to mechanical energy by a pressure drop in the working fluid flowing between the high pressure side and the low pressure side of the working fluid circuit 202. For example, the power turbine 228 may be fluidly coupled with the working fluid circuit 202 downstream from the heat exchanger 120 and/or heat exchanger 122 and may be configured to receive and be powered by the working fluid flowing through and absorbing thermal energy from the heat exchanger 120 and/or the heat exchanger 122. A power generator 240 may be coupled with the power turbine 228 and configured to convert the mechanical energy into electrical energy. A power outlet 242 may be electrically coupled with the power generator 240 and may be configured to transfer or deliver the electrical energy from the power generator 240 to an electrical grid 244.

A gearbox 232 and a driveshaft 230 may be disposed between the power turbine 228 and the power generator 240. The power turbine 228 may be coupled with the power generator 240 via the driveshaft 230. The gearbox 232 may be disposed between the power turbine 228 and the power generator 240 and may be adjacent or may encompass all, or at least a portion of, the driveshaft 230. The driveshaft 230 may be a single segment or contain two or more segments coupled with one another. In one example, a first segment of the driveshaft 230 may extend from the power turbine 228 to the gearbox 232, and a second segment of the driveshaft 230 may extend from the gearbox 232 to the power generator 240. The multiple gears of the gearbox 232 may be disposed between and coupled with the two segments of the driveshaft 230, thereby coupling the power turbine 228 with the power generator 240. [0040]

The power turbine 228 may be or include a turbine, a turbo, an expander, or another device for receiving and expanding the working fluid discharged from the heat exchanger 120 and/or heat exchanger 122. The power turbine 228 may have an axial construction or radial construction and may be a single-staged device or a multi-staged device. Illustrative turbines of the power turbine 228 may include, but are not limited to, an expansion device, a gerotor, a gerotor, a valve, a pressure swing, or any other device capable of transforming a pressure or pressure/enthalpy drop in a working fluid into mechanical energy. A variety of expanding devices may be capable of working within the heat engine system 90 and achieving different performance properties that may be utilized as the power turbine 228.

A stop valve 217 may be fluidly coupled with the working fluid circuit 202 between the heat exchanger 120 and the power turbine 228. The stop valve 217 may be configured to control or regulate the flow of heated working fluid flowing from the heat exchanger 120 into the power turbine 228. In at least one embodiment, the stop valve 217 may be actuated to stop the flow of heated working fluid from the heat exchanger 120 into the power turbine 228. [0042]

A power turbine bypass valve 219 may be fluidly coupled with a power turbine bypass line 208 and may be configured to modulate, adjust, or otherwise control the working fluid flowing through the power turbine bypass line 208. The power turbine bypass line 208 may be fluidly coupled with the working fluid circuit 202 at a point upstream of the power turbine 228 and at a point downstream from the power turbine 228. The power turbine bypass line 208 may be configured to flow the working fluid around the power turbine 228 when the power turbine bypass valve 219 is in an open position. The flowrate and the pressure of the working fluid flowing into the power turbine 228 may be reduced or stopped by adjusting the power turbine bypass valve 219 to the closed position. Alternatively, the flowrate and the pressure of the working fluid flowing into the power turbine 228 may be increased or started by adjusting the power turbine bypass valve 219 to the open position. The power turbine bypass line 208 may be configured to control the flow of heated working fluid from the start pump 280 and/or the turbopump 260 and upstream of the stop valve 217. The attemperator valve 223 may be configured to control the flow of heated working fluid from the start pump 280 and/or the turbopump 260 to the stop valve 217, the power turbine bypass valve 219, and/or the power turbine 228.

A power turbine throttle valve 250 may be fluidly coupled with a bypass line 246 on the high pressure side of the working fluid circuit 202 and upstream of the heat exchanger 120 and/or heat exchanger 122. The power turbine throttle valve 250 may be configured to modulate, adjust, or otherwise control the working fluid flowing through the bypass line 246, thereby providing or controlling a fine flowrate of the working fluid within the working fluid circuit 202. The bypass line 246 may be fluidly coupled with the working fluid circuit 202 at a point upstream of the power turbine 228 and at a point downstream from the pump portion 282 of the start pump 280 and/or the pump portion 262 of the turbopump 260. [0045]

A power turbine trim valve 252 may be fluidly coupled with a bypass line 248 on the high pressure side of the working fluid circuit 202 and upstream of the heat exchanger 124. The power turbine trim valve 252 may be configured to modulate, adjust, or otherwise control working fluid flowing through the bypass line 248, thereby providing or controlling a fine flowrate of the working fluid within the working fluid circuit 202. The bypass line 248 may be fluidly coupled with the bypass line 246 at a point upstream of the power turbine throttle valve 250 and at a point downstream from the power turbine throttle valve 250. [0046]

As discussed above, the waste heat system 100 of the heat engine system 90 may contain the heat exchangers 120, 122, 124 fluidly coupled with the high pressure side of the working fluid circuit 202 and in thermal communication with the heat source stream 110. Such thermal communic-
tion provides the transfer of thermal energy from the heat source stream 110 to the working fluid flowing throughout the working fluid circuit 202. The heat exchanger 120 may be the primary heat exchanger fluidly coupled with the working fluid circuit 202 upstream of the power turbine 228. The heat exchanger 124 may be the secondary heat exchanger fluidly coupled with the working fluid circuit 202 upstream of the inlet 131 of the drive turbine 264 of the turbopump 260. The heat exchanger 122 may be the tertiary heat exchanger fluidly coupled with the working fluid circuit 202 upstream of the heat exchanger 120.

[0047] The heat engine system 90 may further contain one or more recuperators 216 and 218 fluidly coupled with the working fluid circuit 202 and configured to transfer thermal energy between the high and low pressure sides of the working fluid circuit 202. In at least one embodiment, the recuperators 216 and 218 may be configured to transfer the thermal energy from the low pressure side to the high pressure side. The heat engine system 90 may further contain a cooler or condenser 274 in thermal communication with the working fluid contained in the low pressure side of the working fluid circuit 202 and configured to remove or absorb thermal energy from the working fluid in the low pressure side. In at least one embodiment, the cooler 274 may be a condenser configured to transfer thermal energy from the working fluid in the low pressure side to a cooling loop outside of the working fluid circuit 202, thereby controlling a temperature of the working fluid in the low pressure side of the working fluid circuit 202.

[0048] The heat engine system 90 may include a mass management system (MMS) 270 fluidly coupled with the working fluid circuit 202. The mass management system (MMS) 270 may include a mass control tank 286 fluidly coupled with the working fluid circuit 202. The mass control tank 286 may be fluidly coupled with the low pressure side of the working fluid circuit 202 and configured to receive, store, and deliver the working fluid. The mass control tank 286 and the working fluid circuit 202 may share the working fluid such that the mass control tank 286 may receive, store, and/or deliver the working fluid to and/or from the working fluid circuit 202 during one or more modes of operating the heat engine system 90. The mass control tank 286 may be a cryogenic storage vessel, tank, or any other suitable container. The mass control tank 286 or the cryogenic storage vessel may have an internal pressure from about 10 psig (pounds per square inch gauge; approximately 69 kPa) to about 800 psig (approximately 5516 kPa), about 50 psig (approximately 345 kPa) to about 500 psig (approximately 3447 kPa), about 100 psig (approximately 689 kPa) to about 450 psig (approximately 3103 kPa), or about 200 psig (approximately 1379 kPa) to about 400 psig (approximately 2758 kPa). For example, the mass control tank 286 may have an internal pressure of about 300 psig (approximately 2068 kPa).

[0049] An inventory return line 172 may be fluidly coupled with and between the mass control tank 286 and the low pressure side of the working fluid circuit 202, such as downstream from the condenser 274. As depicted in FIG. 1, a fluid line 168 may be fluidly coupled with and extend from the outlet of the condenser 274. The inventory return line 172 may be fluidly coupled with and extend from the fluid line 168 to the mass control tank 286. The inventory return line 172 may include at least one valve, such as an inventory return valve 174, configured to control the flow of the working fluid being transferred from the low pressure side of the working fluid circuit 202 to the mass control tank 286.

[0050] An inventory line 176 may be fluidly coupled with and between the mass control tank 286 and a charging pump 170. The inventory line 176 may be configured to transfer the working fluid contained within the mass control tank 286 to the charging pump 170. An inventory supply line 182 may be fluidly coupled with and between the charging pump 170 and the low pressure side of the working fluid circuit 202 upstream of the pump portion 282 of the start pump 280 and/or the pump portion 262 of the turbopump 260. As depicted in FIG. 1, the fluid line 142 may be fluidly coupled with and disposed between a junction point of both the inventory supply line 182 and the fluid line 168 and extend to the pump portion 282 of the start pump 280. The inventory supply line 182 may contain one or more valves, such as an inventory supply valve 184, configured to control the flow of the working fluid from the mass control tank 286 through the charging pump 170, and to the low pressure side of the working fluid circuit 202.

[0051] The valves 174, 184 may be actuated to one or more positions (e.g., partially opened, fully opened, closed) to remove working fluid from the working fluid circuit 202, add working fluid to the working fluid circuit 202, or a combination thereof. The valves 174, 184 may also be actuated to control or regulate the flowrate of the working fluid to and/or from the working fluid circuit 202. Exemplary embodiments of the mass management system 270, and a range of variations thereof, are found in U.S. Patent App. Ser. No. 13/278, 705, filed Oct. 21, 2011, published as U.S. Pub. No. 2012-0047892, and issued as U.S. Pat. No. 8,613,195, the contents of which are incorporated herein by reference to the extent consistent with the present disclosure.

[0052] Additional or supplemental working fluid may be added to the mass control tank 286, hence, added to the mass management system 270 and the working fluid circuit 202, from an external source, such as by a fluid fill system (not shown) via at least one connection point or fluid fill port, such as a working fluid feed 288. Exemplary fluid fill systems are described and illustrated in U.S. Pat. No. 8,281,593, the contents of which are incorporated herein by reference to the extent consistent with the present disclosure. An additional working fluid storage vessel (not shown) may be fluidly coupled with the mass control tank 286 and utilized to contain further supplemental working fluid. In at least one embodiment, the additional working fluid storage vessel may be fluidly coupled with the mass control tank 286 via the working fluid feed 288.

[0053] The mass management system (MMS) 270 may also include a charging pump 170 fluidly coupled with the working fluid circuit 202. The charging pump 170 may conduct inventory control by removing working fluid from the working fluid circuit 202, by storing working fluid, and/or by adding working fluid into the working fluid circuit 202. The charging pump 170 may be fluidly coupled with the mass control tank 286 via line 176 and may be configured to transfer the working fluid from the mass control tank 286 to the low pressure side of the working fluid circuit 202 via the inventory supply line 182. The charging pump 170 may be an electric-motorized pump, a mechanical-motorized pump, a variable frequency driven pump, a turbopump, or another type of pump.

[0054] The charging pump 170 may also be configured to transfer the working fluid from the mass management system.
270 to one or more bearing housings 238, 268 of the heat engine system 90. For example, during one or more modes (e.g., startup process) of operating the heat engine system 90, the charging pump 170 may transfer or otherwise deliver the working fluid from the mass control tank 286 to one or more bearings contained within a bearing housing 268 of the turbopump 260, a bearing housing 238 of the power generation system 220, and/or other system components containing bearings (e.g., rotary equipment or turbo machinery).

[0055] The power generation system 220 and the turbopump 260 may include a respective bearing housing 238 and 268. The bearing housings 238 and 268 may substantially encompass or enclose one or more bearings disposed within the power generation system 220 and/or the turbopump 260, respectively. The bearing housings 238 and/or 268 may also completely or substantially encompass or enclose the turbines, generators, pumps, driveshafts, gearboxes, other parts of the heat engine system 90, and/or components thereof. For example, the bearing housings 238 and/or 268 may completely or partially include structures, chambers, cases, housings, such as turbine housings, generator housings, driveshaft housings, driveshafts that contain bearings, gearbox housings, derivatives thereof, or combinations thereof.

[0056] As illustrated in FIG. 1, the bearing housing 238 may contain all or a portion of the power turbine 228, the power generator 240, the driveshaft 230, and the gearbox 232 of the power generation system 220. In at least one embodiment, a housing (not shown) of the power turbine 228 may be coupled with and/or form a portion of the bearing housing 238. Similarly, the bearing housing 268 may contain all or a portion of the turbopump 260 including, but not limited to, the drive turbine 264, the pump portion 262, the driveshaft 267, or any combination thereof. In at least one embodiment, a housing (not shown) of the drive turbine 264 and/or a housing (not shown) of the pump portion 262 may be coupled with and/or form portions of the bearing housing 268.

[0057] At least one bearing gas supply line 196 may be fluidly coupled with the bearing housings 238 and/or 268. The bearing gas supply line 196 may be configured to provide working fluid to the bearing housings 238 and/or 268. The bearing gas supply line 196 may be fluidly coupled with one or more systems, components, or parts of the heat engine system 90 and/or the working fluid circuit 202. Accordingly, the bearing gas supply line 196 may receive working fluid from any one or more systems, components, or parts of the heat engine system 90 and/or the working fluid circuit 202. In at least one embodiment, illustrated in FIG. 1, the bearing gas supply line 196 may be fluidly coupled with the charging pump 170 and at least one of the bearing housings 238 and/or 268, and may be configured to deliver working fluid from the charging pump 170 to at least one of the bearing housings 238 and/or 268.

[0058] The bearing gas supply line 196 may have or otherwise split into multiple spurs or segments of fluid lines, such as bearing gas supply lines 196a and 196b, which may independently extend to the bearing housings 238 and 268, respectively. For example, as illustrated in FIG. 4, the bearing gas supply line 196c may be fluidly coupled with and disposed between the charging pump 170 and the bearing housing 238 within the power generation system 220. A bearing gas supply valve 198a may be fluidly coupled with and disposed along the bearing gas supply line 196c. The bearing gas supply valve 198a may control the flow of the working fluid from the charging pump 170 to the bearing housing 238 within the power generation system 220.

[0059] As illustrated in FIG. 1, the bearing gas supply line 196a may be fluidly coupled with and disposed between the charging pump 170 and an inlet 151 of the bearing housing 268 of the turbopump 260. In at least one embodiment, working fluid from the charging pump 170 may be delivered through the bearing gas supply line 196a to the inlet 151 of the bearing housing 268. A bearing gas supply valve 198a may be fluidly coupled with and disposed along the bearing gas supply line 196a. The bearing gas supply valve 198a may control the flow of the working fluid from the charging pump 170 to the bearing housing 268 of the turbopump 260. The flow of the working fluid to the inlet 151 of the bearing housing 268 may determine, at least in part, the pressure of the working fluid contained in the bearing housing 268. Accordingly, the bearing gas supply valve 198a may be modulated to at least partially control the state or phase of matter of the working fluid in the bearing housing 268. For example, the bearing gas supply valve 198a may provide a flow of the working fluid to the bearing housing 268 such that the working fluid may be in a fluid phase, a gas phase, a supercritical state, a subcritical state, or any combination thereof. In at least one embodiment, the bearing gas supply valve 198a may maintain a flow of the working fluid to the inlet 151 of the bearing housing 268 such that all or substantially all the working fluid in the bearing housing 268 is in a supercritical state, thereby preventing a two-phase flow of the working fluid in the bearing housing 268.

[0060] A bearing drain line 155 may be coupled with and extend from an outlet 153 of the bearing housing 268 and may be configured to discharge the working fluid contained in the bearing housing 268. The bearing drain line 155 may be coupled with and extend from the outlet 153 of the bearing housing 268 to any one or more systems, components, or parts of the heat engine system 90 and/or the working fluid circuit 202. For example, the bearing drain line 155 may extend from the outlet 153 of the bearing housing 267 to a point on the low pressure side of the working fluid circuit 202. The bearing drain line 155 may also extend from the outlet 153 of the bearing housing 268 to the mass management system 270 and/or components thereof. In another embodiment, the bearing drain line 155 may provide a passage for the working fluid contained in the bearing housing 268 to be discharged or exhausted to the ambient surrounding atmosphere.

[0061] A bearing drain valve 154 may be fluidly coupled with and disposed along the bearing drain line 155. The bearing drain valve 154 may control the flow of the working fluid out of the bearing housing 268 and/or through the bearing drain line 155. The bearing drain valve 154 may be configured to provide a back pressure for the bearing housing 268 of the turbopump 260 during one or more modes of operating the heat engine system 90. In at least one embodiment, the bearing drain valve 154 may be modulated to control the pressure of the working fluid contained in the bearing housing 268. Accordingly, the bearing drain valve 154 may be modulated to at least partially control the state or phase of matter of the working fluid in the bearing housing 268. For example, the bearing drain valve 154 may maintain a back pressure in the bearing housing 268 such that the working fluid may be in a fluid phase, a gas phase, a supercritical state, a subcritical state, or any combination thereof. In at least one embodiment, the bearing drain valve 154 may maintain the back pressure in the bearing housing 268 such that all or substantially all the...
working fluid in the bearing housing 268 is in a supercritical state, thereby preventing a two-phase flow of the working fluid in the bearing housing 268.

[0062] The heat engine system 90 may contain a process control system 204 communicably connected (e.g., wired and/or wirelessly) with one or more components, parts, and/or systems of the heat engine system 90. For example, the process control system 204 may be communicably connected with one or more sensors, valves, pumps, fluid lines, including components thereof, or any combination thereof. The process control system 204 may be configured to process one or more measured and/or reported parameters or properties of the heat engine system 90. Illustrative measured and/or reported properties of the heat engine system 90 may include, but are not limited to, temperatures, pressures, thrust loads, mass flow rates, and/or fluid densities of the working fluid at one or more designated points within the working fluid circuit 202 and/or within one or more components of the heat engine system 90.

[0063] The process control system 204 may be operatively connected to the heat engine system 90 and/or components thereof, such that the process control system 204 may selectively adjust one or more components, parts, and/or systems of the heat engine system 90. The process control system 204 may selectively adjust the one or more components, parts, and/or systems of the heat engine system 90 in response to the measured and/or reported properties processed from the heat engine system 90. The process control system 204 may adjust the heat engine system 90 and/or components thereof to optimize, adjust, and/or modify the operation of the heat engine system 90 and/or components thereof. The process control system 204 may adjust the heat engine system 90 and/or components thereof to operate the heat engine system 90 in one or more modes (e.g., startup, steady operation, power generation, etc.). In at least one embodiment, the process control system 204 may respond to the measured and/or reported parameters by actuating one or more valves in accordance with a control program or algorithm to optimize the operation of the heat engine system 90.

[0064] In at least one embodiment, the process control system 204 may be communicably connected, wired and/or wirelessly, with the drive turbine 264 and/or the pump portion 262. The process control system 204 may be configured to process measured flow rates, pressures, and/or fluid densities at the inlet 131 and/or the outlet 133 of the drive turbine 264. The process control system 204 may also be configured to process measured flow rates, pressures, and/or fluid densities at the inlet 141 and/or the outlet 143 of the pump portion 262 of the turbopump 260. The process control system 204 may also be configured to measure rotational speeds of one or more of the pumps (e.g., turbopump 260, startup pump 280, and power generation system 220) of the heat engine system 90. In at least one embodiment, the process control system 204 may be communicably connected to the turbopump 260, and/or components thereof, semi-passively via one or more sensors (not shown). For example, a first set of sensors may be arranged at or adjacent the inlets 131, 141, 151 of the turbopump 260 and a second set of sensors may be arranged at or adjacent the outlets 133, 143, 153 of the turbopump 260. The first and second sets of sensors may monitor and report the pressure, temperature, mass flow rate, fluid density, and/or other properties of the working fluid within the turbopump 260, and/or components thereof.

[0065] The process control system 204 may also be operatively connected to the heat engine system 90 and may be configured to adjust the turbopump throttle valve 263 and/or the bearing drain valve 154. The process control system 204 may adjust the turbopump throttle valve 263 and/or the bearing drain valve 154 according to a program and/or algorithm to control the thrust applied to the turbopump 260 during one or more modes of operation of the heat engine system 90.

[0066] The process control system 204 may include a controller 206 and/or communicably connected therewith. The controller 206 may include a multi-controller algorithm configured to control one or more valves, pumps, sensors, or any combination thereof, within the heat engine system 90. In at least one embodiment, the process control system 204 may be configured to move, adjust, modulate, manipulate, or otherwise control the turbopump throttle valve 263 and/or the bearing drain valve 154 of the heat engine system 90 to control the flow of the working fluid therethrough. As further described herein, controlling the flow of the working fluid through the turbopump throttle valve 263 and/or the bearing drain valve 154 may control the thrust load applied to the turbopump 260. In at least one embodiment, the process control system 204 may modulate the turbopump throttle valve 263 and/or the bearing drain valve 154 to optimize the thrust load applied to the turbopump 260. The optimization of the thrust load may be determined by the program and/or algorithm of the controller 206.

[0067] In operation, the heat engine system 90 may circulate a working fluid within the working fluid circuit 202 via the start pump 280 and/or the turbopump 260. The turbopump throttle valve 263 may be modulated to control the flow of the working fluid to the drive turbine 264 to control the circulation or flow of the working fluid through the pump portion 262. The flow of the working fluid through the pump portion 262 may determine, at least in part, the net thrust applied to the turbopump 260. Accordingly, the modulation of the turbopump throttle valve 263 may determine, at least in part, the net thrust applied to the turbopump 260.

[0068] Thermal energy from the heat source 110 may be transferred to the working fluid via the heat exchangers 120, 122, and/or 124. The working fluid containing the thermal energy of the heat source 110 may flow into the power turbine 228 and may be expanded therein to convert the thermal energy from the working fluid to mechanical energy. The mechanical energy from the power turbine 228 may be converted into electrical energy via the power generator 240. The working fluid expanded in the power turbine 228 may flow to the low pressure side of the working fluid circuit 202. The working fluid from the low pressure side of the working fluid circuit 202 may flow to the mass control tank 286, which may be configured to receive and store the working fluid. The mass control tank 286 may also be configured to deliver the working fluid, through the charging pump 170, to a point within the low pressure side of the working fluid circuit upstream of the start pump 280 and/or the turbopump 260. The mass control tank 286 may also deliver the working fluid, through the charging pump 170, to the bearing housing 268 of the turbopump 260 and/or the bearing housing 238 of the power generation system 220. The bearing gas supply valves 198a, 198b, may be modulated to control the rate and/or pressure of the working fluid flowing from the charging pump 170, through the bearing gas supply line 196, 196a, 196b, to the bearing housing 238, 268. The bearing drain valve 154 may be modulated to control the rate and/or pressure of the work-
ing fluid flowing through the bearing drain line 155. The bearing drain valve 154 may also be modulated to control the pressure of the working fluid contained in the bearing housing 268.

[0069] In at least one embodiment, an overall efficiency of the heat engine system 90 and the amount of power ultimately generated therefrom may be determined or influenced, at least in part, by a net thrust load applied to the turbopump 260 and/or components thereof. Accordingly, the ability to control or regulate the net thrust load applied to the turbopump 260 may provide the ability to increase the efficiency and power generation of the heat engine system 90. The ability to control the net thrust load may also provide a method to prevent damage to the turbopump 260 and/or components thereof. For example, the turbopump 260 of the heat engine system 90 may have operational limitations determined by a maximum thrust load that may be applied to the turbopump 260 without causing damage thereto. Thus, the ability to control the net thrust may allow the turbopump 260 to be operated within the thrust load limits during one or more modes of operating the heat engine system 90, thereby avoiding damage thereto.

[0070] The heat engine system 90 described herein may provide a method of predicting a net thrust applied to the turbopump 260 during one or more modes of operating the heat engine system 90. The method of predicting the net thrust applied to the turbopump 260 may be provided as a function of one or more operating conditions of the heat engine system 90 and/or components thereof. For example, the net thrust load may be determined by the pressure and/or flow of the working fluid measured at one or more of the inlets 131, 141, 151 and/or outlets 133, 143, 153 of the turbopump 260. The method of predicting the net thrust may include determining or calculating the net thrust applied to the turbopump 260 during the one or more modes of operating the heat engine system 90. The method may also include determining one or more properties (e.g., pressure) at one or more of the inlets 131, 141, 151 and/or outlets 133, 143, 153 of the turbopump 260 during the one or more modes of operating the heat engine system 90. The determined or calculated net thrust applied to the turbopump 260 may be correlated with the one or more measured properties at the inlets 131, 141, 151 and/or outlets 133, 143, 153 of the turbopump 260. The correlation between the measured or calculated net thrust and the one or more measured properties of the turbopump 260 may be utilized to predict the net thrust applied to the turbopump 260 as a function of one or more operating conditions of the heat engine system 90. The ability to predict the net thrust applied to the turbopump 260 as a function of the one or more operating conditions of the heat engine system 90 may be utilized to optimize the net thrust by adjusting or modifying the one or more operating conditions.

[0071] The net thrust applied to the turbopump 260 may be determined or calculated from a clearance or gap between the bearings (e.g., thrust bearings) contained in the bearing housing 268 and the drive shaft 267. The clearance between the bearings and the drive shaft 267 may be determined or inferred from a pocket pressure ratio of the turbopump 260. The pocket pressure ratio of the turbopump 260 may be determined by one or more measured properties at the inlets 131, 141, 151 and/or outlets 133, 143, 153 of the turbopump 260. Accordingly, the net thrust applied to the turbopump 260 may be determined or calculated by the pocket pressure ratio, which may be determined by the one or more measured properties at the inlets 131, 141, 151 and/or outlets 133, 143, 153 of the turbopump 260.

[0072] In at least one embodiment, the pocket pressure ratio may be determined by the pressure, flow, and/or the fluid density of the working fluid at one or more of the inlets 131, 141, 151 and/or outlets 133, 143, 153 of the drive turbine 264, the pump portion 262, the bearing housing 268, or any combination thereof. One or more constraints may be imposed in the determination of the pocket pressure ratio for the turbopump 260. The constraints may be determined by the one or more modes of operating the heat engine system 90 and/or the operating conditions thereof. For example, the pocket pressure ratio during at least one mode of operation may be limited to a ratio of from about 0.1 to about 1.5. In another example, the pocket pressure ratio during at least one mode of operation may be from a low of about 0.1, about 0.2, about 0.3, about 0.4, about 0.5, about 0.6 to a high of about 0.7, about 0.8, about 0.9, about 1.0, about 1.1, about 1.2, or greater. The pocket pressure ratio during at least one mode of operation may also be from about 0.1 to about 1.2, about 0.2 to about 1.1, about 0.3 to about 1.0, about 0.4 to about 0.9, about 0.5 to about 0.8, or about 0.6 to about 0.7.

[0073] It may be appreciated that the operating conditions, and thus the measured properties at the inlet and/or outlets of the turbopump 260, may vary for each mode of operating the heat engine system 90. For example, operating conditions during a startup process may be the same or different from operating conditions during a steady state mode or any other mode. Accordingly, the pocket pressure ratio may be determined as a function of the operating conditions for each of the modes of operating the heat engine system 90 to measure the net thrust for varying operating conditions. The pocket pressure ratio for each mode of operating the heat engine system 90 may be correlated with the one or more measured properties at the inlets and/or outlets of the turbopump 260 for each respective mode. The correlation may provide a method of predicting the net thrust applied to the turbopump 260 as a function of the one or more operating conditions and/or modes of operating the heat engine system 90.

[0074] As discussed above, the ability to predict the net thrust applied to the turbopump 260 as a function of the one or more operating conditions of the heat engine system 90 may provide a method of controlling and/or optimizing the net thrust by adjusting or modifying the one or more operating conditions. The method of optimizing the net thrust may include varying at least one operating condition of the heat engine system 90 and predicting the net thrust applied to the turbopump 260 as a result of varying the operating condition. For example, the pressure of the working fluid at the outlet 153 of the bearing housing 268, or bearing drain pressure (PHD), may be varied to predict the resulting net thrust applied to the turbopump 260 for one or more modes of operating the heat engine system 90. In at least one embodiment, the net thrust may be directly related to the bearing drain pressure. For example, the net thrust may have a linear relationship with the bearing pressure. Accordingly, as the bearing pressure increases, the net thrust applied to the turbopump 260 may correspondingly increase. Similarly, as the bearing pressure decreases, the net thrust applied to the turbopump 260 may correspondingly decrease.

[0075] The predicted net thrust as a function of the bearing drain pressure may be utilized to provide an optimum bearing drain pressure for each of the one or more modes of operating
the heat engine system 90. The optimum bearing drain pressure may be the bearing drain pressure that results in the lowest predicted net thrust on the turbopump 260. For example, the optimum bearing drain pressure may be the bearing drain pressure where the resulting predicted net thrust is nil or substantially nil.

[0076] One or more constraints may be imposed in determining the optimum bearing drain pressure for the heat engine system 90. For example, the optimum bearing drain pressure may be determined such that the working fluid in the turbopump 260 is in a fluid phase, a gas phase, a supercritical state, a subcritical state, or any combination thereof. In at least one embodiment, the optimum bearing drain pressure may be limited such that the working fluid in the turbopump 260 is in a supercritical state. For example, the working fluid may be carbon dioxide, and the optimum bearing drain pressure may be about 1,000 psig (approximately 6895 kPa), about 1,050 psig (approximately 7240 kPa), about 1,100 psig (approximately 7584 kPa), about 1,150 psig (approximately 7929 kPa), about 1,200 psig (approximately 8274 kPa), about 1,300 psig (approximately 8963 kPa), about 1,400 psig (approximately 9655 kPa), or greater. In another example, the working fluid may be carbon dioxide and the optimum bearing drain pressure may be greater than 1,000 psig (approximately 6895 kPa), greater than 1,050 psig (approximately 7240 kPa), greater than 1,100 psig (approximately 7584 kPa), greater than 1,150 psig (approximately 7929 kPa), greater than 1,200 psig (approximately 8274 kPa), greater than 1,300 psig (approximately 8963 kPa), or greater than 1,400 psig (approximately 9655 kPa).

[0077] The optimum bearing drain pressure provided by the predicted net thrust may be utilized to determine a position of the bearing drain valve 154 that minimizes the thrust applied to the turbopump 260 during one or more modes of operating the heat engine system 90. The determination of the position of the bearing drain valve 154 may be incorporated in the process control system 284 to provide active thrust control during the one or more modes of operating the heat engine system 90. Accordingly, the process control system 204 may automatically modulate the bearing drain valve 154 in response to the operating conditions of the heat engine system 90 to minimize the thrust applied to the turbopump 260.

[0078] FIG. 2 is a flowchart illustrating a method 300 for controlling a thrust load applied to a turbopump of an exemplary heat engine system, according to one or more embodiments disclosed. The method 300 may include circulating a working fluid through a high pressure side and a low pressure side of a working fluid circuit with the turbopump, wherein at least a portion of the working fluid is in a supercritical state, as shown at 302. The method 300 may also include transferring thermal energy from a heat source to the working fluid by a heat exchanger fluidly coupled to and in thermal communication with the heat source and the high pressure side of the working fluid circuit, as shown at 304. The method 300 may further include flowing the working fluid into an expander and converting the thermal energy from the working fluid to mechanical energy of the expander, as shown at 306. The method 300 may also include flowing a portion of the working fluid from the working fluid circuit through a charging pump to an inlet of a bearing housing substantially encompassing bearings of the turbopump, as shown at 308. The method 300 may also include modulating a turbopump throttle valve to control a flow of the working fluid to a drive turbine of the turbopump, thereby at least partially controlling a thrust load applied to the turbopump, as shown at 310. The method 300 may also include modulating a bearing drain valve to control a flow of the working fluid through a bearing drain line fluidly coupled to an outlet of the bearing housing, thereby at least partially controlling the thrust load applied to the turbopump, as shown at 312.

[0079] 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. Those skilled in the art also should realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions and alterations herein without departing from the spirit and scope of the present disclosure.

We claim:

1. A heat engine system, comprising:
   a working fluid circuit having a high pressure side and a low pressure side and being configured to flow a working fluid therethrough, the working fluid being at least partially in a supercritical state and comprising carbon dioxide;
   a heat exchanger fluidly coupled to and in thermal communication with the high pressure side of the working fluid circuit, the heat exchanger fluidly coupled to and in thermal communication with a heat source and configured to transfer thermal energy from the heat source to the working fluid within the high pressure side of the working fluid circuit;
   an expander fluidly coupled to and disposed between the high pressure side and the low pressure side of the working fluid circuit and configured to convert a pressure drop in the working fluid to mechanical energy;
   a recuperator fluidly coupled to the working fluid circuit and operative to transfer thermal energy between the high pressure side and the low pressure side of the working fluid circuit;
   a cooler in thermal communication with the working fluid in the low pressure side of the working fluid circuit and configured to remove thermal energy from the working fluid in the low pressure side of the working fluid circuit;
   a turbopump fluidly coupled between the low pressure side and the high pressure side of the working fluid circuit and configured to circulate the working fluid through the working fluid circuit;
   a turbopump throttle valve coupled to the high pressure side of the working fluid circuit and configured to control a flow of the working fluid to the turbopump, thereby at least partially controlling a thrust load applied to the turbopump;
   a bearing housing substantially encompassing one or more bearings contained within the turbopump;
   a charging pump fluidly coupled with the working fluid circuit and configured to transfer the working fluid to an inlet of the bearing housing; and
   a bearing drain line fluidly coupled to an outlet of the bearing housing, the bearing drain line including a bearing drain valve coupled thereto and configured to control a flow of the working fluid therethrough, thereby at least partially controlling the thrust load applied to the turbopump.
2. The heat engine system of claim 1, further comprising a mass management system fluidly coupled to the working fluid circuit, the mass management system comprising:
   a mass control tank fluidly coupled to the low pressure side of the working fluid circuit and the charging pump, the mass control tank configured to receive the working fluid from the working fluid circuit and to transfer the working fluid to the charging pump.

3. The heat engine system of claim 1, further comprising a bearing gas supply line fluidly coupled to and between the charging pump and the inlet of the bearing housing, the bearing gas supply line including a bearing gas supply valve coupled thereto and configured to control the flow of the working fluid from the charging pump to the bearing housing.

4. The heat engine system of claim 1, wherein the turbopump comprises a pump portion coupled with a drive turbine via a driveshaft, the pump portion coupled between the low pressure side and the high pressure side of the working fluid circuit and configured to be driven by the drive turbine and to circulate the working fluid through the working fluid circuit.

5. The heat engine system of claim 4, wherein the drive turbine is fluidly coupled between the low pressure side and the high pressure side of the working fluid circuit and configured to drive the pump portion by mechanical energy generated by the expansion of the working fluid flowing therethrough.

6. The heat engine system of claim 5, wherein the turbopump throttle valve is configured to control the flow of the working fluid to an inlet of the drive turbine, thereby at least partially controlling the thrust load applied to the turbopump.

7. The heat engine system of claim 1, wherein the bearing drain valve is modulated to at least partially control a pressure of the working fluid contained in the bearing housing to at least partially control the thrust load applied to the turbopump.

8. The heat engine system of claim 1, wherein the bearing drain valve is modulated such that at least a portion of the working fluid in the bearing housing is in a supercritical state.

9. The heat engine system of claim 1, further comprising a process control system operatively and communicably coupled with the bearing drain valve and configured to modulate the bearing drain valve, thereby providing an active thrust control of the turbopump.

10. The heat engine system of claim 1, further comprising a process control system operatively and communicably coupled with the turbopump throttle valve and configured to modulate the turbopump throttle valve, thereby providing an active thrust control of the turbopump.

11. A heat engine system, comprising:
   a working fluid circuit having a high pressure side and a low pressure side and configured to flow a working fluid therethrough, wherein the working fluid comprises carbon dioxide and is at least partially in a supercritical state;
   a heat exchanger fluidly coupled to and in thermal communication with the high pressure side of the working fluid circuit, the heat exchanger fluidly coupled to and in thermal communication with a heat source and configured to transfer thermal energy from the heat source to the working fluid within the high pressure side of the working fluid circuit;
   an expander fluidly coupled to and disposed between the high pressure side and the low pressure side of the working fluid circuit and configured to convert a pressure drop in the working fluid to mechanical energy;
   a recuperator fluidly coupled to the working fluid circuit and operatively to transfer thermal energy between the high pressure side and the low pressure side of the working fluid circuit;
   a cooler in thermal communication with the working fluid in the low pressure side of the working fluid circuit and configured to remove thermal energy from the working fluid in the low pressure side of the working fluid circuit;
   a turbopump comprising a pump portion coupled with a drive portion via a driveshaft, the pump portion coupled between the low pressure side and the high pressure side of the working fluid circuit and configured to be driven by the drive turbine and to circulate the working fluid through the working fluid circuit, the drive portion fluidly coupled between the low pressure side and the high pressure side of the working fluid circuit and configured to drive the pump portion by mechanical energy generated by the expansion of the working fluid flowing therethrough;
   a turbopump throttle valve coupled to the high pressure side of the working fluid circuit and configured to control a flow of the working fluid to an inlet of the drive turbine, thereby at least partially controlling the thrust load applied to the turbopump;
   a bearing housing substantially encompassing one or more bearings of the turbopump;
   a charging pump fluidly coupled with the working fluid circuit and configured to transfer the working fluid to an inlet of the bearing housing;
   and
   a bearing drain line fluidly coupled to an outlet of the bearing housing, the bearing drain line including a bearing drain valve coupled thereto and configured to at least partially control the thrust load applied to the turbopump.

12. The heat engine system of claim 11, further comprising a process control system operatively and communicably coupled with the bearing drain valve and configured to modulate the bearing drain valve, thereby providing an active thrust control of the turbopump.

13. The heat engine system of claim 11, further comprising a process control system operatively and communicably coupled with the turbopump throttle valve and configured to modulate the turbopump throttle valve, thereby providing an active thrust control of the turbopump.

14. A method for controlling a thrust load applied to a turbopump of a heat engine system, comprising:
   circulating a working fluid through a high pressure side and a low pressure side of a working fluid circuit with the turbopump, wherein at least a portion of the working fluid is in a supercritical state;
   transferring thermal energy from a heat source to the working fluid by a heat exchanger fluidly coupled to and in thermal communication with the heat source and the high pressure side of the working fluid circuit;
   flowing the working fluid into an expander and converting the thermal energy from the working fluid to mechanical energy of the expander;
   flowing a portion of the working fluid from the working fluid circuit through a charging pump to an inlet of a bearing housing substantially encompassing bearings of the turbopump;
modulating a turbopump throttle valve to control a flow of the working fluid to a drive turbine of the turbopump, thereby at least partially controlling the thrust load applied to the turbopump; and

modulating a bearing drain valve to control a flow of the working fluid through a bearing drain line fluidly coupled to an outlet of the bearing housing, thereby at least partially controlling the thrust load applied to the turbopump.

15. The method of claim 14, further comprising:

flowing a portion of the working fluid from the low pressure side of the working fluid circuit to a mass control tank fluidly coupled to the working fluid circuit; and

flowing the working fluid from the mass control tank to the charging pump.

16. The method of claim 14, wherein modulating the bearing drain valve to at least partially control the thrust load applied to the turbopump further comprises determining an optimum bearing drain pressure to minimize the thrust load applied to the turbopump.

17. The method of claim 16, wherein determining the optimum bearing drain pressure comprises determining the thrust load applied to the turbopump from a pocket pressure ratio thereof.

18. The method of claim 16, further comprising modulating the turbopump throttle valve with a process control system operatively and communicably coupled therewith to minimize the thrust load applied to the turbopump.

19. The method of claim 16, further comprising modulating the bearing drain valve with a process control system operatively and communicably coupled therewith to minimize the thrust load applied to the turbopump.

20. The method of claim 16, further comprising modulating the bearing drain valve such that the working fluid contained in the bearing housing is in a supercritical state.

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