

POWER CYCLE SYSTEM

Field of the Invention

[01] The present disclosure relates generally to power cycle systems for generating electricity in a power plant, and more specifically to a power cycle system for use with a fusion reactor; in particular, a tokamak type reactor/power plant. Yet more specifically, the present disclosure relates to a power cycle system based on a modified Brayton or Rankine cycle.

Background

[02] One of the great challenges facing nuclear fusion technology is how to convert the energy generated by a fusion reactor into useable electricity. In the context of tokamak type reactors particularly, a closed working fluid heat engine operating according to a (closed) Brayton or Rankine cycle – i.e., a closed cycle gas turbine operating with supercritical, subcritical or transcritical fluid – has been postulated as a potentially advantageous electrical generator.

[03] However, existing power cycle technologies for fusion reactors face a problem of how to handle reactor uncertainty in heat split (quantity and quality), intermittency (pulsed operation), start-up / shut down, trip and dynamics (rapid load ramp rate), and so on.

[04] One solution to some of these problems utilises a thermal storage whereby heat is stored in a suitable salt composition. However, the thermal storage loses heat over time and can be inefficient to heat and maintain, particularly as high temperature salt compositions which are typically used can be highly corrosive. Also, the thermal response to deliver heat to the power cycle is very slow, and so while it can be useful in a startup phase, it is unsuitable for dealing with operations uncertainty. Finally thermal storage is finite in nature, which is particularly challenging when trying to develop a system as uncertain as fusion energy and prototypic.

[05] Another approach utilises an external steam Rankine or Brayton engine to smooth power performance. However, thermal response time is limited by the thermal inertia of the steam boiler, again making such a system unsuitable for responding to short term operational uncertainty.

[06] Hence it is desirable to develop a power cycle system which may more readily adapt to reactor conditions.

Summary

[07] The present invention is defined according to the independent claims. Additional features will be appreciated from the dependent claims and the description herein. Any embodiments which are described but which do not fall within the scope of the claims are to be interpreted merely as examples useful for a better understanding of the invention.

[08] The example embodiments have been provided with a view to addressing at least some of the difficulties that are encountered with current approaches to power cycle systems for intermittent heat sources, whether those difficulties have been specifically mentioned above or will otherwise be appreciated from the discussion herein. Examples of intermittent heat sources include fusion reactors (in particular tokamak type reactors), solar thermal collectors, and fission reactors, although this list is not exhaustive.

[09] In particular, the example embodiments provide a closed loop Brayton or Rankine cycle (supercritical, subcritical or transcritical) configured to indirectly convert heat from an intermittent heat source into electricity, with the cycle being augmented by a backup heat source to directly add heat into the cycle. That is, the same power cycle is used, whether it is directly heated or indirectly heated. Plasma ramps up >1GW thermal very rapidly, and so the backup heat source that directly adds heat into the cycle prepares, and/or maintains the power cycle prior to receiving the heat from plasma (heating the components, rolling the turbine etc.), thereby reducing the thermal expansion/stresses to prolong component lifetime; hence operations are not hindered by the power cycle ramping limits.

[10] Accordingly, in one aspect of the invention there is provided a power cycle system for an intermittent heat source, for example a fusion reactor. The power cycle system comprises means for carrying a working fluid, indirect heating means configured to indirectly heat the working fluid using the intermittent heat source, direct heating means configured to directly heat the working fluid, and a turbine configured to generate electrical power using heated working fluid. The system comprises a first mode in which the system is configured to indirectly heat the working fluid using the indirect heating means while the direct heating means is thermally decoupled from the working fluid, and a second mode in which the direct heating means is configured to heat the working fluid while the indirect heating means is substantially thermally decoupled from the working fluid.

[11] Optionally, the system may operate in a third mode in which the both the indirect heating means and direct heating means are active and thermally coupled to the working fluid. In this way the described system may readily adapt to operational uncertainty of an intermittent heat source, as well as providing other advantages.

[12] Optionally, in the first mode, the direct heating means may be deactivated.

[13] In an example, the means for carrying working fluid comprises a common flow path for carrying working fluid when the system is configured in each of the first and second modes. Suitably, at least some of the same power cycle components may be utilised regardless of mode of operation, thereby reducing overall complexity and footprint of the system.

[14] In an example, the system comprises a first set of control means (e.g., controllable valves) which are open in the first mode and closed in the second configuration.

[15] In an example, the system comprises a second set of control means (e.g., controllable valves) which are open in the second mode and closed in the first mode.

[16] Opening and closing the first and second sets of valves opens and closes dedicated indirect mode flow paths and direct heat mode flow paths which are coupled to the common path.

[17] In an example, the indirect heating means comprises a set of heat exchangers thermally couplable to the intermittent heat source which outputs different grades of heat. In this way the power cycle may be configured to efficiently operate with heat output from an intermittent heat source which outputs multiple grades of heat (i.e., different amounts and quality).

[18] In an example, the set comprises a primary heat exchanger thermally couplable to a primary, high temperature, heat source,

[19] In an example, the set further comprises a second heat exchanger thermally couplable to a secondary, medium or low temperature, heat source.

[20] In an example, the set further comprises a a third heat exchanger thermally couplable to a tertiary, low temperature, heat source.

[21] In another example, the set further comprises a a fourth heat exchanger couplable to a quaternary (or more) heat source.

[22] In an example, the direct heating means comprises a combustor configured to receive a fuel and an oxidant.

[23] In an example, the fuel may comprise hydrogen, carbon or hydrocarbon, or other carbonaceous fuels. In an example the oxidant may be oxygen.

[24] In an example, the working fluid comprises at least one of di-nitrogen, argon, helium, air, Xenon, Neon, CH₄, O₂ or water, though preferably the working fluid comprises primarily carbon dioxide. In particular, a purity level of carbon dioxide may be at least 50%, and further preferably at least about 85% to 99%.

[25] In an example, the working fluid comprises a binary or tertiary mixture of carbon dioxide and at least one of C₆F₆, C₄F₈, C₂H₃N, TiCl₄, NO₂, SO₂, SiCl₄, WCl₆, WF₆, UF₆ to facilitate condensing of the working fluid even at higher ambient temperature (e.g., ~50°C).

[26] In a related aspect of the invention there is provided a method of operation of a power cycle system as described above.

[27] In a related aspect of the invention there is provided a fusion power plant comprising a fusion reactor and the power cycle system as described above, wherein the power cycle system is operated in the first mode when the fusion reactor is in an operational mode. The power cycle system may be operated in the second mode during a startup phase of the nuclear reactor, a shutdown phase of the nuclear reactor, or generally any interrupt in operation of the nuclear reactor. In an example, the power plant may comprise a controller configured to receive a signal

corresponding to a status of the reactor, and (automatically) change the power cycle from operating in the first mode to operating in the second mode, or vice versa, responsive to the received signal.

[28] In an example, the first (operational) mode of the fusion reactor may be a power generation phase/mode.

[29] In an example, the power cycle system may be operated in the second mode during a startup phase of the nuclear reactor.

[30] In an example, the power cycle system may be operated in the second mode during a shutdown phase of the nuclear reactor, or an interrupt in operation of the nuclear reactor.

[31] In an example, the power cycle system may be operated in the first and second mode simultaneously.

[32] In an example, the power plant may comprise a controller configured to receive a signal corresponding to a status of the reactor, and change the power cycle from operating in the first mode to operating in the second mode, or vice versa, responsive to the received signal.

[33] In an example, the power plant may comprise a thermal buffer coupled to a primary heating loop of the power cycle system.

[34] In another aspect of present invention, there is provided a solar thermal power plant (i.e., a power plant for thermal based solar energy production) comprising the power cycle system described above. The power cycle system may be operated in a first mode when the sun is providing suitable heating for power generation, and operated in the second mode when the sun is not able to provide heating for power generation (e.g., during the night), or indeed any other potential interrupt of power generation such as heavy cloud cover.

[35] In another aspect of the present invention, there is provided a nuclear fission power plant comprising the aforementioned power cycle system. Suitably, the power cycle system may be operated in the first mode during a power generation phase of the fission reactor (i.e., during peak demand), and operated in the second mode during an idle, or low power output phase, of the fission reactor (i.e., during low demand). Such operation is not typical for a fission reactor, which are usually operated continuously as a base load power plant. The present invention however may allow the fission plant to be utilised instead as a load following power plant

[36] As used herein, unless otherwise expressly specified, all numbers such as those expressing values, ranges, amounts or percentages may be read as if prefaced by the word "about", even if the term does not expressly appear. The term "about", or substantially, when used herein means +/- 5% of the stated value. Also, any numerical range recited herein is intended to include all sub-ranges subsumed therein, and the terms "from" and "to" a pair of values are intended to indicate such values are included in the range. Singular encompasses plural and vice versa. Additionally, although the present invention has been described in terms of

“comprising”, the processes, materials, and coating compositions detailed herein may also be described as “consisting essentially of” or “consisting of”.

Brief Description of the Drawings

[37] For a better understanding of the present disclosure reference will now be made by way of example only to the accompanying drawings, in which:

[38] Fig. 1 shows a schematic of an example fusion power plant;

[39] Fig. 2 shows a schematic of an improved power cycle system;

[40] Fig. 3 shows an overview of an example fusion power plant including the example power cycle system of Fig. 2;

[41] Fig. 4 shows a schematic of an example improved power cycle system for use with an intermittent heat source;

[42] Fig. 5 shows a schematic of another example improved power cycle system for use with an intermittent heat source;

[43] Fig. 6 shows a schematic of yet another example improved power cycle system for use with an intermittent heat source;

[44] Fig. 7 shows a schematic of yet another example improved power cycle system for use with an intermittent heat source;

[45] Fig. 8 shows a schematic of yet another example improved power cycle system for use with an intermittent heat source;

[46] Fig. 9 shows a schematic of yet another example improved power cycle system for use with an intermittent heat source;

[47] Fig. 10 shows a schematic of yet another example improved power cycle system for use with an intermittent heat source;

[48] Fig. 11 shows a schematic of yet another example improved power cycle system for use with an intermittent heat source;

[49] Fig. 12 shows a schematic of yet another example improved power cycle system for use with an intermittent heat source;

[50] Fig. 13 shows a schematic of yet another example improved power cycle system for use with an intermittent heat source; and

[51] Fig. 14 shows a schematic of yet another example improved power cycle system for use with an intermittent heat source.

[52] In each of Figures 4 to 14, a continuous line shows a common flow path for all modes of operation of the power cycle system (which includes a path to the main turbine), a dash line shows flow paths corresponding to an oxy-combustion (second) mode of operation, a dash-dot line shows flow paths corresponding to an indirect heating (first) mode of operation, and dash-dot-dot lines show energy flow (i.e., heat from a heat source). In each of the Figures, like symbols are used to indicate like components and reference numerals are used consistently across figures.

Detailed Description

[53] At least some of the following example embodiments provide a power cycle system for use in generating electricity from a fusion power plant, or from energy provided by any other suitable intermittent heat source – in particular an improved power cycle system based on a modified Brayton cycle. Other advantages and improvements may also be apparent from the discussed embodiments herein.

[54] Herein, an intermittent heat source may be a heat source that does not provide a constant and reliable energy output, either due to planned dwell periods, reactor variability, maintenance periods, or other operational uncertainties. Examples of intermittent heat sources include fusion reactors, thermal solar arrays/power plants, fission reactors (particularly as a load-following plant), to name but a few. It will of course be appreciated that the list is non-exhaustive and the disclosure is not limited thereto. In some examples the intermittent heat source may be taken to comprise a plurality, or set, of heat sources corresponding to different grades of heat output by the intermittent heat source.

[55] In many examples herein the intermittent heat source is assumed to be a tokamak type (fusion) reactor, for example the Spherical Tokamak for Energy Production 'STEP' project. Tokamak type reactors comprise a variety of heat sources which provide different grades of temperature corresponding to different components of the reactor.

[56] For example, a primary heat source supplying a primary heat, which may be regarded as high grade temperature, may be heat from a blanket module surrounding the vacuum vessel of the reactor, and/or from an outboard first wall of the vacuum vessel. Here the primary heat may be at least 500°C (degrees centigrade), and possibly at least 600°C. Heat from a primary heat source may also be termed a high temperature heat herein.

[57] Heat from a secondary heat source supplying a secondary heat (low grade), may be heat from an inboard first wall of the vacuum vessel and/or inboard radiation shield. Here the secondary heat may be about 300°C or lower, and in general will be always lower than the primary heat. Heat from a secondary heat source may also be termed a medium heat source herein

[58] Some reactors may comprise a third heat source supplying tertiary heat (low grade), which may be heat from heat from a divertor component of the reactor, and maybe lower than the second

heat. Here the tertiary heat may be above 150°C, and in general will be always lower than the primary and secondary heats.

[59] Heat lower than 150°C may be regarded as waste heat from parts of the plant such as heating and current drive, (potentially from) cryogenic plant etc. In some examples such heat may also be utilised as a fourth (or further) heat source. In some examples a fourth heat source may correspond to a decay heat – that is, heat resulting from radioactive decay of activated structural material of the reactor.

[60] It should however be appreciated that the present techniques are not limited to tokamak type reactors. The present disclosure may be readily applied to any fusion reactor where startup phases, shutdown phases, reactor intermittence, and so on, can be expected, and any reactor where heat grade and the number of temperature levels vary.

[61] Figure 1 shows an example arrangement for a fusion power plant 10. The power plant comprises a reactor 12 (e.g., a spherical tokamak) and a power cycle 14 to convert heat from the reactor 12 into electrical energy.

[62] The power cycle 14 is formed from a closed Brayton (or Rankine) cycle. A working fluid (liquid or gas) is compressed by a compressor 16 to increase the temperature and pressure of the working fluid. The high pressure working fluid is heated (ideally isobarically) by a heat exchanger 18, and then the heated fluid is used to turn a turbine 20 to produce useful external work – i.e., generating electricity. The turbine 20 is an expander such that the working fluid reduces temperature and pressure on the outlet side of the turbine before being passed through a cooler 22 to remove any excess heat. The working fluid is then directed back into the compressor for the cycle to continue.

[63] The power plant of course comprises suitable grid infrastructure 24 to transfer electrical power generated by the turbine 22 to an external energy grid 26 (e.g., the national grid). Optionally, the power plant 10 may also comprise a thermal storage 28, which may be configured to (slowly) add heat into the power cycle 14 in certain circumstances; for example, when the reactor 12 is undergoing maintenance, or during a startup phase. Moreover, thermal storage (or buffer) helps add thermal inertia to enable a transition between operating modes of the reactor.

[64] Figure 2 shows an example of an improved power cycle 100 based on an augmented (improved) Brayton cycle for an intermittent heat source (as above, including, but not limited to, a fusion heat source, a solar heat source, a fission heat source, and other examples). Figure 3 shows the example power cycle 100 of Fig. 2 as applied to an example arrangement for a fusion power plant 10.

[65] In the present examples, the working fluid is preferably a gas, for example di-nitrogen, argon, helium, air, water, or preferably carbon dioxide (which may be further preferably supercritical). In some examples the working fluid may be a binary or tertiary mixture of carbon

dioxide with other organic based working fluids such as Hydrofluorocarbons (e.g., C_6F_6 , C_4F_8), C_2H_3N , $TiCl_4$, NO_2 , SO_2 , $SiCl_4$, WCl_6 , WF_6 , UF_6 ; such mixtures facilitate condensing of the working fluid even at higher ambient temperature ($\sim 50^\circ C$), thereby reducing the pumping power. The working fluid may be suitably transported by various fluidically coupling means including a network of piping, inlets, outlets, valves, and other suitable components as would be familiar to those in the art.

[66] Similar to Fig. 1, the power cycle 100 comprises indirect heating means 118, such as a heat exchanger, configured to indirectly heat the working fluid using heat from an intermittent heat source 110 (e.g., reactor 12 of the fusion power plant 10), as well as an electric generator 120 configured to generate electrical power using heated working fluid using a turbine.

[67] The cycle 100 also comprises direct heating means 102 configured to directly heat the working fluid. The direct heating means 102 may be a combustor which is suitably provided with fuel and an oxidant. Preferably the fuel is carbon free (i.e., not a fossil fuel), such as hydrogen or any other green fuel, but may (in non-preferred examples) comprise hydrocarbons. Preferably average levels of carbon dioxide in the working fluid are about 95% or greater, with the remaining percentage formed from impurities such as Argon, N_2 , O_2 and possibly trace amounts of SO_x and NO_x . It will of course be appreciated that the carbon dioxide level may vary throughout the cycle, for example being about 97% or greater at a pump (or compressor) component 116 and about 90% to 95% at a turbine (generator) component 120. In general, carbon dioxide purity should be above about 50%. Operating the entire cycle with a carbon dioxide purity in similar ranges (e.g., between 85% and 99% purity) allows for the establishment of quicker chemical equilibrium when making mode changes in the power cycle (see below). Operating with higher carbon dioxide purity is possible but requires the addition of a purification system (not shown) and results in slower chemical equilibration time.

[68] The combustion products of the direct heating means are primarily water and CO_2 as combustion is conducted with near pure oxygen rather than air. The water level reaches a about 4% at the generator (turbine) 120 inlet, which is removed. There is also a possibility of having some small amount of un-combusted CO and CH_4 remain in the system. The CO_2 (and other combustion products) may be removed from the cycle for subsequent sequestration.

[69] Suitably, the same power cycle that is designed to accept indirect heat from the intermittent heat source (e.g., fusion reactor) may be augmented to include an auxiliary direct heat process. In particular, the power cycle system 100 is configurable to adapt between an indirect heating mode and a direct heat mode.

[70] In the indirect heating mode – otherwise termed a first mode or first configuration herein, and also a fusion mode in fusion specific examples such as Fig. 3 – the intermittent heat source 110 is actively producing heat which is used to indirectly heat the working fluid via heating means 118 (e.g., a heat exchanger). Suitably, in the first mode, the power cycle system operates in a

closed-loop configuration. In particular, in the first mode the heating means 118 are thermally coupled to the working fluid to provide heat to the working fluid. In the first mode the direct heating means 102 may be deactivated (i.e., not in use).

[71] By contrast, in the direct heat mode – otherwise termed a second mode, second configuration, or an oxy-combustion mode herein – the direct heating means 102 are configured to be active to directly heat the working fluid. In this second mode, the indirect heating means 118 are substantially inactive. For example, the indirect heating means may be thermally decoupled from the working fluid 100 (using e.g., one or more valves). In the second mode the power cycle operates in a semi-closed-loop configuration, as the second mode also allows for the possibility of removing combustion products from the power cycle 100.

[72] In some examples the power cycle 100 may also comprise a dual mode, otherwise termed a third mode or configuration herein, in which the both the indirect heating means and direct heating means may be active in providing heat to the working fluid.

[73] It will be appreciated that switching between the modes may be performed manually, for example by a power plant operator, or may be automatic. For example, the power plant 10 may comprise a control unit (not shown) configured to monitor a status of the intermittent heat source 110 and change the operating mode (first or second) of the power cycle 100 responsive to a status signal.

[74] Combining the two modes of operation within a single power cycle provides many advantages for power generation from intermittent heat sources, and especially for nuclear fusion power.

[75] The power cycle 100 is particularly suitable in cases where the intermittent heat source operates in a pulsed fashion – for example, where there is pulsed heat coming from the fusion reactor 12 in short duration – so that the direct heat can be input to smooth over operation between pulses.

[76] Using the same power cycle components during fusion mode and backup oxy-combustion mode of operation facilitates a quick transition between modes as the components are already hot and running, thereby minimising the thermal stresses.

[77] The oxy-combustion mode can be utilised to preheat the intermittent heat source 110 and other components thereof; for example, a breeder blanket and fluid(s) therein of a fusion reactor. Relatedly, the back-up oxy-combustion heat source 102 may be activated during a startup phase of the intermittent heat source 110 to start up the power cycle 100 (i.e., preheat) with the power cycle 100 later being switched to accept indirect heat from the intermittent heat source 110 (i.e., fusion mode).

[78] The back-up oxy-combustion heat source 102 may be configured to come online when the intermittent heat source 110 shuts down or trips (interrupts) to keep the heat source either

continuing to run in an island mode (i.e., until active heat production, such as fusion operation, is restored) or shutdown the intermittent heat source 110 in a controlled manner (again, thereby reducing thermal stresses on the power cycle 100 components). Likewise, uncertainty linked to prototypic operations including lot of trips, but the components may be spared from undergoing severe stresses as the combustion cuts in. When there is a trip of active heat from the intermittent heat source (e.g., fusion heat), the combustion recovers the operation of the power cycle and keeps the power cycle running to enable restarting the cycle whilst also reducing the stresses.

[79] The example power cycle 100 allows for load following potential with the aid of back-up oxy-combustion heat source.

[80] The direct heat mode may be utilised as a black start capability, as the electricity generated from the backup oxy-combustion can be used to supply all of the power plant 10 parasitic loads during start-up.

[81] In dual mode operation, the back-up oxy-combustion heat source 102 may be utilised to balance out uncertainty in performance of the intermittent heat source.

[82] Finally, the same power cycle may be utilized to capture heat from the intermittent heat source 110 with the combustor turned off (i.e., first mode operation), thereby eliminating a need for redundant auxiliary power cycles or components (e.g., reducing a size of required thermal storage), thereby significantly reducing the potential power plant footprint and capital costs

[83] These are but some of the advantages of the presently described power cycle 100. It will be appreciated that there may be other advantages not listed here, whether those advantages apply to use with a fusion reactor or other type of intermittent heat source (such as solar or fission).

[84] Figures 4 to 14 show various embodiments of the above improved power cycle 100 in more detail. These exemplary embodiments are particularly suited for use with a multi-heat intermittent heat source 110; that is, an intermittent heat source 110 which outputs different grades of heat.

[85] By way of example, each embodiment has been particularly envisaged for use with a fusion reactor 12, although it will be appreciated that the embodiments are not limited thereto, and may indeed be applied to any suitable intermittent heat source. Moreover, symbology and reference numerals are shared between figures to show like components and reduce a need for repeat description thereof. Thus, many of the features of the embodiments will be firstly introduced with Fig. 4, and thereafter may be assumed to be the same, or similar, in following embodiments unless otherwise stated.

[86] Figure 4 shows a first example power cycle 100a for a multi-heat intermittent heat source 110. In the example of Figure 4, the indirect heating means 118 may comprise a set of heat exchangers 118 configured to heat the working fluid at various points in the power cycle 100. A primary heat exchanger 104 in the set is thermally coupled to the primary heat 110H of the intermittent heat source 110 (i.e., a high temperature, high grade heat), a secondary heat

exchanger 106 in the set is thermally coupled to the secondary heat 110M of the intermittent heat source 110 (i.e., mid temperature, low grade heat), and a tertiary heat exchanger 108 in the set is thermally coupled to the tertiary heat 110L of the intermittent heat source 110 (i.e., low temperature, low grade heat).

[87] Each of the heat exchangers 104–108 may themselves be part of a subset of heat exchangers. In this example, the secondary heat exchanger 106 thermally coupled to the second heat of the intermittent heat source 110 comprises a pair of such heat exchangers 106a, 106b, while the tertiary heat exchanger 108 comprises a set of three such heat exchangers 108a,b,c. In some examples, however, the tertiary set of heat exchangers 108 may be subdivided between coupling the tertiary heat 110L and also very low grade (fourth) heat such as waste heat or decay heat.

[88] The thermal coupling between the intermittent heat source 110 and the set of heat exchangers 118 may be direct or indirect. For example, as shown the intermittent heat source 110 may heat a set of fluid loops corresponding to each member of the set of heat exchangers 118. In this (and other) examples, a primary heating loop comprising the primary heat exchanger 104 may also comprise couplings to a thermal storage 28.

[89] The power cycle 100 comprises a common flow path 130 (continuous line) through which working fluid flows during all modes of operation. That is, working fluid flows through network of pipes, etc, 130 in both the first mode and second mode of operation (and also third mode of operation). As can be seen, the common path 130 includes the main turbine 120 (i.e., electric generation), the cooler 122 (which may have a corresponding condenser 123), and the pump/compressor 116.

[90] The common flow loop 130 may also include an auxiliary turbine 132 which is configured in flow parallel with the main turbine (path 112). That is, the auxiliary turbine 132 is not in a direct flow path with the primary heat exchanger 104 (by being arranged on separate fluid path 114 to the fluid path 112), so that the auxiliary turbine 132 does not receive working fluid heated by the first heat exchanger 104. Suitably the auxiliary turbine 132 may form part of the same electrical generator as the main turbine 120 or may be coupled to a separate electrical generator.

[91] The common flow loop 130 may also include one or more recuperators; recuperators are heat exchangers arranged to thermally couple turbine inflow paths with turbine outflow paths, which allows excess heat to be recovered from the turbine outflows (i.e., to remove enthalpy from a turbine exit stream). In this way the inflow heating may be made more efficient, and less heat wasted.

[92] A first recuperator 134, also termed a high temperature recuperator, may be configured to thermally couple working fluid outflow with working fluid inflow to the primary heat exchanger 104. A second recuperator 136, also termed a low temperature recuperator, may be configured to thermally couple the outflow from the main turbine to the inflow path of the (optional) auxiliary

turbine 132. Suitably, the second recuperator forms a series flow (along path 114) with the auxiliary turbine 132. Such a recuperator may significantly increase the temperature of the auxiliary turbine inflow.

[93] The power cycle 100 also comprises an indirect heating (or fusion) mode flow path 138 corresponding to the fusion mode of operation; that is, a working fluid loop corresponding to the first mode/configuration. In this mode a set of first control means (e.g., valves) 140 which are coupled to the common flow path 130 are controlled to be open (e.g., by an operator or automatic control unit). Suitably, opening the control means 140 allows for working fluid to flow through each heat exchanger in the set of heat exchangers 118. Most importantly, there are valves providing access for working fluid to the primary heat exchanger 104. Similarly, the control means 140 may complete the parallel path 114 for the auxiliary turbine 132. Put another way, the first set of control means 140 may be used to define a first controllable flow path for the working fluid.

[94] In this first configuration, a corresponding set of second control means (e.g., valves) 142 coupled to the common flow path 130 are controlled to be closed. This second set of control means 142 relate to a combustion mode path 144, so that closing these valves thereby isolates the combustion mode path 144 from the common path 130. Suitably, in this configuration the direct heater 102 may be controlled to be off.

[95] Conversely, in the direct heat (second) mode of operation, the second set of valves 142 are controlled to be opened and the direct heater 102 turned on. The first set of control means 140 are controlled to be closed. Put another way, the second set of control means 142 may be used to define a second controllable flow path for the working fluid. In some examples, the first set of control means 140 may not be completely closed, but controlled to a trickle setting whereby a smaller volume of working fluid than normal may pass through the valves to access the set of heat exchangers 118. This may be desirable so that working fluid in the heat exchangers is not completely isolated and allowed to cool. Herein it is taken that 'isolating' the indirect heating means 118 (e.g., heat exchangers 104–108) includes allowing for a trickle setting.

[96] Suitably, closing the first set of control means 140 and opening the second set of control means 142 bypasses the indirect heating means 118 of the power cycle 100, while directing working fluid to the direct heat source 102 for direct heating.

[97] Figure 5 shows a second example power cycle 100b for a multi-heat intermittent heat source 110. In particular, in the example of Figure 5 the cycle 100b has been configured to allow further control over the inflow to the auxiliary turbine 132. It will of course be appreciated that the system 100c can also be applied to other intermittent heat sources where large temperature variations can be expected.

[98] In the example of Fig. 4, working fluid inflow 146 to the auxiliary turbine 132 is always heated by the second, medium, heat 110M via the second set of heat exchangers 106.

[99] By contrast, the present embodiment allows for control over whether the auxiliary turbine 132 utilises working fluid heated by the secondary heat exchangers 106. Here, working fluid heated by the secondary heat exchangers 106 is joined with the bulk flow to the primary heat exchanger 104, after the first recuperator 134, as before (shown here as point 148). The inflow 146 to the auxiliary turbine 132 comprises parallel paths 146a,b which are split off from the bulk from either before or after the point 148; i.e., before or after working fluid heated by the medium heat exchangers 106 rejoins the bulk flow.

[100] Suitably, a pair of valves 150a,b are oppositely controlled to be open or closed, depending on whether it is desired to add heat medium heat captured by the secondary heat exchangers 106 for operating the auxiliary turbine 132.

[101] Figure 6 shows a third example power cycle 100c for a multi-heat intermittent heat source 110. In this example the system 100c is adapted to better handle large temperature deltas arising from the high temperature components of an intermittent heat source 110. In a fusion context, that may be the reactor blanket and outboard first wall.

[102] In this example, the primary (high temperature) heat exchanger 104 is arranged in parallel with the first recuperator 134.

[103] More specifically, a flow path 152 which includes working fluid flowing to, and from, the primary heat exchanger 104, is arranged parallel with a flow path 154 which includes working fluid flowing to/from the first recuperator 134. Working fluid flow from the primary heat exchanger 104 joins the working fluid flow from the first recuperator 134, at point 156, to form the bulk flow input to the main turbine 120.

[104] Yet more specifically, a branch point 158 for fluid flow to the primary heat exchanger 104 may be arranged at a point in the network after working fluid has been heated by the low temperature heat exchangers 108, but before the working fluid is heated by the medium temperature heat exchangers 106.

[105] In other words, the present example allows for the primary heat exchanger 104 to be isolated from the heat provided by the secondary heat exchanger(s) 106. Put another way, the high temperature heat 110H and medium temperature heat 110M from the intermittent heat source may be utilised to heat working fluid in parallel.

[106] Figure 7 shows a fourth example power cycle 100d for a multi-heat intermittent heat source 110. This example is also adapted for better handling of large temperature deltas arising from the high temperature components of an intermittent heat source 110. Once again, in a fusion context, that may be the reactor blanket and outboard first wall.

[107] Here the primary heat exchanger 104 is realised as a set of primary heat exchangers; for example, a set of two primary heat exchangers comprising a first primary heat exchanger 104a and a second primary heat exchanger 104b. It will of course be appreciated that the set could

comprise more than two heat exchangers. Suitably, the set of first control means 140 and set of second control means 142 may be expanded to include control valves arranged to control flow to, and provide a bypass around, the second heat exchanger 104b analogous to previously described with regards to the first heat exchanger 104a (which is analogous to the sole primary heat exchanger 104 described above).

[108] In this example, the set of primary heat exchangers 104a,b are arranged in series in an indirect heating loop 160 which takes the high temperature heat from the intermittent heat source 110 via heat exchanger 162. Suitably, by being arranged in series, the first heat exchanger 104a in the set will operate at a higher temperature than the second heat exchanger 104b in the set.

[109] In this example, working fluid heated by the second heat exchanger(s) 106 is not fed to the second primary heat exchanger 104b. Rather, heated working fluid output from the second primary heat exchanger 104b is combined with working fluid heated by the secondary heat exchanger(s) 106. That is, the lower heat coupled into the working fluid by the second primary heat exchanger 104b is combined with working fluid which has been heated by the medium temperature components of the intermittent heat source 110.

[110] More specifically, the working fluid heated by the second primary heat exchanger 104b may be combined with working fluid from the secondary heat exchanger(s) 106 at either point 164 or point 166. The choice of whether to combine the working fluid flow is dependent on whether it is desired for the working fluid from the secondary heat exchangers 106 and second primary heat exchanger 104b to join the bulk flow before or after the first recuperator 134 – i.e., at point 168 or 170. Suitably, a set of control means 172, e.g., valves, may be provided on the respective fluid paths to control the choice over where the working fluid rejoins the bulk flow.

[111] Figure 8 shows a fifth example power cycle 100e for a multi-heat intermittent heat source 110, which builds particularly on the principles previously introduced by Figs. 5 & 7. This arrangement is also particularly adapted for better handling of large temperature deltas arising from the high temperature components of an intermittent heat source 110. Once again, in a fusion context, that may be the reactor blanket and outboard first wall.

[112] Here, the primary heat exchanger 104 is once again realised as set of two (or more) heat exchangers; e.g., a first primary heat exchanger 104a and a second primary heat exchanger 104b. In this example, however, the second primary heat exchanger 104b is essentially treated as an additional medium temperature (i.e., secondary) heat exchanger 106.

[113] Suitably, the system 100e is configured such that working fluid heated by the second primary heat exchanger 104b is joined with working fluid heated by the secondary heat exchangers 106. Put another way, the working fluid output by the second primary heat exchanger 104b is fed through the same working fluid loops that have otherwise already been provided for handling working fluid from the secondary heat exchangers 106.

[114] For example, the working fluid from the second primary heat exchanger 104b may join the working fluid flow from the secondary heat exchangers 106 at point 174, which may be before the point 148 where working fluid heated by the secondary heat exchangers 106 joins the bulk flow to the primary heat exchanger 104a.

[115] Like with Figure 5, the system 100 may be arranged such that the auxiliary turbine 132 may be operated using working fluid heated by the secondary heat exchangers 106 (plus the second primary heat exchanger 104b in this example), or not.

[116] Figure 9 shows a sixth example power cycle 100f for a multi-heat intermittent heat source 110. In this example the power cycle system 100f is configured to better accommodate very low grade heat 100VL.

[117] In this example, what was previously categorised generously as low grade, or third, heat 110L is further subdivided into a very low grade heat 110VL (the very low grade heat of course having lower temperature than the low grade heat 110L). Suitably, low grade heat 100L may be considered coupled to the working fluid via a first tertiary heat exchanger 108a, while the very low grade heat exchanger may be considered coupled to the working fluid via at least one of a second or third tertiary heat exchanger 108b,c.

[118] In general, the present example is concerned with configured the flow of working fluid heated by the very low grade heat to either flow in parallel or series with the second (i.e., low temperature) recuperator.

[119] More specifically, it is the very low grade heat taken by the second tertiary heat exchanger 108b which may be coupled to the working fluid in parallel or series with the second recuperator 136.

[120] In a parallel configuration, fluid output from the pump/compressor is branched at point 176 to be directed to both the second tertiary heat exchanger 108b and the second recuperator 136. Suitably, control means 178 and 180 (e.g., valves) may be controlled to be open. As shown, control means 180 may comprise a set of such means which all share the same state (e.g., open/closed). Working fluid heated by the second tertiary heat exchanger 108b rejoins working fluid output from the second recuperator 136 at one or a combination of points 182, 184 and 186. Paths to these points may be suitably controlled by corresponding control means 188, 190, 192.

[121] In the case of the working fluid being rejoined at points 182 or 184, in both cases the working fluid from the second tertiary heat exchanger 108b is combined with working fluid which has been heated by the third tertiary heat exchanger 108c (and optionally compressed), and before the working fluid is subsequently heated by the first tertiary heat exchanger 108a. The selection between whether to combine the working fluid from the second tertiary heat exchanger 108b before or after the point 194 (where it is joined by working fluid from the third

tertiary heat exchanger 108c) depends on the heat involved and corresponding pressure dynamics of the system.

[122] Rejoining the bulk flow at point 186 allows for working fluid heated by the second tertiary heat exchanger 108b to be joined with working fluid heated by the first tertiary heat exchanger 108a (and optionally working fluid heated by the third tertiary heat exchanger 108c). Again, the choice of where to recombine the working fluid flows at any given time depends on the heat and pressure dynamics of the system in the moment.

[123] In a series configuration, the second tertiary heat exchanger 108b may be arranged either before or after the second recuperator 136.

[124] Suitably, in one example of a series configuration, control means 178 are closed such that working fluid is firstly directed to the second tertiary heat exchanger 108b, and then is controlled to be input to the second recuperator 136. Suitably, control means 196 may be controlled to be open while control means 188, 190, 192 are all closed.

[125] In an alternative series configuration, control means 178 are open while means 180 are closed. Thus working fluid from the compressor 116 flows firstly to the recuperator 136 and then is directed to the second tertiary heat exchanger 108b. Control means 196 are closed while at least one of means 188, 190 and 192 are open as desired.

[126] Figure 10 shows a seventh example power cycle 100g for a multi-heat intermittent heat source 110. Like Fig. 9, this example is also arranged to better accommodate very low grade heat 100VL. Whereas Fig. 9 shows an approach where low grade heat 110L is coupled into the working fluid in series with the very low grade heat 110VL, Fig. 10 demonstrates an example of coupling the low grade heat and very low grade heat to the working fluid in parallel. This arrangement is particularly suitable where there are large changes in temperature for the low grade heat.

[127] Here, the first tertiary heat exchanger 108a is formed as a set of such heat exchangers arranged in series. Here a pair of such heat exchangers 108a-1,2 are shown, but it will of course be appreciated that there may be more provided. The first heat exchanger 108a-1 in the pair couples to the outflow from the second recuperator 136 as in previous examples.

[128] The second heat exchanger 108a-2 in the pair couples to the working fluid in parallel with the second tertiary heat exchanger 108b. More specifically, working fluid which is branched off at point 176 from the line to the second recuperator 136 to couple to the second tertiary heat exchanger 108b, is itself also partly split off at point 198 to inflow to the heat exchanger 108a-2, and is rejoined with the working fluid from the second tertiary heat exchanger 108b at point 199. The combined working fluid from both heat exchangers 108b, 108a-2, is combined with the working fluid outflow from the second recuperator at point 197.

[129] Figure 11 shows an eighth example power cycle 100h for a multi-heat intermittent heat source 110. Here, a first source of high grade heat is treated instead as a higher temperature

medium grade heat source. Meanwhile, a second source of high grade heat continues to be treated as high grade heat. Suitably the second source of high grade heat may have a higher temperature than the first source of high grade heat. In a fusion context, the present example may be appropriate where heat from the outboard first wall may be low enough to be treated as a medium grade heat, while heat from the reactor blanket is treated as the sole source of high grade heat.

[130] Suitably, in this example the secondary set of heat exchangers 106 comprises first to third heat exchangers 106a,b,c, with corresponding additions to the first set of control means 140. The third secondary heat exchanger 106c being of course the addition to accommodate the additional heat from the intermittent heat source 110.

[131] Figure 12 shows a ninth example power cycle 100i for a multi-heat intermittent heat source 110. In this example, the high grade heat may be taken to arise from a plurality of sources (at least two), and the system 100i is arranged to couple the high grade heat to the working fluid in series. In a fusion context, the high grade heat may come from the outboard first wall and the breeder blanket. The working fluid heated by the high grade heat may be joined with the bulk flow to the main turbine before or after the first recuperator 134.

[132] Suitably, the primary heat exchanger 104 comprises a set of heat exchangers corresponding to each of the plurality of high grade heat sources. In this example with two high grade heat sources, the set of primary heat exchangers 104 comprises first and second heat exchangers 104a,b. Each primary heat exchanger 104a,b is provided with a corresponding indirect heating loop 160a,b for receiving the corresponding heat from the intermittent heat source 110. E.g., loop 160a may be coupled to the breeder blanket while loop 160b may be coupled to the outboard first wall.

[133] As mentioned above, the set of primary heat exchangers 104 are arranged in series to heat the working fluid. Suitably, a set of control means 195 are provided to control the working fluid heated by the second primary heat exchanger 108b to rejoin the bulk flow to the first primary heat exchanger 108a (and onward to the main turbine 120).

[134] In one example, the control means 195 are controlled to cause the working fluid to combine at a point 193 after the first recuperator 134, or a point 191 before the first recuperator 134. Similar to previous examples, control means 189 may also be provided to control whether working fluid heated by the secondary heat exchangers 106 joins the bulk fluid flow before or after the first recuperator 134.

[135] In one example, at least some of the working fluid outflowing the first recuperator 134 is directed into a flow path comprising second primary heat exchanger using control means 187.

[136] Figure 13 shows a tenth example power cycle 100j for a multi-heat intermittent heat source 110. Similar to Fig. 11, this example assumes that there are additional sources of medium

grade heat, in particular where one of the previously assumed high grade heats has high variability.

[137] In this example, once again the set of secondary heat exchangers 106 comprises first to third heat exchangers 106a-c. One of the heat exchangers, here shown as heat exchanger 106b, is itself a set of heat exchangers. The set may comprise a pair of first secondary heat exchangers 106b-1,2 which are arranged in series in an indirect heating loop 185 which receives heat from the aforementioned variable heat source (e.g., the outboard first wall).

[138] The first heat exchanger 106a-1 couples heat into the working fluid in the same way as for previous embodiments.

[139] The second heat exchanger 106a-2 is coupled to the working fluid outflow from the second recuperator 134. Moreover, as shown, the second heat exchanger 106a-2 may be arranged in parallel flow with the first tertiary heat exchanger 108a. In this way additional heat may be added into the working fluid which is then split at junction 183 between the bulk flow 181 to the first recuperator 134, primary heat exchanger 104, and main turbine 120, and the heating loop 179 which collects heat from the remainder of the secondary heat exchangers 106a, c.

[140] Figure 14 shows an eleventh example power cycle 100k for a multi-heat intermittent heat source 110. In this example the system 100k allows the option of heat reintegration following recompression of the working fluid.

[141] As shown (in all embodiments for that matter), there may be provided an optional flow path 177 from the main pump/compressor 116 which comprises a re-compressor 175; this path may also include the third tertiary heat exchanger 108c before the re-compressor 175.

[142] In previous examples, working fluid from the re-compressor 175 is joined with working fluid heated by the remainder of the set of tertiary heat exchangers 108 at junction point 173. Optionally, however, control means (e.g., valves) 171 may be provided which close the flow path to point 173, and instead divert working fluid from the re-compressor 175 to before the first tertiary heat exchanger 108a (i.e., to join the flow at point 169).

[143] In other words, re-compressed working fluid may be integrated into the bulk fluid flow either before or after low temperature heat integration.

[144] In summary, exemplary embodiments of an improved power cycle system for an intermittent heat source have been described. The described exemplary embodiments enable multi-mode operation of the power cycle in order to better meet operational demand of the intermittent heat source, notably utilising the same power cycle components for both a direct heat and indirect heat configuration. The example embodiments are particularly suited for a nuclear fusion reactor, however the heat source is not limited thereto. The power cycles described herein may be readily applied to other intermittent heat sources such as thermal solar and fission reactors.

[145] The example apparatus may be manufactured industrially. An industrial application of the example embodiments will be clear from the discussion herein. Additionally, the described exemplary embodiments are convenient to manufacture and straightforward to use.

[146] Although preferred embodiment(s) of the present invention have been shown and described, it will be appreciated by those skilled in the art that changes may be made without departing from the scope of the invention as defined in the claims and as described above.

[147] Attention is directed to all papers and documents which are filed concurrently with or previous to this specification in connection with this application and which are open to public inspection with this specification, and the contents of all such papers and documents are incorporated herein by reference.

[148] All of the features disclosed in this specification, and/or all of the steps of any method or process so disclosed, may be combined in any combination, except combinations where at least some of such features and/or steps are mutually exclusive.

[149] Each feature disclosed in this specification may be replaced by alternative features serving the same, equivalent or similar purpose, unless expressly stated otherwise. Thus, unless expressly stated otherwise, each feature disclosed is one example only of a generic series of equivalent or similar features.

[150] The invention is not restricted to the details of the foregoing embodiment(s). The invention extends to any novel one, or any novel combination, of the features disclosed in this specification, or to any novel one, or any novel combination, of the steps of any method or process so disclosed.

CLAIMS

1. A power cycle system for an intermittent heat source, comprising:
 - means for carrying a working fluid;
 - indirect heating means configured to indirectly heating the working fluid using heat from the intermittent heat source;
 - direct heating means configured to directly heat the working fluid;
 - a turbine configured to generate electrical power using the heated working fluid;
 - wherein the power cycle system comprises a first mode in which the system is configured to indirectly heat the working fluid using the indirect heating means while the direct heating means is thermally decoupled from the working fluid, and a second mode in which the direct heating means is configured to heat the working fluid while the indirect heating means is substantially thermally decoupled from the working fluid.
2. The system of claim 1 wherein, in the first mode, the direct heating means are deactivated.
3. The system of claim 1 or 2, further comprising a third mode in which the both the indirect heating means and direct heating means are active and thermally coupled to the working fluid.
4. The system of any preceding claim, wherein the means for carrying working fluid comprises a common flow path for carrying working fluid when the system is configured in each of the first and second modes.
5. The system of any preceding claim, wherein the means for carrying working fluid comprises a first set of controllable valves which are open in the first mode and closed in the second configuration.
6. The system of any preceding claim, wherein the means for carrying working fluid comprises a second set of controllable valves which are open in the second mode and closed in the first mode.

7. The system of any preceding claim, wherein the indirect heating means comprises a set of heat exchangers thermally couplable to the intermittent heat source, wherein the set comprises a primary heat exchanger thermally couplable to a primary, high temperature, heat source of the intermittent heat source.

8. The system of claim 7, wherein the set of heat exchangers comprises a second heat exchanger thermally couplable to a secondary, medium temperature, heat source of the intermittent heat source.

9. The system of claim 8, wherein the set of heat exchangers comprises a third heat exchanger thermally couplable to a tertiary, low temperature, heat source of the fusion reactor.

10. The system of any preceding claim, wherein the direct heating means comprises a combustor configured to receive a fuel and an oxidant.

11. The system of claim 10, wherein a fuel for the combustor comprises hydrogen, hydrocarbon, ammonia or other carbonaceous fuels.

12. The system of any preceding claim, wherein the working fluid comprises at least one of di-nitrogen, argon, helium, air, Xenon, Neon, CH₄, O₂, or water.

13. The system of any preceding claim, wherein the working fluid comprises carbon dioxide.

14. The system of claim 13, wherein a purity level of carbon dioxide is at least 50%

15. The system of claim 13 or 14, wherein a purity level of carbon dioxide is in a range of about 85% to 99%.

16. The system of any of claims 13 to 15, wherein the working fluid further comprises at least one of C₆F₆, C₄F₈, C₂H₃N, TiCl₄, NO₂, SO₂, SiCl₄, WCl₆, WF₆, UF₆.

17. A fusion power plant comprising a fusion reactor and the power cycle system of any preceding claim, wherein the power cycle system is operated in the first mode when the fusion reactor is in an operational mode.
18. The power plant of claim 17, wherein the power cycle system is operated in the second mode during a startup phase of the nuclear reactor.
19. The power plant of claims 17, wherein the power cycle is operated in the first and second mode simultaneously.
20. The power plant of claim 17 or 19, wherein the power cycle system is operated in the second mode during a shutdown phase of the nuclear reactor, or an interrupt in operation of the nuclear reactor.
21. The power plant of any of claims 17 to 20, further comprising a controller configured to receive a signal corresponding to a status of the reactor, and change the power cycle from operating in the first mode to operating in the second mode, or vice versa, responsive to the received signal.
22. The power plant of any of claims 17 to 21, further comprising a thermal buffer coupled to a primary heating loop of the power cycle system.