US 20100287934A1

(19) United States

(12) Patent Application Publication

(10) Pub. No.: US 2010/0287934 A1

(43) Pub. Date: Nov. 18, 2010

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(54) HEAT ENGINE SYSTEM

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(21) Appl. No.: 12/438,945

(22) PCT Filed: Aug. 24, 2007

(86) PCT No.: PCT/AU07/01226

§ 371 (c)(1),
(2), (4) Date: May 6, 2010

(30) Foreign Application Priority Data

Aug. 25, 2006 (AU) 2006904633
Aug. 25, 2006 (AU) 2006904634

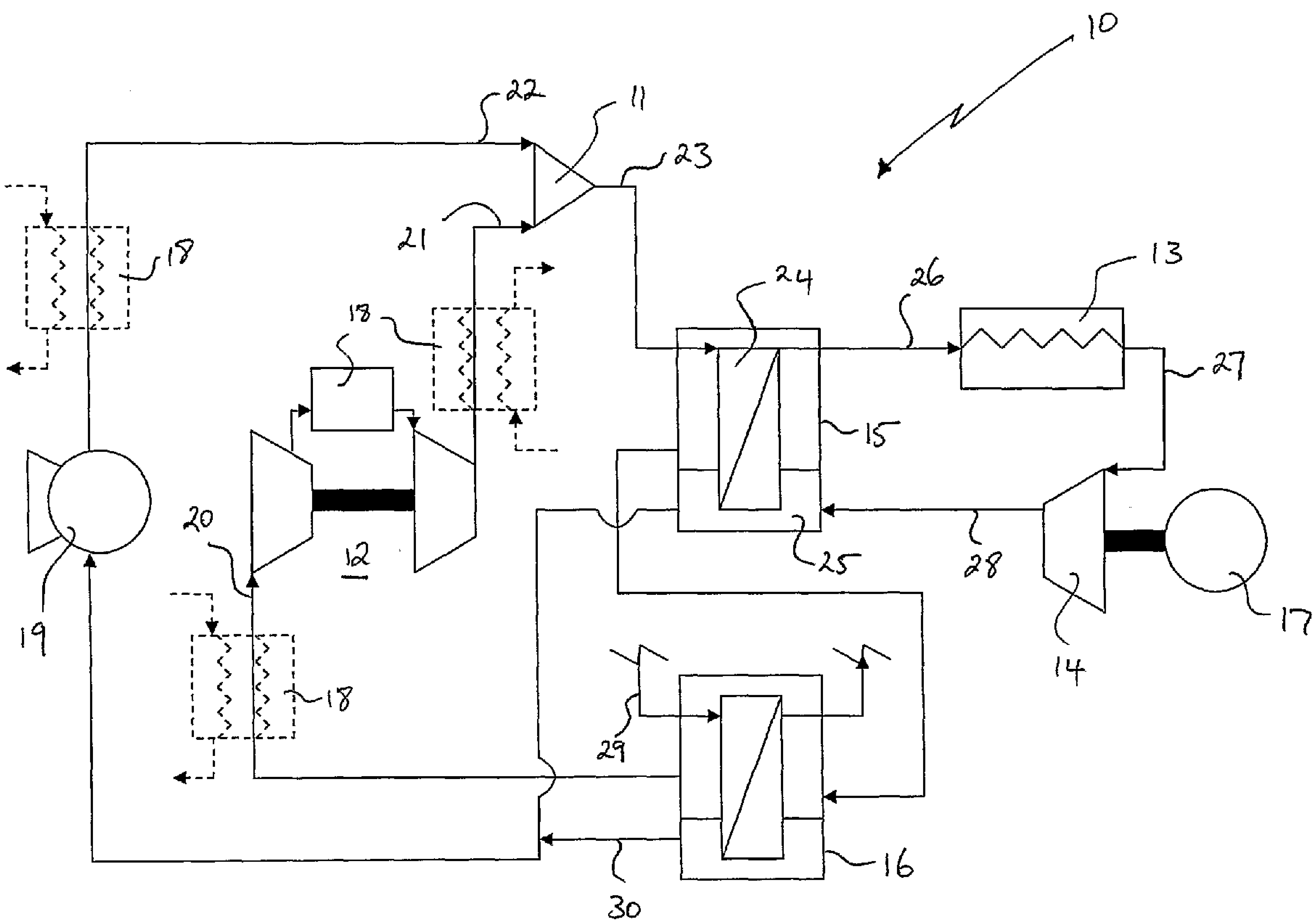
Publication Classification

(51) Int. Cl.
F01K 27/00 (2006.01)

(52) U.S. Cl. 60/645; 60/643

(57) ABSTRACT

A heat engine system for producing work by expanding a working fluid comprising first and second components, the system comprising, an apparatus for combining the second component of the working fluid as a liquid with the first component, the first component being a gas throughout the system, a compressor for compressing the first component, a pump for compressing at least most of the second component, a heater for heating the first and second components, an expander for expanding the first and second components to produce the work, and a recuperator for transferring at least some of the energy of the working fluid from the outlet of the expander, to the working fluid from the outlet of the apparatus, wherein a substantial portion of the energy transferred in the recuperator is at least a portion of the latent heat of the second component from the outlet of the expander.



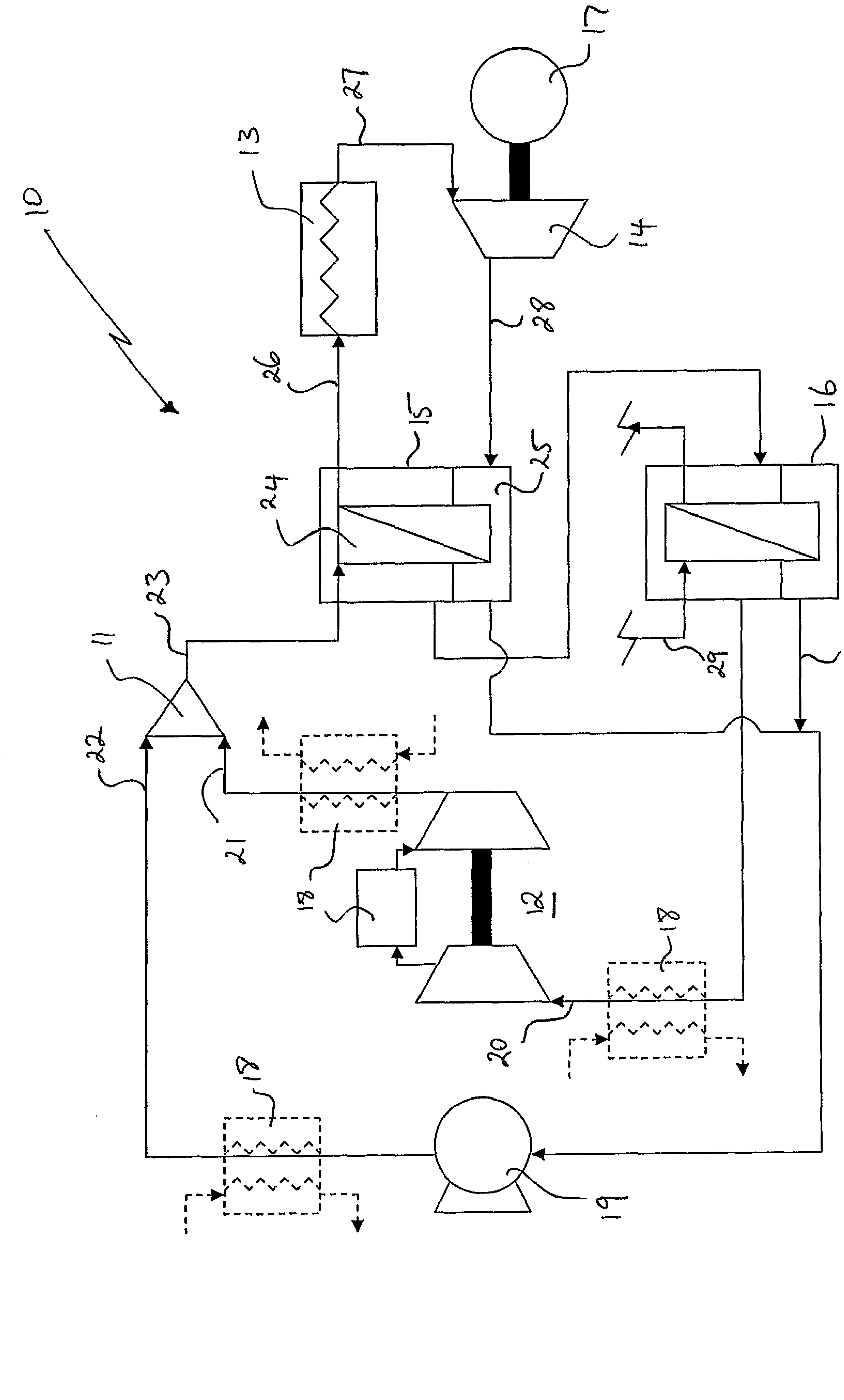


Figure 1

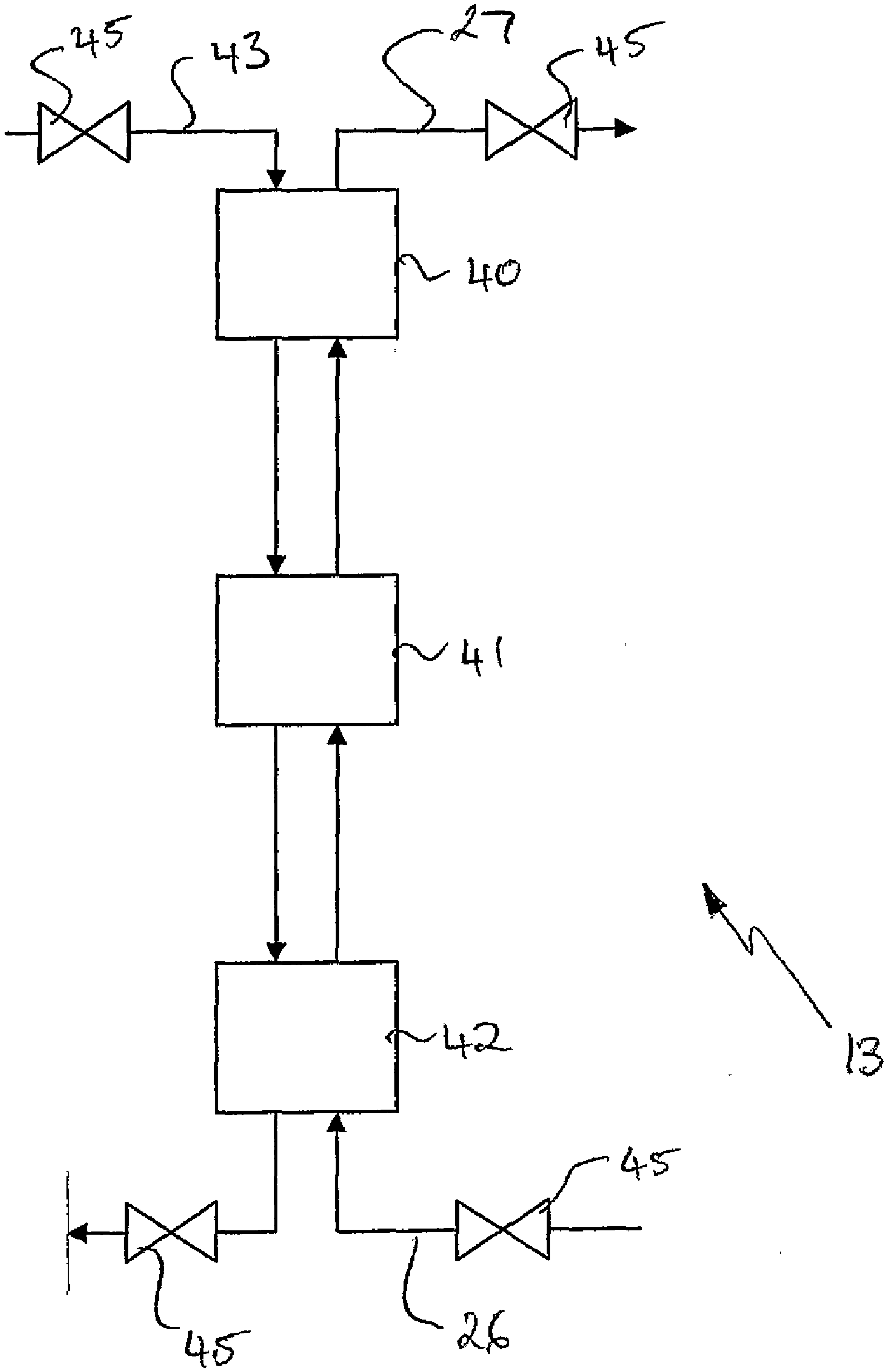
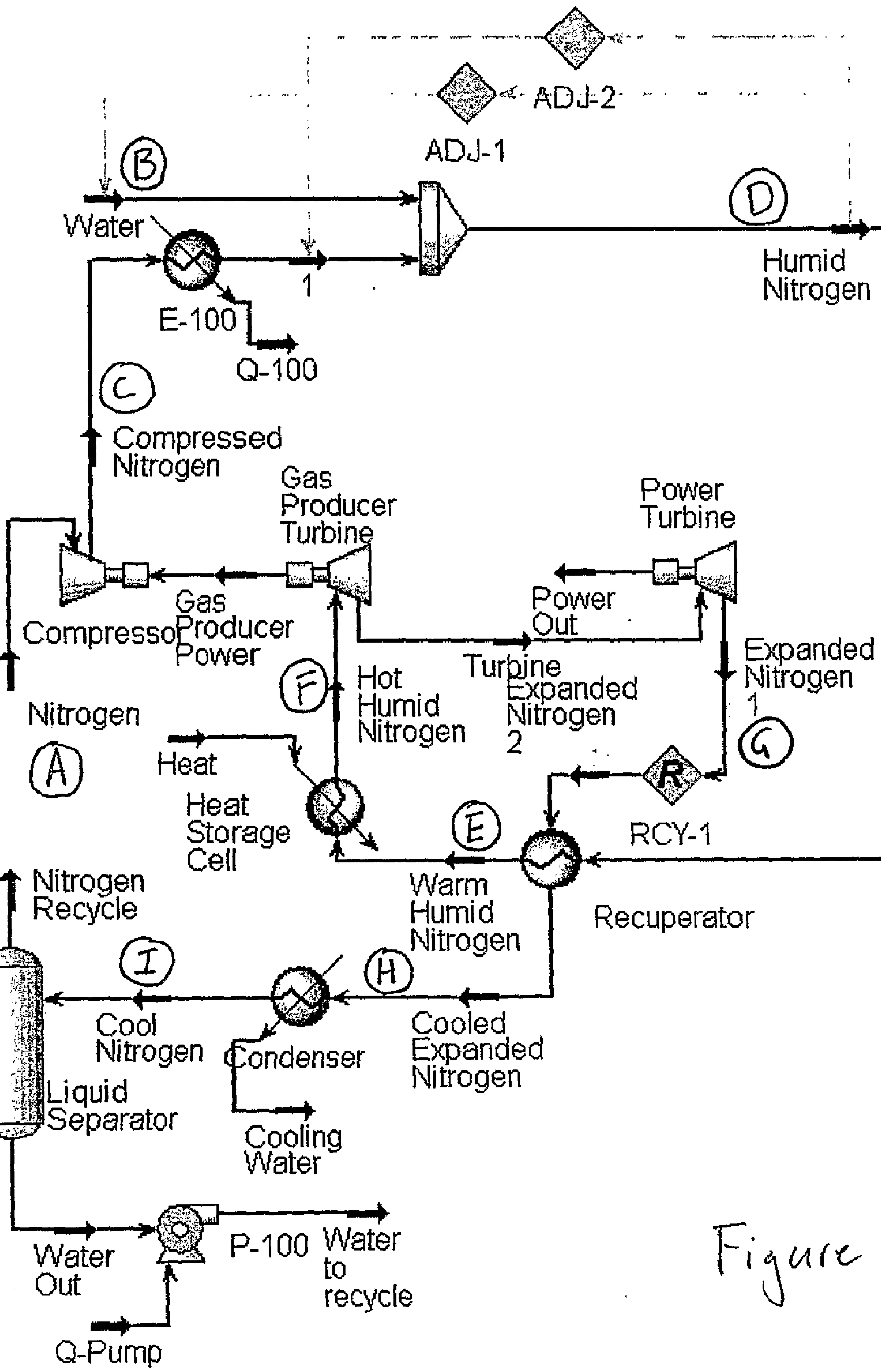


Figure 2


ADJ-2
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Recycle
Warm
Humid
Nitrogen
Recuperator
I
H
Cool
Nitrogen
Condenser
Cooled
Expanded
Nitrogen
Liquid
Separator
Cooling
Water
Water
Out
P-100
Water
to
recycle
Q-Pump

Figure 3

HEAT ENGINE SYSTEM

FIELD OF THE INVENTION

[0001] The present invention relates to a heat engine system and to a method for producing work.

BACKGROUND OF THE INVENTION

[0002] A heat engine is a system arranged to convert thermal energy to mechanical work. The heat engine does this by transferring energy from a high temperature heat source (T_H) to a low temperature heat sink (T_L). The efficiency of any heat engine is understood to be determined by, amongst other factors, the difference in temperature between the heat source and the heat sink. The efficiency of various heat engines currently in use range from 3% to about 60%. Most automotive engines have an efficiency of approximately 25% and supercritical coal-fired power stations have an efficiency of approximately 35-41%.

[0003] Because the efficiency of any heat engine is understood to be dependent on the temperature gradient between the heat source and heat sink, many attempts have been made to increase heat engine efficiencies by increasing this temperature gradient. It is generally understood that in order to increase the temperature gradient in a heat engine, then the temperature of the heat source has to be raised, because the temperature of the heat sink is limited by the atmospheric temperature of the Earth.

[0004] Theoretically, the most efficient heat engine is defined by the Carnot cycle and comprises a boiler, a turbine, a condenser and a pump. Under the Carnot cycle, the working fluid undergoes reversible isothermal heating from the high temperature reservoir in the boiler, reversible adiabatic expansion of the working fluid with a reduction in temperature from the high temperature (T_H) to the low temperature (T_L), reversible isothermal cooling of the working fluid to the low temperature reservoir in the condenser, and reversible adiabatic compression of the working fluid with an increase in temperature from T_L to T_H in the pump. The thermal efficiency (η_{TH}) of a heat engine operating according to the Carnot cycle is defined by the equation:

$$\eta_{TH}=1-T_L/T_H.$$

[0005] In practice, however, it is not possible to operate a heat engine according to the ideal Carnot cycle because none of the process steps are truly "reversible". A reversible process is an ideal process that once having taken place can be reversed and in doing so leave no change in either the system or its surroundings. A number of factors are responsible for the processes in the Carnot cycle being irreversible, including friction losses in the system.

[0006] An alternative, but not as efficient, cycle for operating a heat engine is the Rankine cycle. The ideal Rankine cycle involves reversible adiabatic compression from a low pressure to a high pressure by the pump, constant pressure (isobaric) heat transfer from the high temperature heat source in the boiler, reversible adiabatic expansion from the high pressure to the low pressure in the turbine, and a constant pressure (isobaric) transfer of heat from the working fluid to the low temperature heat sink in the condenser.

[0007] The Rankine cycle differs from the Carnot cycle primarily in that complete condensation of the working fluid from a vapour to a liquid in the condenser occurs in the Rankine cycle. The reason for doing this is that whilst it reduces the efficiency of the heat engine, in practice, it is difficult for a pump to handle a mixture of liquid and vapour as is the case in the Carnot cycle. A further difference is that if the working fluid is heated to a superheated vapour in the boiler, in the Carnot cycle all the heat transfer is at a constant temperature and hence during this process the pressure must be reduced. This means that the heat must be transferred to the vapour as it undergoes an expansion process (which is difficult to carry out in practice), as opposed to the Rankine cycle in which the vapour is superheated at a constant pressure. The isobaric heat transfer process in the Rankine cycle is easier to achieve in practice than the isothermal process in the Carnot cycle.

[0008] Most common power generation plants, including coal fired power generation plants operate according to the Rankine cycle. In practice, however, heat engines operating according to the Rankine cycle have a lesser efficiency than the maximum theoretical efficiency (ie. the efficiency of the ideal Rankine cycle) for similar reasons to those outlined for the Carnot cycle above.

[0009] Another cycle is the Brayton cycle. The Brayton cycle operates similarly to the Rankine cycle except that the working fluid exists only in the gaseous phase throughout the cycle (ie. the Brayton cycle does not involve condensing and boiling of the working fluid). In a closed Brayton cycle, the system involves isentropic compression, followed by isobaric heating, before isentropic expansion of the working fluid occurs to produce work, followed by isobaric cooling of the working fluid. Gas turbines generally operate according to an open Brayton cycle, in which a combustible fuel is added to the working fluid after the compressor, whereupon combustion of the fuel raises the temperature of the working fluid prior to it being expanded in the turbine to produce work. The exhaust from the turbine containing working fluid mixed with products of the combustion of the fuel is sent to waste and not returned to the inlet of the compressor.

[0010] Variations on the Rankine cycle, in order to increase the efficiency of the heat engine, have been considered. Two such variations include the Rankine cycle with reheat and the regenerative Rankine cycle. In the Rankine cycle with reheat, the heat engine comprises two turbines in series. Working fluid as a vapour from the boiler at high pressure enters the first turbine where it is expanded to a lower pressure. The reduced pressure vapour exiting the first turbine re-enters the boiler where it is reheated before passing through the second turbine which operates at lower pressures. One advantage of this system is that reheating of the working fluid between the turbines prevents the working fluid from condensing from a vapour to a liquid during expansion in the turbines which could result in significant damage to the turbine.

[0011] The regenerative Rankine cycle involves preheating of the working fluid prior to its entry to the boiler by splitting a small portion of steam from an intermediary stage in the turbine and mixing it with the liquid working fluid after it has been cooled in the condenser in a "feed water heater" which is located at an intermediary pumping stage prior to the inlet of the working fluid to the boiler.

[0012] Many other attempts have been made to increase the efficiency of real heat engines, such as the combined Brayton-Rankine cycle or COGAS cycle, which involves using the hot exhaust gas from a gas combustion heat engine operating according to the Brayton cycle as the heat source for the boiler of a second heat engine operating according to the Rankine cycle.

[0013] However, the efficiencies of all real heat engines remain significantly limited, and improvements which increase the efficiency of power and refrigeration production are still sought.

SUMMARY OF THE INVENTION

[0014] According to a first aspect of the present invention, there is provided a heat engine system for producing work by expanding a working fluid comprising first and second components, the system comprising, an apparatus for combining the second component of the working fluid as a liquid with the first component, the first component being a gas throughout the system, a compressor for compressing the first component, a pump for compressing at least most of the second component, a heater for heating the first and second components, an expander for expanding the first and second components to produce the work, and a recuperator for transferring at least some of the energy of the working fluid from the outlet of the expander, to the working fluid from the outlet of the apparatus, wherein a substantial portion of the energy transferred in the recuperator is at least a portion of the latent heat of the second component from the outlet of the expander.

[0015] In an embodiment, the apparatus comprises an injector.

[0016] In another embodiment, the apparatus comprises an atomiser.

[0017] In an embodiment, the apparatus is arranged to spray the liquid second component into a space having the first component therein.

[0018] In another embodiment, the apparatus is a diffuser.

[0019] In an embodiment, the apparatus is arranged to diffuse the first component into the liquid second component.

[0020] In an embodiment, the apparatus comprises multiple injectors, atomisers or diffusers.

[0021] In an embodiment, the apparatus is located between the compressor and the recuperator, to enable the liquid second component to be combined with the gaseous first component after it has been compressed.

[0022] Preferably, there is also some sensible heat transferred in the recuperator.

[0023] Preferably, a substantial portion of the latent heat of the second component is transferred in the recuperator.

[0024] In an embodiment, the recuperator converts at least some of second component from the outlet of the apparatus from liquid to gas.

[0025] In an embodiment, the recuperator converts at least some of the second component from the outlet of the expander from gas to liquid.

[0026] In an embodiment, the recuperator is generally in the form of a shell and tube heat exchanger.

[0027] In an embodiment, the recuperator is generally in the form of a falling film condensor.

[0028] In an embodiment, the recuperator is arranged to provide separation of a liquid fraction of the working fluid from a gaseous fraction upon cooling of the working fluid from the outlet of the expander.

[0029] In an embodiment, the recuperator comprises a boiling side and a condensing side.

[0030] In an embodiment, working fluid from the outlet of the apparatus enters the boiling side of the recuperator where the second component of the working fluid substantially boils as it receives energy from the working fluid on the condensing side.

[0031] In an embodiment, working fluid from the outlet of the expander enters the condensing side of the recuperator where the second component of the working fluid substantially condenses as it loses energy to the working fluid on the boiling side.

[0032] In an embodiment, the condensing side of the recuperator comprises a liquid separator basin that collects the liquid second component for recycling in the system.

[0033] In an embodiment, the boiling side of the recuperator is the tubes of a shell and tube heat exchanger, and the condensing side is the shell of a shell and tube heat exchanger.

[0034] In an embodiment, the system comprises multiple recuperators connected in parallel and/or series.

[0035] In an embodiment, the pressure at the inlet to the expander is the pressure to which the first component is compressed in the compressor, less any losses in the system therebetween. Compression of the first component of the working fluid also increases its temperature.

[0036] In an embodiment, the compressor compresses a small portion of the second component as a gas in addition to the first component.

[0037] In an embodiment, the compressor is any suitable compressor such as an axial, centrifugal, reciprocating or scroll compressor for example.

[0038] In an embodiment, the system comprises multiple compressors connected in parallel and/or series.

[0039] In an embodiment, the system also comprises at least one cooler for cooling the first and/or second components prior to combining them in the apparatus.

[0040] In an embodiment, at least one of the coolers comprises an inter-cooler in the compressor to provide inter-stage cooling of the first compressor.

[0041] In an embodiment, at least one of the coolers comprises a post compressor cooler for cooling the first component after it has been compressed.

[0042] In another embodiment, at least one of the coolers comprises a pre-compressor cooler for cooling the first component prior to it being compressed in the compressor.

[0043] In an embodiment, the at least one cooler has a cooling source.

[0044] In an embodiment, the cooling source is cooling water, ambient air or any suitable refrigeration system to which heat may be rejected.

[0045] In an embodiment, the heat rejected to the at least one cooler may be used as a heat source for any other suitable process such as heating hot water, creating low pressure steam, desalination, as the heat input to a heat pump vapour compression system or as the heat input for any low temperature power generation or refrigeration cycle.

[0046] In an embodiment, the at least one cooler comprises a liquid cooler for cooling the liquid second component.

[0047] In another embodiment, the liquid second component when combined with the first component by the apparatus is at ambient temperature.

[0048] In these embodiments, the second component when combined with the first component cools the first component.

[0049] Preferably, the at least one cooler acts to ensure that the temperature of the first component entering the apparatus is less than a temperature which would cause vaporisation of the second component upon its combination with the first component by the apparatus.

[0050] In an embodiment, the pump compresses at least most of the second liquid component to a pressure above the ambient pressure.

[0051] In an embodiment, the pump compresses at least most of the liquid second component to at or about the pressure to which the compressor compresses the first component.

[0052] In an embodiment, the system comprises multiple pumps connected in parallel and/or series.

[0053] In an embodiment, the working fluid is a gas-liquid mixture after the second component (liquid) has been combined with the first component (gas) by the apparatus.

[0054] In an embodiment, the expander comprises any suitable unit for producing mechanical work by the expansion of a working fluid.

[0055] In an embodiment, the expander may be a turbine, a positive displacement rotary expander, a scroll expander a linear expander or a reciprocating engine for example.

[0056] The expander may also comprise multiple turbines, rotary expanders, linear expanders or reciprocating engines, connected in either parallel or series, with or without interstage reheat.

[0057] The expander may or may not be directly coupled to the compressor to the drive the compressor.

[0058] In an embodiment, the expander is in the form of a turbine.

[0059] In an embodiment, the turbine has variable pitch blades.

[0060] It is noted that the system may comprise any number of multiple expanders and/or compressors arranged in parallel or series.

[0061] The heater provides a heat input to the working fluid from any suitable heat source.

[0062] In an embodiment, the heater heats the working fluid to a super-critical gas.

[0063] In an embodiment, the heat source for the heater may be steam or any other heated medium generated by nuclear power, coal or another combustible fuel, hot exhaust gasses from a gas turbine, waste heat from any other process, direct heating from a furnace, electrical, solar thermal, stored heat or a thermal energy cell(s) for example.

[0064] In an embodiment, the heat engine system also comprises a condenser for cooling the working fluid after it exits the recuperator.

[0065] In an embodiment, the condenser is arranged to substantially condense the second component of the working fluid to a liquid.

[0066] The condenser may be in the form of a shell and tube heat exchanger, a radiator, a finned cooling coil with cooling fluid in serpentine coils, located inside a plenum with condensate recovery or any other suitable condenser.

[0067] In an embodiment, one side of the condenser receives the working fluid exiting the condensing side of the recuperator.

[0068] In an embodiment, cooling fluid flows through the other side of the condenser for cooling the working fluid to condense most of the second component of the working fluid to liquid.

[0069] The cooling fluid may be air, refrigerant of any composition or water or brine at or below ambient conditions.

[0070] In an embodiment, the heat removed from the working fluid by the condenser may be used as the heat input to any other suitable system, such as an external heat engine, a heat pump, a refrigeration cycle, desalination or for process heating of water for example.

[0071] In an embodiment, the condenser is a separator for separating the second component, as it condenses from the first component.

[0072] In an embodiment, the separated second component, is recycled to the apparatus.

[0073] In this embodiment, the remaining working fluid which comprises the first component and any of the second component remaining as a gas, flows to the inlet to the compressor.

[0074] In an embodiment, the system comprises multiple condensers connected in parallel and/or series.

[0075] In an embodiment, the system also comprises a load, connected to the expander for converting the work produced by the expander to mechanical or electrical power.

[0076] In an embodiment, the system is a closed system having substantially no mass inputs or outputs during operation of the system, other than replacement of incidental losses.

[0077] In an embodiment, the system comprises a top-up feed of the working fluid for replacing any incidental losses. Incidental losses may result from leaks, maintenance, or high-pressure or high-temperature releases for example.

[0078] In an embodiment, the system comprises an energy transfer controller for controlling the energy transfer in the recuperator during operation of the system.

[0079] In an embodiment, the energy transfer controller controls the energy transfer in the recuperator by changing the conditions at the inlet of the expander and subsequently the expansion done in the expander and hence the conditions at the outlet of the expander.

[0080] In an embodiment, the energy transfer controller controls the energy transfer in the recuperator by changing the amount of the liquid second component combined with the first component in the apparatus.

[0081] In an embodiment, the system comprises a mass flow controller for controlling the mass flow rate of the second component relative to the mass flow rate of the first component.

[0082] In an embodiment, the mass flow controller comprises a variable speed control on the pump.

[0083] In an embodiment, the mass flow controller comprises a pump diverter, arranged to divert flow of the second component from the outlet of the pump to the inlet of the pump.

[0084] In an embodiment, the mass flow controller comprises variable inlet guide vanes in the compressor.

[0085] In an embodiment, the mass flow controller comprises a variable speed control on the compressor.

[0086] In an embodiment, the mass flow controller comprises a compressor diverter, arranged to divert flow of the first component from the outlet of the compressor to the inlet of the compressor.

[0087] In an embodiment, the mass flow controller comprises appropriate valving on the apparatus.

[0088] In an embodiment, the system comprises an energy storage unit upstream of the compressor for storing compressed working fluid (largely the first component with any gaseous second component), for use in particular during start-up for example.

[0089] In another embodiment, start-up may be effected by supplying power to the compressor, pump and expander shafts.

[0090] In an embodiment, the first and second components of the working fluid are substances which are substantially inert with respect to each other.

[0091] In an embodiment, the first and second components will not react with one another, nor substantially dissolve in one another, nor substantially dissociate at high temperatures.

[0092] In an embodiment, the second component is a substance which has a high volumetric expansion ratio from liquid to gas.

[0093] In an embodiment, the first component is a substance which is highly compressible as a gas.

[0094] In an embodiment, the first component may be nitrogen, argon, helium, hydrogen or methane for example.

[0095] In an embodiment, the second component may be water, propane, butane, ethanol or carbon dioxide for example.

[0096] A preferred working fluid is nitrogen as the first component and water as the second component.

[0097] In an embodiment, the working fluid may comprise more components than the first and second components. These additional components will generally each follow the flow path of either the first component (as a gas) or the second component (as a liquid and a gas) in the system.

[0098] In an embodiment, the heater is a heat exchanger.

[0099] In an embodiment, the heater is a regenerative heater.

[0100] In an embodiment, the regenerative heater comprises at least one volume of material arranged to be heated to at or above the melting temperature of the material, the heater also comprising passages through the at least one volume of material for the flow therethrough of the working fluid.

[0101] In an embodiment, the regenerative heater comprises at least two volumes of material, preferably three. The heater may comprise more than three volumes of material.

[0102] In an embodiment, when the regenerative heater comprises at least two volumes of material, the passages are arranged for the working fluid to flow through the volumes of material in series.

[0103] In other embodiments, however, the passages may be arranged for the working fluid to flow through the volumes of material in parallel.

[0104] In an embodiment, the volume(s) of material is heated using a heating fluid flowing through spaces through the volume(s) of material.

[0105] The heating fluid may be steam or any other heated medium generated by nuclear power, coal or other combustible fuel or hot exhaust gases from a gas turbine for example.

[0106] In an embodiment, the passages through which the working fluid flow are separate from the spaces through which the heating fluid flow.

[0107] In other embodiments, the volume(s) of material may be heated using any other suitable means, such as waste heat from another process, direct heating from a furnace, electrical or solar thermal heat.

[0108] In an embodiment, when the regenerative heater comprises at least two volumes of material, the materials in the volumes are different. The different materials preferably have different melting temperatures.

[0109] In one embodiment, the materials are of progressively decreasing melting temperatures from the first volume to the last volume, the passages being arranged for the flow of the working fluid through the last volume first and the first volume last.

[0110] In an embodiment, working fluid flows counter-currently to the heating fluid. Thus, the spaces are arranged for the flow of the heating fluid through the first volume first and the last volume last.

[0111] In an embodiment, at least one of the volumes of material contains a mixture of two or more different materials.

[0112] In an embodiment, one of the materials in the mixture of materials of the or each volume is for improving the heat transfer of the or each volume of material. Such a material may be graphite.

[0113] In an embodiment, one of the materials in the mixture of materials of the or each volume is for affecting the melting temperature of the or each volume of material.

[0114] In one such embodiment, aluminium is mixed with silicon to reduce the melting temperature of the volume of material.

[0115] In an embodiment, when the regenerative heater comprises at least two volumes of material, the material in the volumes are each mixtures of the same materials but at different ratios.

[0116] The different ratios preferably have different melting temperatures.

[0117] The materials in the volumes may be referred to as "phase change materials" or "PCMs". Any suitable phase change materials may be employed.

[0118] In an embodiment of the invention, when the regenerative heater comprises three volumes of material the first volume contains silicon, which has a melting temperature of about 1410° C., the second volume contains lithium fluoride, which has a melting temperature of about 870° C. and the third volume contains magnesium oxide or calcite, which have a melting temperature of about 560° C.

[0119] In an embodiment, the volume(s) of material is held in a container(s) which is able to withstand the temperatures of the molten material(s) held therein.

[0120] In an embodiment, the container(s) is manufactured from a ceramic, preferably silicon carbide.

[0121] In an embodiment, the regenerative heater also comprises a number of valves on the inlets and outlets to the heater which can be used to control the flow rate of the working fluid and the heating fluid through the heater to maintain the temperature of the material(s) in the volume(s) so as to keep them in a molten phase and to control the temperature of the working fluid as it leaves the heater.

[0122] In an embodiment, the system comprises multiple regenerative heaters. In one such embodiment, the system comprises three regenerative heaters, whereby while one heater is in operation a second is on stand-by and the other is shut-down for maintenance.

[0123] According to a second aspect of the present invention, there is provided a method for producing work, the method comprising the steps of:

[0124] compressing a first component of a working fluid in a compressor, the first component being a gas at all times during the method;

[0125] compressing at least most of a second component of the working fluid as a liquid in a pump;

[0126] combining the second component as a liquid with the first component in an apparatus;

[0127] heating the combined first and second components in a heater;

[0128] expanding the heated first and second components to produce the work in an expander; and

[0129] transferring in a recuperator at least some of the energy of the working fluid after it has been expanded to the working fluid prior to it being heated in the heater, wherein a substantial portion of the energy transferred is at least a portion of the latent heat of the second component after the working fluid has been expanded in the expander.

[0130] In an embodiment, the step of combining the second component with the first component comprises spraying the liquid second component into a space having the first component therein.

[0131] In another embodiment, the step of combining the second component with the first component comprises diffusing the first component into the liquid second component.

[0132] In an embodiment, the step of combining the second component with the first component occurs after the steps of compressing the first component and compressing at least most of the second compound.

[0133] Preferably, some of the energy transferred in the recuperator is sensible heat.

[0134] In an embodiment, the step of transferring at least some of the energy in the recuperator converts at least some of the second component from liquid to gas prior to it being heated in the heater.

[0135] In an embodiment, the step of transferring at least some of the energy in the recuperator converts at least some of the second component from gas to liquid after it has been expanded in the expander.

[0136] In an embodiment, the method also comprises the step of separating a liquid fraction of the working fluid from a gaseous fraction after the working fluid has been expanded.

[0137] In an embodiment, the step of separating occurs at least partially in the recuperator.

[0138] Preferably, the method is a closed cycle method also comprising the step of repeating the steps of the method after at least some of the working fluid's energy has been transferred in the recuperator to the working fluid which is yet to be heated in the heater.

[0139] In an embodiment, the method also comprises the step of returning the first component to the compressor.

[0140] In an embodiment, the method also comprises the step of returning at least most of the second component to the pump.

[0141] In an embodiment, the step of compressing the first component occurs in at least two stages.

[0142] In another embodiment, the step of compressing the first component occurs in only one stage.

[0143] In an embodiment, the method also comprises the step of cooling the first and/or second components prior to the step of combining them.

[0144] In an embodiment, the cooling step comprises cooling the first component between at least two of the stages of the compressor using an intercooler.

[0145] In an embodiment, the cooling step comprises cooling the first component after the step of compressing the first component, preferably before the step of combining with the second component.

[0146] In an embodiment, the cooling step comprises cooling the first component prior to the step of compressing the first component.

[0147] In an embodiment, the cooling step comprises cooling the second component prior to combining the second component with the first component.

[0148] In an embodiment, the liquid second component when combined with the first component in the apparatus is at ambient temperature.

[0149] In an embodiment, the step of compressing at least most of the second component compresses at least most of the second component to a pressure above the ambient pressure.

[0150] In an embodiment, the step of compressing at least most of the second component compresses most of the second component to at or about the pressure to which the first component is compressed in the compressor.

[0151] In an embodiment, the method comprises the step of maintaining the temperature of the first component prior to the step of combining with the second component to a temperature which is less than one which would cause vaporisation of the second component during the combining step.

[0152] In an embodiment, the step of separating the liquid fraction from the gaseous fraction of the working fluid comprises separating at least most of the second component as a liquid from the first component as a gas.

[0153] Typically, the step of separating does not completely separate all of the second component from the first component. Some of the second component remains as a gas mixed with the first component.

[0154] In an embodiment, the step of separating occurs at least in part in the recuperator.

[0155] In an embodiment, the step of separating the first component from the second component occurs at least in part in a condenser, and preferably after at least some of the energy of the working fluid has been transferred in the recuperator to the working fluid which is yet to be heated in the heater.

[0156] In an embodiment, the step of separating the first component from the second component comprises cooling the working fluid to condense at least most of the second component.

[0157] In an embodiment, the method also comprises the step of controlling the energy transferred in the recuperator.

[0158] In an embodiment, the step of controlling the energy transferred in the recuperator comprises changing the conditions of the working fluid prior to expanding it in the expander.

[0159] In an embodiment, the step of controlling the energy transferred in the recuperator comprises changing the amount of the second component which is combined with the first component in the apparatus.

[0160] In an embodiment, the method also comprises the step of controlling the mass flow rate of the second component relative to the mass flow rate of the first component.

[0161] In an embodiment, the step of heating comprises transferring heat from a high temperature source to the working fluid in the heater, such as for example by using a heating medium in a heat exchanger.

[0162] In an embodiment, the step of heating comprises flowing the combined first and second components through at least one volume of material which is heated to at or above the melting temperature of the material.

[0163] In an embodiment, the step of heating comprises flowing the combined first and second components through at least two volumes of material, preferably three.

[0164] In an embodiment, the step of heating also comprises heating the at least one volume of material using a heating fluid.

[0165] In an embodiment, heating the at least one volume of material comprises flowing the heating fluid through spaces through the volume(s) of material.

[0166] In an embodiment, the step of heating comprises flowing the heating fluid through the at least one volume of material in a counter current direction to the flow of the combined first and second components.

[0167] In an embodiment, the step of heating comprises heating the working fluid to a super-critical gas.

BRIEF DESCRIPTION OF THE DRAWINGS

[0168] Embodiments of the present invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

[0169] FIG. **1** is a schematic view of a heat engine system according to embodiments of the present invention;

[0170] FIG. **2** is a schematic view of the heat engine regenerative heater for heating the working fluid of the heat engine system according to an embodiment of the present invention; and

[0171] FIG. **3** is a schematic view of a HYSYS® model of a system heat engine according to an embodiment of the present invention.

DETAILED DESCRIPTION OF EMBODIMENTS

[0172] Referring firstly to FIG. **1**, a heat engine system **10** according to embodiments of the present invention is shown. The heat engine system **10** produces work by expanding a working fluid. The working fluid comprises first and second components, the first component being a gas throughout the system **10**. The system **10** comprises an apparatus **11** for combining the second component of the working fluid as a liquid with the first component. The apparatus **11** may comprise an injector or atomiser arranged to spray the liquid second component as a mist into a space of sufficient volume having the first component therein. The apparatus **11** may alternatively comprise a diffuser, which is arranged to diffuse the first component into the liquid second component.

[0173] The system **10** also comprises a compressor **12** for compressing the first component of the working fluid, a pump **19** for compressing at least most of the second component, a heater **13** for heating the first and second components and an expander **14** for expanding the first and second components to produce the work. The apparatus **11** is located after the compressor **12** and the pump **19**, to enable the liquid second component to be combined with the gaseous first component after they have been compressed.

[0174] The system **10** also comprises a recuperator **15** for transferring some of the energy of the working fluid from the outlet of the expander **14**, to the working fluid from the outlet of the apparatus **11**. A substantial portion of the energy transferred in the recuperator **15** is at least some of the latent heat of the second component of the working fluid (ie. the energy associated with the phase change of a material such as between liquid and gaseous states). There is typically also some sensible heat of the working fluid transferred in the recuperator **15**. In the recuperator **15** at least some of second component from the outlet of the apparatus **11**, which is liquid, is converted to gas and at least some of the second component from the outlet of the expander **14**, which is gas, is converted to liquid.

[0175] The change of phase for the second component of the working fluid produces a large expansion in the volume of the working fluid, thus substantially increasing the volumetric flow through and hence the work produced by the expander **14** compared to a gas turbine in a conventional Brayton cycle for the same mass flow rate. Furthermore, the recycling of energy, particularly the latent heat, in the recuperator **15**, reduces the load on the heater **13** and hence the energy input to the system **10**. These factors enable the system **10** to operate with greater comparative power, improved efficiency and less net energy consumption to produce the same work (in the expander **14**) as for an equivalently sized conventional system.

[0176] The compressor **12** has interstaged cooling provided by an intercooler **18**. The primary purpose of this is to ensure that the temperature of the first component entering the apparatus **11**, is less than a temperature which would cause vaporisation of the second component upon its combination with the first component in the apparatus **11**. This enables the recuperator **15** to provide efficient transfer of the substantial portion of the latent heat of the second component of the working fluid as described above. Ensuring that the temperature of the first component exiting the compressor **12** is at this temperature may alternatively (or in combination with the intercooler **18**) be provided by post compression cooling of the first component, pre-compression cooling of the first component or by pre-cooling the second component prior to it being combined with the first component in the apparatus **11** as outlined in FIG. **1**.

[0177] The intercooler **18** has a cooling source (as do any of the other coolers described above) for cooling the first component between stages of the compressor **12**. The cooling source may be cooling water, ambient air or any suitable refrigeration system to which heat from the first component may be rejected. It is noted that the heat rejected from the compressor **12** by cooling of the first component (either using the intercooler **18**, or by pre or post compression cooling) may be used as a heat input to any other suitable process such as for heating hot water, creating low pressure steam, desalination, as the heat input to a heat pump vapour compression system or for any low temperature power generation or refrigeration cycle.

[0178] The compressor **12** is any suitable compressor such as an axial, centrifugal, reciprocating or scroll compressor for example.

[0179] The expander **14** comprises any suitable unit for producing mechanical work by the expansion of a working fluid. The expander **14** may or may not be directly coupled to the compressor **12**. The expander **14** may be a turbine, a positive displacement rotary expander, a linear expander, a scroll expander or a reciprocating engine for example. The expander **14** may also comprises multiple turbines, rotary expanders, linear expanders or reciprocating engines, connected in either parallel or series, with or without inter-stage reheat. In the embodiment of FIG. **1**, the expander **14** is in the form of a turbine which may or may not have variable pitch blades. In this embodiment, all the working fluid at the outlet of the expander **14** is in the gas phase. Of course, it is to be understood that the system **10** may comprise any number of multiple expanders and/or compressors arranged in parallel or in series.

[0180] The heater **13** provides a heat input to the working fluid from any suitable heat source, which heats the working fluid to a super-critical gas (ensuring that all of the second component is vaporised). The heat source for the heater **13** may be steam or any other heated medium generated by nuclear power, coal or another combustible fuel, hot exhaust gasses from a gas turbine, waste heat from any other process, direct heating from a furnace, solar thermal, electrical, stored heat or a thermal energy cell(s) for example. One suitable heater **13** which provides a heat input from stored heat source is shown in FIG. **2**, and will be described in more detail further on in the specification.

[0181] The heat engine system **10** also comprises a condenser **16** for cooling the working fluid after it exits the expander **14** (and also the recuperator **15**) to substantially condense the second component of the working fluid to a liquid. This enables the majority of the second component to be readily separated from the first component (which is a gas) prior to the first component (and any residual gaseous second component) being compressed in the compressor **12**. The separated second component is recycled to the pump **19**.

[0182] The system **10** also comprises a load **17**, connected to the expander **14** for converting the work produced by the expander **14** to mechanical or electrical power.

[0183] The system **10** is a closed system, with theoretically no mass inputs or outputs during operation of the system **10**, other than replacement of incidental losses. However, a top-up of either of the components of the working fluid may need to be provided due to some incidental losses such as those resulting from leaks, maintenance, or high-pressure or high-temperature releases for example.

[0184] A general description of the operation of the system **10** will now be provided:

[0185] The gaseous first component of the working fluid enters the compressor **12** through inlet **20**, where it is compressed. Compression of the first component of the working fluid tends to increase its temperature, however, the interstage cooler **18** ensures that this rise is not significant enough to cause the temperature of the first component to be above a temperature at which combination with the second component would cause vaporisation of the second component.

[0186] The first component flows from the outlet **21** of the compressor **12** to the apparatus **11**, where the liquid second component is combined with the first component through second component inlet **22** having been compressed in the pump **19**. The liquid second component may be at ambient temperature (or lower) and may cool the working fluid. The liquid second component is compressed in the pump **19** to a pressure greater than ambient, and preferably to at or about the pressure of the first component at the outlet of the compressor **12**, prior to being combined with the first component. Because there are gas and liquid components of the working fluid compressed separately in the compressor **12** and pump **19** respectively, the compressor **12** can be smaller than a compressor which is compressing an equivalent mass flowrate of working fluid which is all gas. This is advantageous to the system because compressing a gas requires much more work than compressing (in a pump) an equivalent mass flowrate of liquid. Therefore, the overall efficiency of the system (s) is improved by this arrangement of the pump **19** and the compressor **12**. The working fluid as a gas-vapour mixture exits the apparatus **11** through outlet **23**.

[0187] The recuperator **15** is generally in the form of a shell and tube heat exchanger, preferably a falling film condenser and comprises a boiling side **24** (shell) and a condensing side **25** (tubes). Working fluid from the outlet **23** of the apparatus **11** enters the boiling side **24** of the recuperator **15** where the second component of the working fluid substantially boils as it receives energy from the working fluid on the condensing side **25**.

[0188] The working fluid exiting the boiling side **24** of the recuperator flows to the inlet **26** of the heater **13**, where it is heated. From the heater **13**, the working fluid flows to the inlet **27** of the expander **14**. The working fluid is expanded in the expander **14** to produce the work. The working fluid at the outlet **28** of the expander **14** is consequently lower in pressure and temperature. In the embodiment shown in FIG. **1**, the conditions of the working fluid at the outlet **28** of the expander **14** are such that both the first and second components are a gas. The working fluid from the outlet **28** of the expander **14** is received by the condensing side **25** of the recuperator **15** where the second component of the working fluid substantially condenses as it loses energy to the working fluid on the boiling side **24**.

[0189] The recuperator **15** is also arranged to act as a separator on the condensing side to provide a separation of a liquid fraction of the working fluid (the second component) from a gaseous fraction (primarily the first component).

[0190] The gaseous fraction of the working fluid exiting the condensing side **25** of the recuperator **15** enters one side of the condenser **16**. The condenser **16** may be a shell and tube heat exchanger but alternatively may be a radiator, a finned cooling coil with cooling fluid in serpentine coils, located inside a plenum with condensate recovery or any other suitable condenser. Cooling fluid **29** (possibly air, water or refrigerant of any composition at or below ambient conditions) flows through the other side of the condenser **16**, cooling the working fluid so that most of the (remaining) second component of the working fluid is condensed into a liquid. The liquid second component is separated from the first component in the condenser **16**, which is thus acting as a separator. The separated second component **30**, is recycled to the pump **19**. The remaining working fluid which comprises the first component and any of the second component remaining as a gas flows to the inlet **20** to the compressor **12**.

[0191] The liquid fraction of the working fluid exiting the condensing side **25** of the recuperator **15** may bypass the condenser **16** and flow to the pump **19** as shown in FIG. **1**. However, in an alternative arrangement, the liquid fraction of the working fluid exiting the condensing side **25** of the recuperator **15** may also be sent to the condenser **16**. The pump **19** pumps the liquid second component from the condenser **16** and the recuperator **15** back to the apparatus **11**. Notably, during operation of the system **10**, the energy transfer in the recuperator **15** is controlled to maintain the optimum system efficiency using an energy transfer controller. This is compared to conventional heat engines in which it is the conditions across the expander **14** that are controlled. Temperature and pressure sensors at the inlets and outlets of both the condensing and boiling sides **24**, **25** of the recuperator **15** monitor the conditions across the recuperator **15**. The energy transfer in the recuperator **15** is subsequently controlled by changing the conditions at the inlet of the expander and subsequently the expansion done in the expander **14** and hence the conditions at the outlet **28** of the expander **14**. The conditions at the inlet of the expander may be changed by, for example, changing the amount of compression carried out in the compressor **12** and/or pump **19** as well as changing the amount of heat transfer to the working fluid in the heater **13**. The energy transfer controller may also control the energy transferred in the recuperator **15** by changing the amount of the liquid second component combined with the first component in the apparatus **11**.

[0192] The system **10** may also comprise a mass flow controller for controlling the mass flowrate of the second component relative to the mass flowrate of the first component. If the mass flow rate of the second component relative to the first component becomes too high, then the second component may not completely evaporate which could cause problems, particularly in the expander **14** if it is in the form of a turbine.

The mass flow controller may comprise variable speed controllers on the compressor **12** and pump **19**, respectively. For the compressor **12**, alternatively, the mass flow controller may comprise variable inlet guide vanes. The mass flow controller may in addition to or alternatively comprise diverters on the compressor **12** and/or the pump **19** which divert flow from the outlet of the compressor and/or pump to their respective inlets. The mass flow controller may also comprise appropriate valving on the apparatus **11**.

[0193] The system may also comprise an energy storage unit located upstream from the compressor **12** for storing compressed working fluid from the compressor. The energy storage unit may be used in particular during start-up of the system **10**, during which the expander **14** is gradually increased from zero to full capacity. Rather than wasting the energy of the compressed working fluid from the compressor during this time, by bypassing the expander **14**, some of the working fluid is diverted to the energy storage unit. The working fluid held in the energy storage unit can be reintroduced to the system cycle once the expander **14** has reached full capacity. Alternatively, the system **10** may be started up by supplying power to the compressor, pump and expander shafts.

[0194] These system controllers provide the system **10** with a high degree of operational flexibility, thus enabling the system **10** (in particular the expander **14**) to closely follow the load **17** should it vary. For example, the mass flow controller enables the pump **19** and the compressor **12** to each be turned down to 30-50% of their full load.

[0195] The first and second components of the working fluid should be substances which are substantially inert with respect to each other, both chemically and physically, ie. they will not react with one another nor substantially dissolve in one another nor substantially dissociate at high temperatures. It is also desirable if the second component is a substance which has a high volumetric expansion ratio from liquid to gas. Further, it is also desirable if the first component is a substance which is highly compressible as a gas. The first component may be nitrogen, argon, helium, hydrogen or methane for example. The second component may be water, propane, butane, ethanol or carbon dioxide for example. A preferred working fluid is nitrogen as the first component and water as the second component. It is noted that the working fluid may comprise more components than the first and second components, ie. different substances. However, these additional components will each generally follow the flow path of either the first component (as a gas) or the second component (as a liquid and a gas) in the system **10** as described above.

[0196] Referring now to FIG. **2**, the heater **13** is shown in an embodiment, as a regenerative heater. It is noted that in other embodiments, the heater **13** may be a heat exchanger or another type of suitable heater. The heater **13** of FIG. **2** comprises first, second and third volumes **40**, **41**, and **42** respectively, of material. It is readily understood that the heater **13** may comprise less or more volumes of material to that shown in FIG. **2**. The volumes **40**, **41**, **42** are arranged to be heated to at or above the melting temperature of the material. The heater **13** also comprises passages through the volumes **40**, **41**, **42** of material for the flow therethrough of the working fluid. The working fluid, is thus heated by the volumes **40**, **41**, **42** of material. In the embodiment shown in FIG. **2**, the passages are arranged for the working fluid to flow through the volumes **40**, **41**, **42** of material in series. However, in other embodiments the passages may be arranged for the working fluid to flow through the volumes **40**, **41**, **42** of material in parallel.

[0197] In the embodiment shown in FIG. **2** the volumes of material **40**, **41**, **42** are heated using a heating fluid flowing through spaces through the volumes of material **40**, **41**, **42**. The heating fluid may be steam or any other heated medium generated by nuclear power, coal or other combustible fuel or hot exhaust gasses from a gas turbine. The volumes **40**, **41**, **42** of material may be heated using any other suitable means, such as waste heat from another process, direct heating from a furnace, electrical or solar thermal heat. The passages through which the working fluid flow are separate from the spaces through which the heating fluid flow. This enables continuous operation of the heater **13** as well as preventing any mixing of the two fluids, which avoids problems such as contamination, particularly dust contamination, oxygenation and carbonation of the working fluid.

[0198] The materials in the volumes **40**, **41**, **42** may be different and in one embodiment are of progressively decreasing melting temperatures from the first volume **40** to the third volume **42**. The materials used may be referred to as “phase change materials” or “PCMs”. Any suitable phase change materials may be employed. In an embodiment of the invention, however, the first volume **40** contains silicon, which has a melting temperature of about 1410° C., the second volume **41** contains lithium fluoride, which has a melting temperature of about 870° C. and the third volume **42** contains magnesium oxide or calcite, which have a melting temperature of about 560° C. The volumes of material **40**, **41**, **42** are all held in containers, which are of a material which is able to withstand the temperatures of the molten materials held therein. A particularly suitable material in this regard is a ceramic material, preferably silicon carbide.

[0199] In another arrangement, the volumes of material **40**, **41**, **42** may contain a mixture of two or more different materials. In one form, each volume of material **40**, **41**, **42** comprises the mixture of the same materials but at different ratios. The different ratios preferably have different melting temperatures, thus providing the graduated heating of the working fluid flowing through the volumes of material **40**, **41**, **42**. In this respect, at least one of the materials in the mixture of materials of each volume is for affecting the melting temperature of the volumes of material. For example, aluminium may be mixed with silicon to reduce the melting temperature of the silicon. Alternatively, or in addition to this, one of the materials in the mixture of materials may be for improving the heat transfer of the volume of material. Such a material for example is graphite, which may be added to salts for example such as lithium fluoride, magnesium oxide, calcite or sodium chloride to improve the heat transfer of these materials. This, advantageously, enables the volumes of material **40**, **41**, **42** to reach their melting temperatures more rapidly as well as improving the heat transfer from the volumes of material **40**, **41**, **42** to the working fluid. This in turn enables faster start-up and shut down of the system **10**.

[0200] The working fluid flows counter-currently to the heating fluid, entering the heater **13** through the inlet **26** to be heated firstly by the lowest temperature volume of material, in this case the third volume **42**, and finally by the highest temperature volume of material, in this case the first volume **40** before exiting to the inlet **27** of the expander **14**. The heating fluid heats the volumes **40**, **41**, **42** in reverse order, that is, it enters the heater **13** through inlet **43** to heat the first volume **40**, which is required to be at the highest temperature, first and heats the third volume **42** last.

[0201] In another embodiment, the material in each or two of the volumes **40**, **41**, **42** is the same. In this embodiment, the volumes may not be as readily heated to at or above the melting temperature of the material using the heating fluid in series because as the heating fluid flows through the heater **13**, it loses energy and heat as it flows through the volumes **40**, **41**, **42**. Thus, the volumes **40**, **41**, **42** in this embodiment may need to be heated in parallel or alternatively by a different source of heat.

[0202] The heater **13** also comprises a number of valves **45** on the inlets and outlets to the heater **13** which can be used to control the flow rate of the working fluid and the heating fluid through the heater **13** to maintain the temperature of the phase change materials in the volumes **40**, **41**, **42** so as to keep them in a molten phase and to control the temperature of the working fluid as it leaves the heater.

[0203] The flowrate of the working fluid is also controlled with respect to its temperature at the outlet of the heater **13** (ie. the inlet **27** to the expander **14**). The temperature of the working fluid required at the inlet **27** of the expander is much less than the melting temperature of silicon (and hence the temperature of the first volume **40**). If the working fluid at the inlet **27** of the expander was at this temperature (approximately 1410° C.) then this could cause damage to the expander **14**. Because of this large temperature difference, the heater **13** advantageously enables quick start-up of the heat engine system **10**.

[0204] The expander inlet temperatures can be varied and controlled by a modulating bypass control valve that diverts flow around the regenerative heater **13**. This will allow the precise setting of expander inlet temperatures with variable output. This level of temperature control cannot be achieved with conventional gas turbines that rely on internal combustion. Also, when this control is used with the other control elements as described previously, good efficiency is attained when the system is turned down.

EXAMPLE

[0205] A model of a heat engine system according to embodiments of the present invention was constructed in HYSYS®. FIG. **3** provides a schematic view of the model. The model was prepared on the basis of an approximately 1:1 mass flow ratio of nitrogen as the first component and water as the second component. Other parameters assumed for the model include:

[0206] an ambient temperature of 35° C. (for Queensland ambient temperature conditions)

[0207] compression ratio for the compressor of 6.2:1

[0208] Compressor efficiency of 85%

[0209] Expander efficiency of 85%

[0210] Pressure drops of 5 kPa for the apparatus, 30 kPa for the boiling side of the recuperator, 20 kPa for the heater, 300 Pa for the condensing side of the recuperator.

[0211] Exit temperature for the recuperator condensing side of 60° C.

[0212] Table 1 below sets out the conditions at points A-I in the system as indicated on FIG. **3**.

TABLE 1

	A (Nitrogen)	B (Water)	C	D	E	F	G	H	I
Temperature (° C.)	35.00	35.00	273.5	45.91	617.6	1100	742.9	60.00	35.00
Pressure (kPa)	100.0	620.0	620.0	620.0	590.0	570.0	103.0	100.00	100.0
Total Mass Flow (kg/s)	1.000	0.9256	1.000	1.926		1.926			
Total Volume Flow (m^3/h)		3.332	963.3	540.5					
Vapour Fraction				0.3979				0.4910	
Mass Fraction (H_2O)				0.5005					

[0213] The model system was calculated to produce a net shaft power output of 0.9736 MW at 58.95% efficiency.

[0214] In the claims which follow and in the preceding description of the invention, except where the context requires otherwise due to express language or necessary implication, the word "comprise" or variations such as "comprises" or "comprising" is used in an inclusive sense, ie. to specify the presence of the stated features but not to preclude the presence or addition of further features in various embodiments of the invention.

1. A heat engine system for producing work by expanding a working fluid comprising first and second components, the system comprising, an apparatus for combining the second component of the working fluid as a liquid with the first component, the first component being a gas throughout the system, a compressor for compressing the first component, a pump for compressing at least most of the second component, a heater for heating the first and second components, an expander for expanding the first and second components to produce the work, and a recuperator for transferring at least some of the energy of the working fluid from the outlet of the expander, to the working fluid from the outlet of the apparatus, wherein a substantial portion of the energy transferred in the recuperator is at least a portion of the latent heat of the second component from the outlet of the expander.

2. A heat engine system as claimed in claim **1**, wherein the apparatus is arranged to spray the liquid second component into a space having the first component therein.

3. A heat engine system as claimed in claim 1, wherein the apparatus is arranged to diffuse the first component into the liquid second component.

4. A heat engine system as claimed in any one of the preceding claims, wherein the recuperator is in the form of a shell and tube heat exchanger.

5. A heat engine system as claimed in any one of the preceding claims, wherein the recuperator is in the form of a falling film condenser.

6. A heat engine system as claimed in any one of the preceding claims, wherein the recuperator is arranged to provide separation of a liquid fraction of the working fluid from a gaseous fraction upon cooling of the working fluid from the outlet of the expander.

7. A heat engine system as claimed in any one of the preceding claims, wherein the system also comprises at least one cooler for cooling the first and/or second components prior to combining them in the apparatus.

8. A heat engine system as claimed in claim 7, wherein at least one of the cooler comprises an intercooler in the compressor to provide interstage cooling of the first component.

9. A heat engine system as claimed in either one of claim 7 or claim 8, wherein the or at least one of at least one cooler comprises a post compressor cooler for cooling the first component after it has been compressed.

10. A heat engine system as claimed in any one of claims 7 to 9, wherein the or at least one of at least one cooler comprises a pre-compressor cooler for cooling the first component prior to being compressed in the compressor.

11. A heat engine system as claimed in any one of claims 7 to 10, wherein the or at least one of at least one cooler comprises a liquid cooler for cooling the liquid second component.

12. A heat engine system as claimed in any one of the preceding claims, wherein the pump compresses at least most of the liquid second component to a pressure above the ambient pressure.

13. A heat engine system as claimed in any one of the preceding claims, wherein the pump compresses the liquid second component to at or about the pressure to which the compressor compresses the first component.

14. A heat engine system as claimed in any one of the preceding claims, wherein the system also comprises a condenser for cooling the working fluid from the expander after it exits the recuperator.

15. A heat engine system as claimed in claim 14, wherein the condenser is arranged to substantially condense the second component of the working fluid from the expander to a liquid.

16. A heat engine system as claimed in either one of claim 14 or claim 15, wherein the condenser is a separator for separating the second component as it condenses from the first component.

17. A heat engine system as claimed in any one of the preceding claims, wherein the system is a closed system having substantially no mass inputs or outputs during operation of the system, other than replacement of incidental losses.

18. A heat engine system as claimed in any one of the preceding claims, the system also comprising an energy transfer controller for controlling the energy transfer in the recuperator during operation of the system.

19. A heat engine system as claimed in any one of the preceding claims, wherein the system also comprises a mass flow controller for controlling the mass flow rate of the second component relative to the mass flow rate of the first component.

20. A heat engine system as claimed in any one of the preceding claims, wherein the first and second components of the working fluid are substances which are substantially inert with respect to each other.

21. A heat engine system as claimed in any one of the preceding claims, wherein the second component is a substance which has a high volumetric expansion ratio from liquid to gas.

22. A heat engine system as claimed in any one of the preceding claims, wherein the first component is a substance which is highly compressible as a gas.

23. A heat engine system as claimed in any one of the preceding claims, wherein the first component is nitrogen and the second component is water.

24. A heat engine system as claimed in any one of the preceding claims, wherein the heater comprises at least one volume of material arranged to be heated to at or above the melting temperature of the material, the heater also comprising passages through the at least one volume of material for the flow therethrough of the working fluid.

25. A heat engine system as claimed in claim 24, wherein the at least one volume of material is heated using a heating fluid flowing through space through the at least one volume of material.

26. A heat engine system as claimed in either one of claim 24 or 25, wherein the heater comprises at least two volumes of material, the materials in the volumes being different and having different melting temperatures.

27. A heat engine system as claimed in claim 26, wherein the materials are of progressively decreasing melting temperatures from the first volume to the last volume, the passages being arranged for the flow of the working fluid through the last volume first and the first volume last.

28. A heat engine system as claimed in claim 25, wherein the working fluid is arranged to flow through the at least one volume of material countercurrently to the flow of the heating fluid.

29. A heat engine system as claimed in any one of claims 24 to 28, wherein at least one of the volumes of material contains a mixture of two or more different materials.

30. A heat engine system as claimed in claim 29, wherein one of the materials in the mixture of materials of the or each volume is for improving the heat transfer of the or each volume of material.

31. A heat engine system as claimed in either one of claim 29 or 30, wherein one of the materials in the mixture of materials of the or each volume is for effecting the melting temperature of the or each volume of material.

32. A method for producing work, the method comprising the steps of:

compressing a first component of a working fluid in a compressor, the first component being a gas at all times during the method;

at least most of compressing a second component of the working fluid as a liquid in a pump;

combining the second component as a liquid with the first component in an apparatus;

heating the combined first and second components in a heater;

expanding the heated first and second components to produce the work in an expander; and transferring in a recuperator at least some of the energy of the working fluid after it has been expanded to the working fluid prior to it being heated in the heater, wherein a substantial portion of the energy transferred is at least a portion of the latent heat of the second component after the working fluid has been expanded in the expander.

33. A method as claimed in claim **32**, wherein the step of transferring at least some of the energy in the recuperator converts at least some of the second component from liquid to gas prior to it being heated in the heater.

34. A method as claimed in either one of claim **32** or **33**, wherein the step of transferring at least some of the energy in the recuperator converts at least some of the second component from gas to liquid after it has been expanded in the expander.

35. A method as claimed in any one of claims **32** to **34**, wherein the method is a closed cycle method also comprising the step of repeating the steps of the method performed on the working fluid after at least some of its energy has been transferred in the recuperator to the working fluid which is yet to be heated in the heater.

36. A method as claimed in any one of claims **32** to **35**, the method also comprising the step of returning the first component to the compressor.

37. A method as claimed in any one of claims **32** to **36** the method also comprising the step of returning at least most of the second component to the pump.

38. A method as claimed in any one of claims **32** to **37**, the method also comprising the step of cooling the first and/or second components prior to the step of combining them.

39. A method as claimed in claim **38**, wherein the cooling step comprises cooling the first component between at least two stages of the compressor using an intercooler.

40. A method as claimed in either one of claim **38** or **39**, wherein the cooling step comprises cooling the first component after the step of compressing the first component.

41. A method as claimed in any one of claims **38** to **40**, wherein the cooling step comprises cooling the first component prior to the step of compressing the first component.

42. A method as claimed in any one of claims **38** to **41**, wherein the cooling step comprises cooling the second component prior to combining the second component with the first component.

43. A method as claimed in any one of claims **32** to **42**, wherein the method comprises the step of maintaining the temperature of the first component, prior to the step of combining it with the second component, to a temperature which is less than one which would cause vaporisation of the second component during the combining step.

44. A method as claimed in any one of claims **32** to **43**, wherein the method also comprises a step of separating a liquid fraction of the working fluid from a gaseous fraction after the working fluid has been expanded.

45. A method as claimed in claim **44**, wherein the step of separating occurs at least partially in the recuperator.

46. A method as claimed in either one of claim **44** or **45**, wherein the step of separating comprises separating at least most of the second component as a liquid from the first component as a gas.

47. A method as claimed in claim **46**, wherein the step of separating the first component from the second component comprises cooling the working fluid to condense most of the second component.

48. A method as claimed in any one of claims **32** to **47**, wherein the method also comprises the step of controlling the energy transferred in the recuperator.

49. A method as claimed in claim **48**, wherein the step of controlling the energy transferred in the recuperator comprises changing the conditions of the working fluid prior to expanding it in the expander.

50. A method as claimed in either one of claim **48** or **49**, wherein the step of controlling the energy transferred in the recuperator comprises changing the amount of the second component which is combined with the first component in the apparatus.

51. A method as claimed in any one of claims **32** to **50**, wherein the method also comprises the step of controlling the mass flow rate of the second component relative to the mass flow rate of the first component.

52. A method as claimed in any one of claims **32** to **51**, wherein the step of heating comprises flowing the combined first and second components through at least one volume of material which is heated to at or above the melting temperature of the material.

53. A method as claimed in claim **52**, wherein the step of heating also comprises heating the at least one volume of material using a heating fluid.

54. A method as claimed in claim **53**, wherein the step of heating comprises flowing the heating fluid through the at least one volume material in a counter current direction to the flow of the combined first and second components.

55. A method as claimed in any one of claims **32** to **54**, wherein the step of heating comprises heating the working fluid to a super-critical gas.

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