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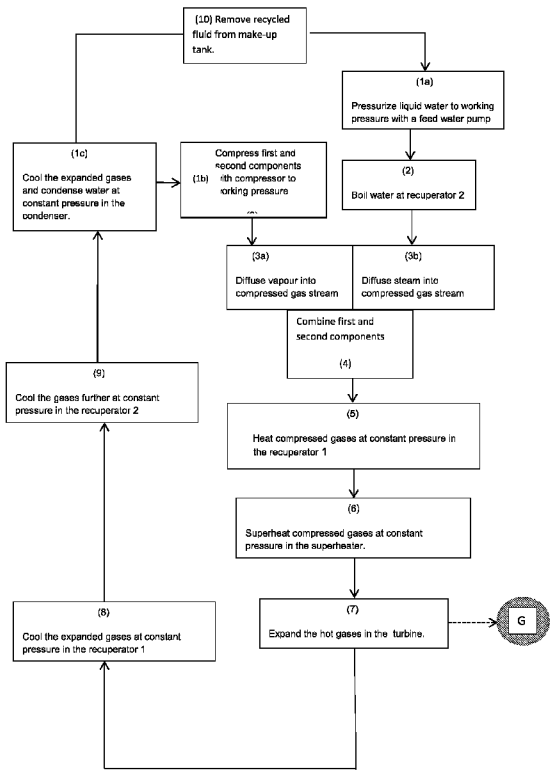
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(54) **Title**: HEAT ENGINE SYSTEM

Fig. 2



(57) **Abstract**: The present invention provides methods and apparatus for a heat engine system for converting thermal energy to mechanical work by expansion and condensation of working fluids. The heat engine system comprises of means for combining a second component with a first component, means for compressing the first component, means for compressing at least most of the second component, means for heating the first and second components, means for expanding the first and second components to produce the work, and means for transferring at least some of the energy of the working fluid from the outlet of the means for expanding to the working fluid from the outlet of the apparatus. The transferring means may be one or more recuperators. A portion of the energy transferred in the means for transferring is at least a portion of the latent heat of the second component from the outlet of the expander.

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Title

Heat Engine System

Field of the Invention

This invention relates to methods and apparatus for heat engine systems.

Background of the Invention

Heat engines are known in the art as systems arranged to convert thermal energy to mechanical work. The heat engine does this by transferring energy from a high temperature heat source (Th) to a low temperature heat sink (TL). 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%.

Because the efficiency of any heat engine is understood to be dependent on the temperature difference between the heat source and heat sink, many attempts have been made to increase heat engine efficiencies by increasing this temperature difference. 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 generally limited by the temperature of the nearby atmosphere or water.

Theoretically, the most efficient heat engine is defined by the Carnot cycle and comprises of 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 (Th) to the low temperature (TL), 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 TL to Th in the pump. 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 and there are unavoidable frictional heat losses. A reversible process is an ideal process that once having taken place can be reversed and in doing so leaves no change in either the system or its surroundings.
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.

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. 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 (i.e. the efficiency of the ideal Rankine cycle) for similar reasons to those outlined for the Carnot cycle above.

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 (i.e. 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 increase the efficiency of the heat engine, variations to these thermodynamic cycles have

been considered. Two such variations include the Rankine cycle with reheat and the regenerative Rankine cycle.

In the Rankine cyc1e with reheat, the heat engine comprises of two turbines in series. Working f1uid 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 f1uid 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.

The regenerative Rankine cycle invo1ves preheating of the working f1uid 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 boi1er.

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. However, the efficiencies of all real heat engines remain significantly limited. What is needed is a heat engine with improved efficiency of power, electricity and refrigeration production.

Summary of the Invention

According to a first aspect of the present invention, there is provided a heat engine system for producing work by expanding a working f1uid comprising of first and second components, the system comprising of means for combining the second component of the working fluid with the first component, means for compressing the first component, means for compressing at least most of the second component, means for heating the first and second components, means for expanding the first and second components to produce the work, and a means for transferring at least some of the energy of the working fluid from the outlet of the means for expanding to the working fluid from the outlet of the apparatus, wherein a portion of the energy transferred in the means for transferring is at least a portion of the

latent heat of the second component from the outlet of the expander. Preferably, the means for transferring is a recuperator.

Most advantageously, the invention may incorporate more than one means for transferring energy in the working fluid stream. The incorporation of multiple energy transferring means provides the advantage of increasing the thermal efficiency of the system. Embodiments of the invention in which there are multiple energy transferring means enable the combination of first and second components in the same physical state, such as both being in the gaseous state. The energy transfer means may be disposed in series in the working fluid stream to achieve the more efficient energy transfer.

Preferably, the heat engine system further comprises of a second recuperator for transferring at least some of the energy of the working fluid from the outlet of the first recuperator to the working fluid from the outlet of the cold feed vessel to the injector, hereafter referred to as the "apparatus".

The first and second components of the working fluid are substances which are substantially inert with respect to each other. The first and second components will not react with one another, nor substantially dissolve in one another, nor substantially dissociate at high temperatures. The second component is a substance which has a high volumetric expansion ratio from liquid to gas. The first component is a substance which is highly compressible as a gas. The first component may be any of nitrogen, argon, helium, hydrogen or methane, for example. The second component may be any of water, propane, butane, ethanol or carbon dioxide. A preferred working fluid is nitrogen as the first component and water as the second component. 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.

Preferably, the apparatus also comprises of an atomiser. Preferably, the apparatus is arranged to spray the second component into a space having the first component therein. Preferably, the apparatus is also a diffuser.

The apparatus is arranged to diffuse the first component into the second component.

The apparatus may comprise of multiple injectors, atomisers or diffusers.

The apparatus is located between the compressor and a recuperator, to enable the second component to be combined with the gaseous first component after it has been compressed. Preferably, a substantial portion of the latent heat of the second component is transferred in a recuperator. The system may comprise of multiple recuperators connected in parallel and/or in series. The recuperators collect and convert at least some of second component from the outlet of the apparatus. A first recuperator converts at least some of the second component from the outlet of the expander from gas to liquid. A second recuperator converts at least some of the second component from the outlet of the first recuperator from liquid to a gas. The recuperators are generally in the form of a shell and tube heat exchanger. The recuperators are generally in the form of a falling film condenser from liquid to gas.

The first 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. The second recuperator is arranged to provide separation of a liquid fraction of the working fluid from the outlet of the first recuperator. Both recuperators comprise of a boiling side and a condensing side.

The working fluid from the outlet of the apparatus enters the boiling side of a recuperator where the second component of the working fluid substantially boils as it receives energy from the working fluid on the condensing side.

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 there between compressions of the first component of the working fluid also increases its temperature. The compressor is any suitable compressor such as an axial, centrifugal, reciprocating or scroll compressor, for example. The compressor compresses a small portion of the second component as a gas in addition to the first component. The system may comprise multiple compressors connected in parallel and/or series.

The system also comprises of at least one cooler for cooling the first and/or second components prior to combining them in the apparatus. At least one of the coolers comprises of an inter-cooler in the compressor to provide inter-stage cooling of the first compressor. At least one of the coolers comprises of a post compressor cooler for cooling the first component after it has been compressed. At least one of the coolers comprises of a pre-compressor cooler for cooling the first component prior to it being compressed in the compressor. At least one cooler has a cooling source. The cooling source may be cooling water, ambient air or any suitable refrigeration system to which heat may be transferred.

The heat transferred 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. At least one cooler comprises of a liquid cooler for cooling the second component.

The second component when combined with the first component by the apparatus is within close proximity to ambient temperature. The second component when combined with the first component cools the first component.

Preferably, 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 admixture with the first component by the apparatus.

The system may comprise of multiple pumps connected in parallel and/or series. A pump pressurises at least most of the second component as a liquid phase to a pressure above the ambient pressure. A pump pressurises at least most of the second component liquid phase to at or about the pressure to which the compressor compresses the first component.

The working fluid is a mixture after the second component has been combined with the first component by the apparatus.

The expander comprises of any suitable unit for producing mechanical work by the expansion of a working fluid. The expander may be a turbine, a positive displacement rotary expander, a scroll expander a linear expander or a reciprocating engine, for example. The expander may also comprise of multiple turbines, rotary expanders, linear expanders or reciprocating engines, connected in either parallel or series, with or without inter-stage reheat. The expander may or may not be directly coupled to the compressor to the drive the compressor. Preferably, the expander is in the form of a turbine. The turbine may have variable pitch blades. The system may 'comprise any number of multiple expanders and/or compressors arranged in parallel or series.

The heater provides a heat input to the working fluid from any suitable heat source. The heater heats the working fluid to a super-critical gas temperature.

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.

The heat engine system also comprises of a condenser for cooling the working fluid after it exits the second stage recuperator. The system may comprise of multiple condensers connected in para1lel and/or series. A condenser is arranged to substantially condense any remaining gaseous phase of the second component of the working fluid to a liquid. A 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. One side of the condenser receives the working fluid exiting the condensing side of the recuperator. 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. The coo1ing fluid may be air, refrigerant of any composition or water or brine.

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.

A condenser is a separator for separating the second component, as it condenses from the first component. The separated second component is recycled to the apparatus.

The remaining working medium which comprises of the first component and any of the second components flows to the inlet to the compressor.
The system also comprises of a load, connected to the expander for converting the work produced by the expander to mechanical or electrical power.

The system is a closed system having substantially no mass inputs or outputs during operation of the system, other than replacement of incidental losses.

The system comprises of 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 re1eases for example.

The system comprises of an energy transfer controller for controlling the energy transfer in the recuperator during operation of the system. The energy transfer controller controls the

energy transfer in a 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. The energy transfer controller may control the energy transfer in a recuperator by changing the amount of the liquid second component combined with the first component in the apparatus.

The system comprises of a mass flow controller for controlling the mass flow rate of the second component relative to the mass flow rate of the first component. The mass flow controller comprises of a variable speed control on the pump. The mass flow controller may also comprise a pump diverter, arranged to divert flow of the second component from the outlet of the pump to the inlet of the pump. The mass flow controller may also comprise variable inlet guide vanes in the compressor. The mass flow controller may comprise of a variable speed control on the compressor. The mass flow controller may also comprise a compressor diverter, arranged to divert flow of the first component from the outlet of the compressor to the inlet of the compressor. The mass flow controller comprises of appropriate valving on the apparatus.

The system comprises of 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.

Start-up may be affected by supplying power to the compressor, pump and expander shafts.

The heaters are heat exchangers. The heaters may be regenerative heaters. A regenerative heater comprises of at least one volume of material arranged to be heated to at or above the melting temperature of the material, the heaters also comprising passages through the at least one volume of material for the flow therethrough of the working fluid. A regenerative heater comprises of at least two volumes of material, preferably three. A heater may comprise of more than three volumes of material. When a regenerative heater comprises of at least two volumes of material, the passages are arranged for the working fluid to flow through the volumes of material in series. The passages may be arranged for the working fluid to flow through the volumes of material in parallel.

The volume(s) of material is heated using a heating fluid flowing through spaces through the volume(s) of material.

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.

The passages through which the working fluid flows are separate from the spaces through which the heating fluid flows.

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.

When the regenerative heaters comprise at least two volumes of material, the materials in the volumes are different. The different materials preferably have different melting temperatures. 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.

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.

At least one of the volumes of material contains a mixture of two or more different materials. One of the materials in the mixture of materials is for improving the heat transfer of each volume of material. Such a material may be graphite. One of the materials in the mixture of materials is for affecting the melting temperature of the volume of material. Aluminium may be mixed with silicon to reduce the melting temperature of the volume of material.

When the regenerative heaters comprise at least two volumes of material, the materials in the volumes are each a mixture of the same materials but at different ratios. The different ratios preferably have different melting temperatures. The materials in the volumes may be referred to as “phase change materials" or “PCMs". Any suitable phase change materials may be employed.

When the regenerative heaters comprise three volumes of material the first volume preferably contains silicon, which has a melting temperature of about 1410°C, the second volume may contain 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.

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. The container(s) is manufactured from a ceramic, preferably silicon carbide.

A regenerative heater also comprises of 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. The system preferably comprises of multiple regenerative heaters. The system most preferably comprises of three regenerative heaters, whereby while one heater is in operation a second can be on stand-by and the other can be shut-down for maintenance.

According to a second aspect of the present invention, there is provided a method for producing work, the method comprising the steps of compressing a first component of a working fluid, the first component being a gas at all times during the method; pressurising at least most of a second component of the working fluid as a liquid; transferring of the energy to convert the second component into a gas before injection; combining the second component as a gas with the first component; heating the combined first and second components; expanding the heated first and second components to produce the work; and transferring at least some of the energy of the working fluid after it has been expanded to the working fluid prior to it being heated, 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 expanding step.

The step of combining the second component with the first component may comprise of spraying the second component into a space having the first component therein.

The step of combining the second component with the first component may comprise of diffusing the first component into the second component.

The step of combining the second component with the first component preferably occurs after the steps of compressing the first component and pressurising at least most of the second component.

Preferably, some of the energy transferred in a recuperator is sensible heat of the working fluid after the expander. The step of transferring at least some of the energy in a recuperator converts at least some of the second component from liquid to gas prior to it being heated in the heater.

The step of transferring at least some of the energy in a recuperator converts at least some of the second component after it has been expanded in an expander.

The step of transferring at least some of the energy in a second recuperator converts at least some of the second component before it has been expanded in an expander.

The method also comprises of the step of separating a liquid fraction of the working fluid from a gaseous fraction after the working fluid has been expanded. The step of separating occurs at least partially in a recuperator.

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.

The method also comprises of the step of returning the first component to the compressor.

The method also comprises of the step of returning at least most of the second component to the pump.

Preferably, the step of compressing the first component occurs in at least two stages. However, the step of compressing the first component may occur in only one stage.

The cooling step comprises of cooling the first component between at least two of the stages of the compressor using an intercooler. The cooling step may comprise of cooling the first component after the step of compressing the first component, preferably before the step of combining with the second component. This method also comprises of the step of cooling the first and/or second components prior to the step of combining them. The cooling step comprises of cooling the first component prior to the step of compressing the first component. The cooling step comprises of cooling the second component prior to combining the second component with the first component.

The second component when combined with the first component in the apparatus is at or near ambient temperature.

The step of pressurising at least most of the second component preferably pressurises at least most of the second component to a pressure above the ambient pressure. The step of pressurising at least most of the second component pressurises most of the second component to at or about the pressure to which the first component is compressed in the compressor.

The method comprises of 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.

The step of separating the liquid fraction from the gaseous fraction of the working fluid comprises of separating at least most of the second component as a liquid from the first component as a gas.

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.

The step of separating occurs at least in part in a recuperator.

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 recuperators to the working fluid which is yet to be heated in the heater.

The step of separating the first component from the second component comprises of cooling the working fluid to condense at least most of the second component.

The method also comprises of the step of controlling the energy transferred in a recuperator.

The step of controlling the energy transferred in a recuperator may comprise of changing the conditions of the working fluid prior to expanding it in the expander.

The step of controlling the energy transferred in a recuperator may comprise of changing the amount of the second component which is combined with the first component in the apparatus.

The method may also comprise of the step of controlling the mass flow rate of the second component relative to the mass flow rate of the first component.

The step of heating may comprise of transferring heat from a high temperature source to the working fluid in a heater, such as for example by using a heating medium in a heat exchanger.

The step of heating may comprise of 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.

The step of heating may also comprise of flowing the combined first and second components through at least two volumes of material, preferably three.

The step of heating may also comprise of heating the at least one volume of material using a heating fluid. Heating at least one volume of material may comprise of flowing the heating fluid through spaces through the volume(s) of material. The step of heating comprises of 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. The step of heating comprises of heating the working fluid to a super-critical gas.

Brief Description of the Drawings

Figure 1 shows a schematic diagram of the apparatus for a heat engine system according to the invention.

Figure 2 shows the steps of the method according to the invention.

Detailed Description of the Invention and Preferred Embodiments

The heat engine system produces work by expanding a working fluid. The working fluid comprises of first and second components, the first component being a gas throughout the system

The system comprises of an apparatus for combining the second component of the working fluid as a liquid with the first component.

In one embodiment, the apparatus 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. In another embodiment the apparatus may alternatively comprise of a diffuser, which is arranged to diffuse the first component into the second component.

The system also comprises of a compressor for compressing the first component of the working fluid, a pump for compressing at least most of the second component, a heater for heating the first and second components and an expander for expanding the first and second components to produce the work. The apparatus is located after the compressor and the pump, to enable the liquid second component to be combined with the gaseous first component after they have been compressed. The invention advantageously exploits the transfer of energy as latent heat and sensible heat in multiple energy transfer means such as recuperators within the heat engine system. A first recuperator transfers some of the energy of the working fluid from the outlet of the expander to the working fluid from the outlet of the apparatus. A second recuperator transfers some of the energy of the working fluid from the

outlet of the expander to the working fluid before the inlet of the second component into the apparatus.

A substantial portion of the energy transferred in a recuperator, located in the component pathway after the apparatus, is at least some of the latent heat of the second component of the working fluid (i.e. 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 a recuperator. In a recuperator at least some of second component from the outlet of the apparatus, which is liquid, is converted to gas and at least some of the second component from the outlet of the expander, which is gas, is converted to liquid.

The change of phase for the second component of the working fluid most advantageously 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 compared to a gas turbine in a conventional Brayton cycle for the same mass flow rate. Furthermore, the recycling of energy, according to the invention, particularly the latent heat, in a recuperator(s), reduces the load on the heater and hence the energy input to the system. These factors enable the system to operate with greater comparative power, improved efficiency and less net energy consumption to produce the same work (in the expander) as for an equivalently sized conventional system.

The compressor has interstaged cooling provided by an intercooler. The primary purpose of this is 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 in the apparatus. This enables a recuperator 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 is at this temperature may alternatively (or in combination with the intercooler) 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.

The intercooler has a cooling source (as do any of the other coolers described herebefore) for cooling the first component between stages of the compressor.

The cooling source may be cooling water, ambient air or any suitable refrigeration system to which heat from the first component may be transferred. The heat rejected from a compressor by cooling of the first component (either using the intercooler, 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.

A compressor is any suitable compressor such as an axial, centrifugal, reciprocating or scroll compressor.

An expander comprises of any suitable unit for producing mechanical work by the expansion of a working fluid. The expander may or may not be directly coupled to the compressor. The expander may be a turbine, a positive displacement rotary expander, a linear expander, a scroll expander or a reciprocating engine for example. The expander may also comprises of multiple turbines, rotary expanders, linear expanders or reciprocating engines, connected in either parallel or series, with or without inter-stage reheat. The expander when in the form of a turbine may or may not have variable pitch blades.

All the working fluid at the outlet of an expander is in the gas phase.

It is to be understood that the system may comprise of any number of multiple expanders and/or compressors arranged in parallel or in series. The heater provides a heat input to the working fluid from any suitable heat source, which heats the working fluid to become a super-critical gas (ensuring that the entire second component is vaporised). 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, solar thermal, electrical, stored heat or a thermal energy cell(s) for example.

One suitable heater which provides a heat input from stored heat source is shown in Figure 1, which is described in more detail in this specification. The heat engine system also comprises of a condenser for cooling the working fluid after it exits the expander (and also the recuperators) 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. The separated second component is recycled to the pump.

The system also comprises of a load (G) in communication with the expander for converting the work produced by the expander to mechanical or electrical power.

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

A description of the apparatus according to the invention is now provided with respect to Figure 1. It will be understood that Figure 1 is a non-limiting embodiment, that many embodiments of the invention are possible, and that the invention is limited only by the scope of the claims appended hereto. Figure 2 shows the steps of the method of the invention as described herein.

Figure 1 shows the movement of the first component as a dotted line and the first component admixed with the second component as a dashed line. Figure 1 further shows a mixture of hot gases as a dash dot line. The gaseous first component 5 of the working fluid enters the compressor 1 through the inlet 2 where it is compressed.

Compression of the first component 5 of the working fluid tends to increase its temperature; however the interstage cooler 3 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 11 would cause vaporisation of the second component.

The first component 5 flows from the outlet 8 of the compressor 1 to the apparatus 9 where the second component is combined with the first component through second component inlet 10 having been compressed in the pump and preheated in the second recuperator.

The second component may be at ambient temperature (or lower) and may cool the working fluid.

The liquid second component 11 is pressurised in the pump 6 to a pressure greater than ambient and preferably to be at or about the pressure of the first component at the outlet 8 of the compressor 1 prior to being combined with the first component 5.

Because there are gas and liquid components of the working fluid (shown as dashed lines or dashed and dotted lines in Fig. 1) compressed and pressurised separately in the compressor 1 and pump 6, respectively, the compressor 1 can be smaller than a compressor which is compressing an equivalent mass f1ow rate of working fluid which is all gas.

This is advantageous to the system because compressing a gas requires much more work than pressurising (in a pump) an equivalent mass f1ow rate of liquid.

Therefore, the overall efficiency of the system(s) is improved by this arrangement of the pump and the compressor. The working fluid as a gas-vapour mixture exits the apparatus through the outlet 7.

The recuperators 12 are generally in the form of a shell and tube heat exchanger, preferably a falling film condenser and comprises of a boiling side 13 (shell) and a condensing side 14 (tubes). Working fluid 15 from the outlet of the apparatus 7 enters the boiling side of the recuperators where the second component of the working fluid substantially boils as it receives energy from the working fluid on the condensing side 14.

Working fluid from the outlet of the first recuperator 17 enters the boiling side of the second recuperator 18 where the second component of the working fluid substantially boils, prior to entering the apparatus (9), as it receives energy from the working fluid on the condensing side.

The working fluid exiting the boiling side of the second recuperator flows to the inlet of the heater 16, where it is heated. From the heater 16, the working fluid flows to the inlet of the expander 30. The working fluid is expanded in the expander to produce the work.

The working fluid at the outlet 19 of the expander 30 is consequently lower in pressure and temperature.

The conditions of the working fluid at the outlet 19 of the expander 30 are such that both the first and second components are a gas. The working fluid from the outlet of the expander is received by the condensing side 14 of the first recuperator 12 where the second component of the working fluid substantially condenses as it loses energy to the working fluid on the boiling side 13.

The recuperators 12 are also configured to act as separators 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)

The gaseous fraction of the working fluid exiting the condensing side of the first recuperator enters one side 22 of the condenser 20. The condenser 20 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 21 (possibly air, water, or refrigerant of any composition at

or about ambient conditions) flows through the other side 23 of the condenser 20 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 which is thus acting as a separator.

The separated second component 24 is recycled to the pump 6 through the main feed tank 4. The remaining working fluid which comprises of the first component 5 and any of the second component remaining as a gas flows to the inlet 2 to the compressor 1.

The liquid fraction of the working fluid exiting the condensing side 14 of the recuperators 12 may bypass the condenser 20 and flow 25 to the pump 6. However in an alternative arrangement the liquid fraction of the working fluid exiting the condensing side of the recuperators may also be sent to the condenser 22. The pump pumps the liquid second component from the condenser and the recuperator back to the apparatus 9.

Notably during operation of the system the energy transfer in the recuperators 12 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 that are controlled.

Temperature and pressure sensors at the inlets 26 and outlets 27 of both the condensing 14 and boiling 13 sides of the recuperators monitor the conditions across the recuperators.

The energy transfer in the recuperators 12 are subsequently controlled 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.

The conditions at the inlet 28 of the expander 30 may be changed by, for example, changing the amount of compression carried out in the compressor and/or pump as well as changing the amount of heat transfer to the working fluid in the heater.

The energy transfer controller may also control the energy transferred in the recuperators 12 by changing the amount of the liquid second component combined with the first component in the apparatus 9.

The system may also comprise a mass flow controller for controlling the mass flow rate of the second component relative to the mass flow rate of the first component as known in the art.

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 if it is in the form of a turbine.

The mass flow controller may comprise variable speed controllers on the compressor 1 and pump 6, respectively. For the compressor, 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 and/or the pump 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. The system may also comprise an energy storage unit located upstream from the compressor for storing compressed working fluid from the compressor.

An embodiment of the invention may include an energy storage unit (not shown.) The energy storage unit may be used in particular during start-up of the system, during which the expander 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, same 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 has reached full capacity. Alternatively, the system may be started up by supplying power to the compressor, pump and expander shafts.

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

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, i.e. 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, i.e. 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 as described above.

The heater is shown as a regenerative heater. It is noted that in other designs the heater may be a heat exchanger or another type of suitable heater. The heater comprises of first, second and third volumes of material. It is readily understood that the heater may comprise less or more volumes of material

The volumes are arranged to be heated to at or above the melting temperature of the material. The heater also comprises of passages through the volumes of material for the flow there through of the working fluid. The working fluid is thus heated by the volumes of material. The passages are arranged for the working fluid to flow through the volumes of material in series. However, in other embodiments the passages may be arranged for the working fluid to flow through the volumes of material in parallel.

The volumes of material are heated using a heating fluid flowing through spaces through the volumes of material. 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 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 flows are separate from the spaces through which the heating fluid flows. This enables continuous operation of the heater as well as preventing any mixing of the two fluids, which avoids problems such as contaminations particularly dust contamination, oxygenation and carbonation of the working fluid.

The materials in the volumes may be different and in one embodiment are of progressively decreasing melting temperatures from the first volume to the third volume. 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 contains silicon, which has a melting temperature of about 1410ºC, the second volume contains lithium fluoride, which has a melting temperature of about 870 ºC and the third volume contains magnesium oxide or calcite, which have a melting temperature of about 560 ºC. The volumes of material 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.

In another arrangement, the volumes of material may contain a mixture of two or more different materials. In one form, each volume of material comprises of 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. 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 to reach their melting temperatures more rapidly as well as improving the heat transfer from the volumes of material to the working fluid. This in turn enables faster start-up and shut down of the system.

The working fluid flows counter-currently to the heating fluid, entering the heater through the inlet to be heated firstly by "the lowest temperature volumes of material, in this case the third volume, and finally by the highest temperature volumes of material, in this case the first volume before exiting to the inlet of the expander. The heating fluid heats the volumes in reverse order, that is, it enters the heater through inlet to heat the first volume, which is required to be at the highest temperature, first and heats the third volume last. In another example, the material in each or two of the volumes is the same. In this example, 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, it loses energy and heat as it flows through the volumes. Thus, the volumes may need to be heated in parallel or alternatively by a different source of heat.

The heater also comprises of 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 phase change materials in the volumes so as to keep them in a molten phase and to control the temperature of the working fluid as it leaves the heater.

The flow rate of the working fluid is also controlled with respect to its temperature at the outlet of the heater (i.e. the inlet to the expander).

The temperature of the working fluid required at the inlet of the expander is much less than the melting temperature of silicon (and hence the temperature of the first volume). If the working fluid at the inlet of the expander was at this temperature (approximately 1410ºC)

then this could cause damage to the expander. Because of this large temperature difference, the heater advantageously enables “quick start-up” of the heat engine system.

The expander inlet temperatures can be varied and controlled by a modulating bypass control valve that diverts flow around the regenerative heater. 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.

The method of the invention is illustrated in Figure 2 as a group of numbered boxes. The steps of the method as shown by the numbered boxes may occur both sequentially and in parallel. The numbers of the boxes indicate the different steps and are not intended to show a specific sequence that must be followed. The succession of one step to the next is illustrated by the arrows connecting the boxes. Since the method involves a cyclic regeneration of the components, it will be understood that the method may commence at any one of the illustrated steps and continue through the sequence of steps. Box 1a shows that in one step, liquid water is pressurized to a working pressure. Box 2 shows that the pressurised water is boiled, preferably in a recuperator. Box 3b shows that the steam created at the step in box 2 is subsequently diffused into a compressed gas stream in a next step. Box 1b shows that in another step, first and second components are compressed to a working pressure. Box 3a shows that vapour is diffused into the stream of compressed components. The outputs of box 3 and box 3a are combined in box 4a. In a step as shown in box 5, the compressed gases are heated at constant pressure, preferably in a recuperator. In a step as shown in box 6, the compressed gases are superheated at constant pressure. In a next step as shown in box 7, the hot gases are expanded to produce work, as indicated by G. In a step as shown in box 8, the expanded gases are cooled at constant pressure, preferably in a recuperator. In a step as shown in box 9, the gases are cooled further at constant pressure, preferably in a recuperator. In a step as shown in box 1c, the expanded gases are cooled further and water is condensed at constant pressure. In a step shown at box 10, the recycled fluid is removed. The cycle of steps then may repeat to create a continuous output of work at G.

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 of" or "comprising" is used in an inclusive sense, i.e. to specify the presence of the stated features but not to preclude the presence or addition of further features in the invention.

We claim:

1. A heat engine system for producing work comprising of:

a working fluid comprising of a gaseous first component and a second component;

apparatus for combining the second component of said working fluid as a liquid with said first component;

a compressor for compressing said first component;

a pump for compressing at least most of the second component;

a heater for heating said first and second components;

an expander for expanding said first and second components to produce work; and

at least two recuperators for transferring at least a portion of the energy of the working fluid from the outlet of the expander, to the working fluid from the outlet and inlet of the apparatus,

wherein a substantial portion of the energy transferred in said recuperators is at least a portion of the latent heat of said second component from the outlet of said expander.

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

3. A heat engine system as claimed in claim 1, wherein said apparatus is arranged to diffuse said first component into said 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 preceding claim, wherein said recuperators are in the form of a falling film condenser.

6. A heat engine system as claimed in any preceding claim, wherein said recuperators are arranged to provide separation of a liquid fraction of said working fluid from a gaseous fraction upon cooling of said working fluid from the outlet of said expander.

7. A heat engine system as claimed in any preceding claim, further comprising of at least one cooler for cooling said first and/or second components prior to combining them in said apparatus.

8. A heat engine system as claimed in claim 7, wherein at least one of said coolers comprises of 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 of 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 of 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 one or at least one cooler comprises of 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 pressurises at least most of said second component in liquid form to a pressure above the ambient pressure.

13. A heat engine system as claimed in any preceding claim, wherein said pump pressurises 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 of 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 control1ing 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 of 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 method for producing work comprising of the steps of:

(a) compressing a gaseous first component of a working fluid;

(b) pressurising at least most of a liquid second component of said working fluid;

(c) combining said second component and said first component;

(d) heating said combined first and second components;

(e) expanding the heated first and second components to produce work; and

(f) transferring at least some of the energy of said working fluid after it has been expanded to the working fluid prior to it being heated,

wherein a substantial portion of the energy transferred is at least a portion of the latent heat of said second component after the working fluid has been expanded and transferring at least some of the energy of the working fluid after it has been expanded to the second fluid prior to it being injected into an apparatus.

22. The method of claim 21 wherein the step of transferring at least some of the energy converts at least some of said second component from liquid to gas prior to being injected into the apparatus.

23. The method as claimed in either one of claims 21 or 22, wherein the step of transferring at least some of the energy converts at least some of said second component from gas to liquid after it has been expanded.

24. The method of claims 21 to 23, wherein the method is a closed cycle method further 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 to the working fluid before heating.

25. The method of claims 21 to 24, the method further comprising of the step of returning said first component to a compressor.

26. The method of claims 21 to 25 the method further comprising of the step of returning at least most of said second component to a pump.

27. The method of claims 21 to 26, the method further comprising of the step of cooling said first and/or second components prior to combining them.

Fig. 1

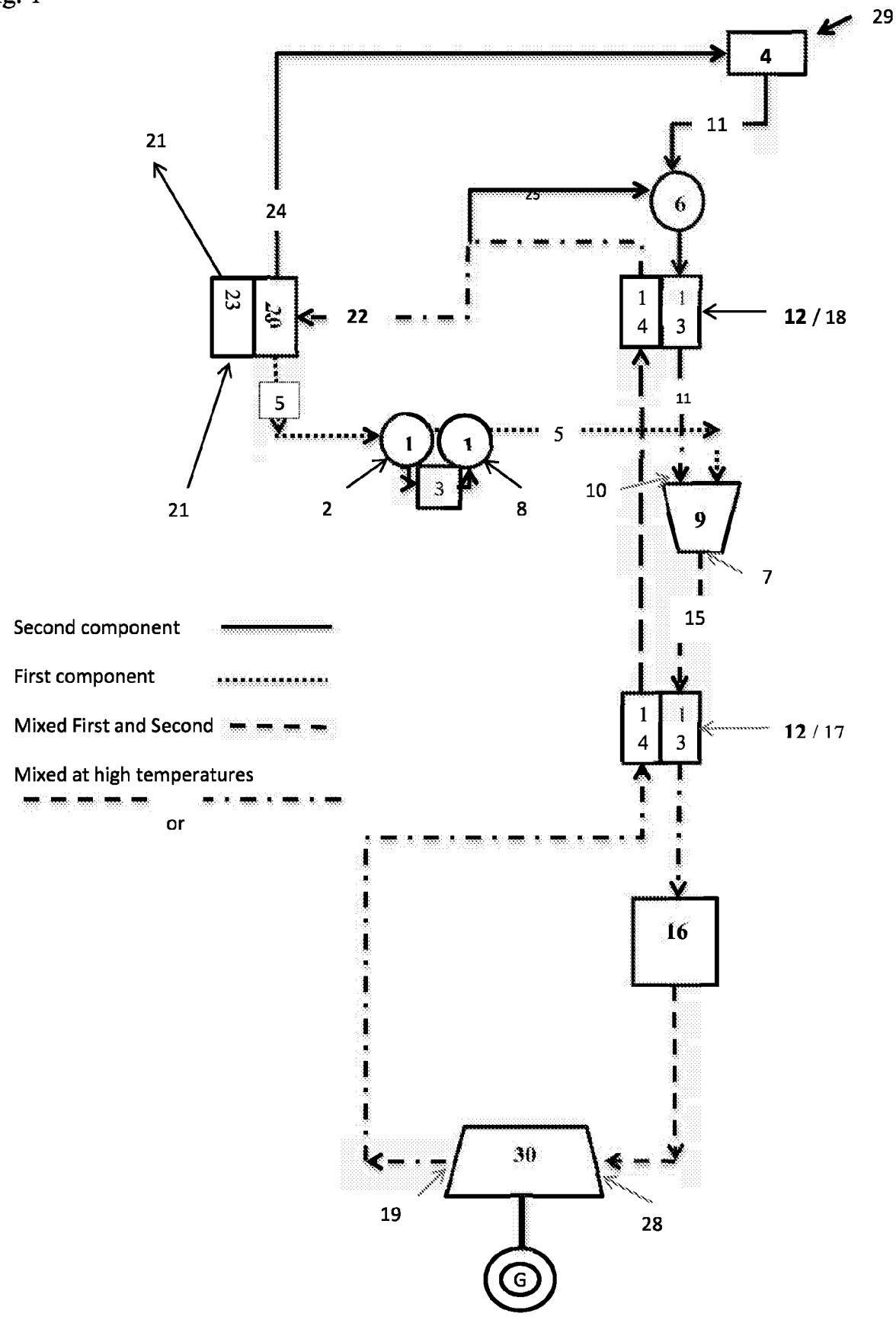
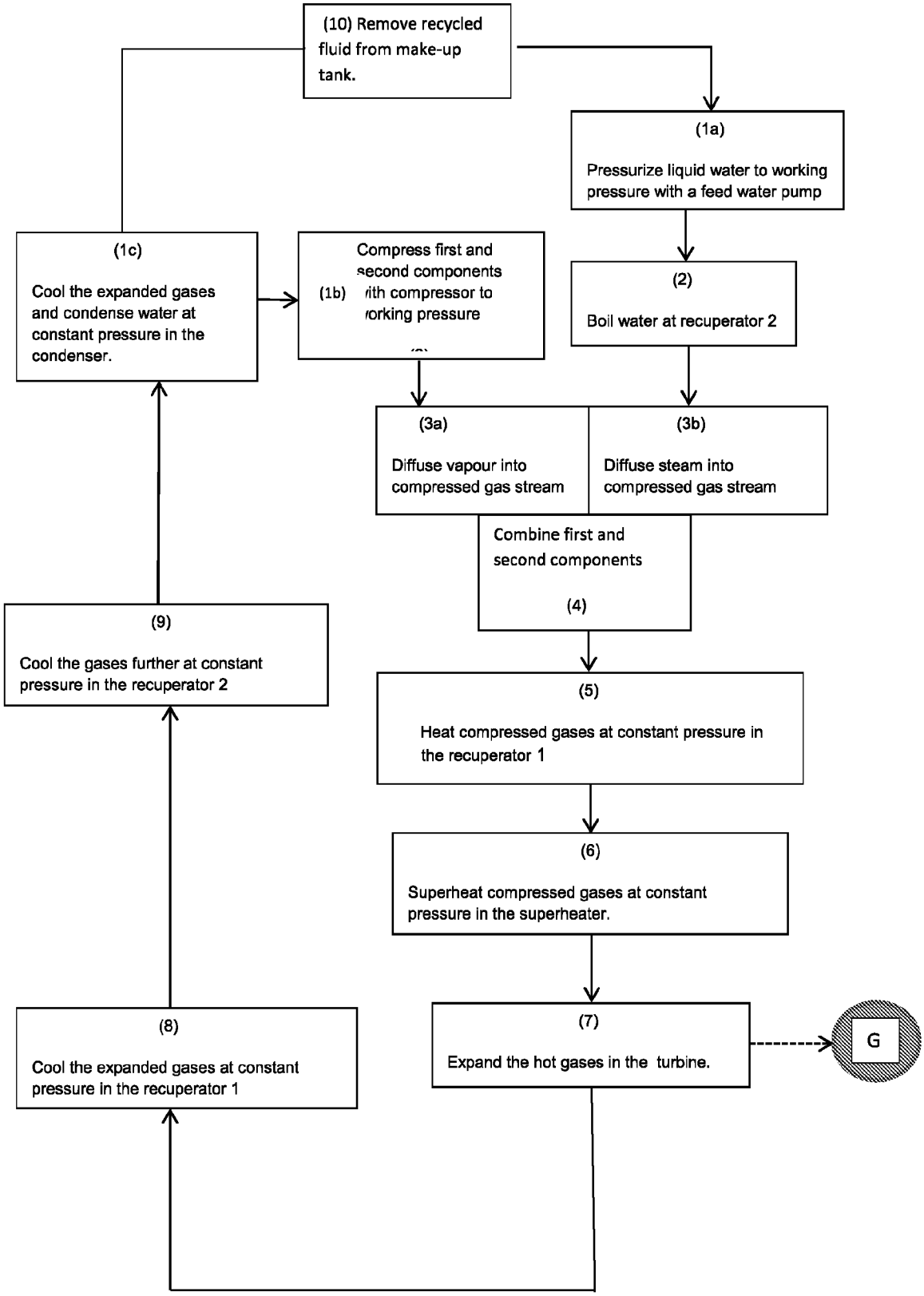

29
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21
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23
20
22
14
13
12 / 18
5
11
1
1
5
21
2
3
8
10
9
7
15
Second component
First component
Mixed First and Second
Mixed at high temperatures
or
14
13
12 / 17
16
30
19
28
G

Fig. 2


(10) Remove recycled fluid from make-up tank.
(1a)
Pressurize liquid water to working pressure with a feed water pump
(1c)
Cool the expanded gases and condense water at constant pressure in the condenser.
(1b)
Compress first and second components with compressor to working pressure
(2)
Boil water at recuperator 2
(3a)
Diffuse vapour into compressed gas stream
(3b)
Diffuse steam into compressed gas stream
Combine first and second components
(4)
(9)
Cool the gases further at constant pressure in the recuperator 2
(5)
Heat compressed gases at constant pressure in the recuperator 1
(6)
Superheat compressed gases at constant pressure in the superheater.
(8)
Cool the expanded gases at constant pressure in the recuperator 1
(7)
Expand the hot gases in the turbine.
G