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(54) **Title:** LIQUID FLOODED CLOSED CYCLE

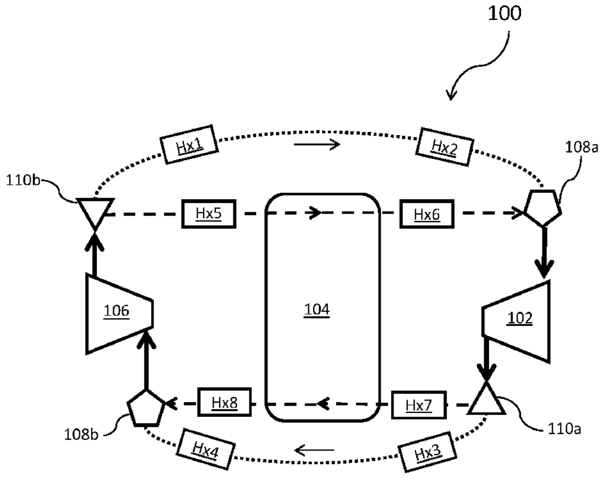

FIG. 1

(57) **Abstract:** A thermodynamic system including a compressor for compressing a liquid-gas mixture, an expander for expanding a liquid-gas mixture, first and second liquid-gas mixers, first and second liquid-gas separators, and a liquid recuperator. The first and second liquid-gas mixers are in fluid communication with the compressor and expander, and mixes liquid and gas into a liquid-gas mixture prior to or during compression and expansion, respectively. The first and second liquid-gas separators are in fluid communication with the compressor and expander, and separates gas from liquid after compression and expansion, respectively. The liquid recuperator is in fluid communication with the compressor and expander, and transfers heat between liquid received from the compressor and liquid received from the expander. The liquid moves in a closed liquid cycle. The gas moves in a closed gas cycle and does not undergo recuperation.

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LIQUID FLOODED CLOSED CYCLE

TECHNICAL FIELD

[001] The present invention relates to thermodynamic systems, and in particular to a liquid flooded closed cycle thermodynamic system.

BACKGROUND

[002] A thermodynamic cycle consists of a linked sequence of thermodynamic processes that involve transfer of heat and work into and out of the system, while varying pressure, temperature and other state variables within the system, and that eventually returns the system to its initial state. In the process of passing through a cycle, the working fluid (system) may convert heat from a warm source into useful work and dispose of the remaining heat to a cold sink, thereby acting as a heat engine. Conversely, the cycle may be reversed and use work to move heat from a cold source and transfer it to a warm sink thereby acting as a heat pump. At every point in the idealized cycle, the system is in thermodynamic equilibrium, so the cycle is reversible (its entropy change is zero, as entropy is a state function).

[003] There are many different types of thermodynamic cycles that have been known for a long time, such as the Brayton Cycle or the Ericsson Cycle, which can operate as engines or refrigerators. The Ericsson cycle is attractive since it can theoretically operate at the Carnot efficiency, which is the maximum possible efficiency for a heat engine or refrigerator. Brayton cycle devices, such as gas turbine engines and Brayton cycle cryocoolers have achieved widespread commercial use. However, Ericsson cycle devices have not achieved widespread commercial success.

[004] A principal difficulty of implementing a practical device that operates in a manner substantially similar to the Ericsson cycle is the requirement for isothermal or near isothermal compression and expansion of the working fluid. Various attempts have been devised to overcome the challenge of effective heat addition during the expansion processes and heat expulsion during the compression process. For example, one such attempt is described by J. Hugenroth et. al. in "Liquid-Flooded Ericsson Cycle Cooler: Part 1 – Thermodynamic Analysis" (2006). International Refrigeration and Air Conditioning

Conference. Paper 823. Their approach describes a Liquid Flooded Ericsson Cooler (LFEC), which is essentially a modification of the basic reverse Ericsson cycle that addresses the practical difficulties of achieving isothermal compression and expansion processes by mixing a nonvolatile liquid with the non-condensable gas during the compression and expansion processes. The term “flooded” comes from the notion that the compressor and expander are flooded with large quantities of liquid. Liquid mass flow rates may be significantly greater than gas flow rates. If the liquid’s capacitance rate (liquid specific heat times the liquid mass flow rate) is much greater than the gas’ capacitance rate most of the heat of compression of the gas can be absorbed by the liquid. In the limiting case where the ratio of liquid to gas capacitance rate is infinite and perfect thermal contact between the gas and the liquid are assumed, isothermal compression and expansion will be achieved. As with the basic Ericsson cycle, the Coefficient of Performance (COP) for the ideal LFEC is the Carnot COP. Other, similar approaches are described, for example, in U.S. Patent Nos. 7,401,475 and 9,482,450, and by B. Woodland et al. in "Performance Benefits for Organic Rankine Cycles with Flooded Expansion" (2010). Publications of the Ray W. Herrick Laboratories. Paper 5. All of these publications are incorporated herein by reference.

[005] While the LFEC provides improvements to existing cycles, there are still several factors prevent the LFEC from operating in the ideal sense. For example, finite capacitance rates lead to non-isothermal compression and expansion, which results in heat transfer irreversibilities in the external heat exchangers required for the cycle. Additional irreversibilities arise due to imperfect thermal contact between the liquid and the gas during the compression and expansion processes, which implies irreversible heat transfer. Further, as with all gas cycles, the flooded Ericsson cycle is very sensitive to inefficiencies that exist in real compressors and expanders. Thus, there is room for novel and improved thermodynamic systems.

SUMMARY

[006] According to a first aspect, the invention relates to a thermodynamic system. The thermodynamic system comprises:

- a compressor configured to compress a liquid-gas mixture;

- an expander configured to expand the liquid-gas mixture;
- a first liquid-gas mixer in fluid communication with the compressor and expander, configured to mix liquid and gas into a liquid-gas mixture prior to or during compression;
- a second liquid-gas mixer in fluid communication with the compressor and expander, configured to mix liquid and gas into a liquid-gas mixture prior to or during expansion;
- a first liquid-gas separator in fluid communication with the compressor and expander, configured to separate gas from liquid after compression;
- a second liquid-gas separator in fluid communication with the compressor and expander, configured to separate gas from liquid after expansion; and
- a liquid recuperator in fluid communication with the compressor and expander, configured to transfer heat between liquid received from the compressor and liquid received from the expander;
- wherein the gas moves in a closed gas cycle, the liquid moves in a closed liquid cycle, and the gas does not undergo recuperation.

[007] This novel thermodynamic system is based on the insight that the benefits associated with the liquid flooding of an LEFC system can be further enhanced by recuperating only the liquid and not the gas. As a result, a thermodynamic cycle can be designed, which is much more efficient than current thermodynamic systems and which can be used in a wide range of applications, both as a heat engine and as a heat pump, respectively. As a heat engine, the system can convert heat into shaft power, typically to a generator. It can also be used for medium and low-grade waste heat to power systems. The heat sources can be essentially any known or future heat external heat source applied to the system. The heat can be applied, for example, through heat exchangers to the gas or liquid, or to the exterior of the expander. Cooling can be similarly applied to the compressor side of the cycle elements, i.e., through heat exchangers to the gas or liquid, or to the exterior of the compressor. When the thermodynamic system is operated as a heat pump, temperatures can be reached that are well above the maximum temperatures of current vapor compression cycles.

[008] According to one embodiment, the thermodynamic system includes at least one heat exchanger configured to expel heat from at least one of the gas, the liquid, and the liquid-gas mixture, prior to or after expansion, prior to or after compression. The heat exchangers make it possible to expel heat to the surroundings and/or to other external systems. In most cases, the main portion of the heat is expelled through the liquid heat exchanger. However, by having separate heat exchangers for the gas and the liquid, respectively, it is possible to tune the cycle to optimize the heat expulsion for particular applications, making the system more versatile for different uses. In some cases, it may also be advantageous to have a heat exchanger that uses the mixed gas and liquid. The placement of the heat exchangers may also vary, such that they may be located prior to or after the compressor. In some embodiments they can be located prior to the separator, and in other embodiments they can be located after the separator. This variable configuration allows for a wide range of options to fine tune the system for particular applications.

[009] According to one embodiment, the thermodynamic system includes at least one heat exchanger configured to expel heat from at least one of the gas, the liquid, and the liquid-gas mixture, prior to or after expansion. This results in similar advantages to those discussed in the previous paragraph.

[0010] According to one embodiment, the compressor and the expander are configured to operate at different mass flow rates. Having the ability to operate the compressor and expander at different mass flow rates makes it possible to adjust the mass flow rates based on the temperature of the compressor and expander, respectively, and thus the density of the compression and expander fluids. This makes it possible to match desired compression or expansion ratios, and thus avoid over- or under compression in the system.

[0011] According to one embodiment, the compressor and the expander are configured to drive by independent drives. This enables easy and precise individual control of the drive for each of the compressor and expander, such that the RPM (and thereby the mass flow) can be individually controlled for the compressor and expander, respectively.

[0012] According to one embodiment, the compressor and the expander are configured to be driven by the same drive, and wherein at least one of the compressor and expander comprises variable transmission means. Numerous continuous variable transmission systems are known in the art and can be integrated with the system of the invention. Having only one drive simplifies the control and complexity/cost of the system compared to a setup using individual drives for the compressor and expander, respectively.

[0013] According to one embodiment, wherein one or more of the following parameters are variable to achieve a closed optimum cycle operation: the ratio of mass of gas to the mass of liquid in the liquid-gas mixture, the mechanical volume ratio of at least one of the compressor and the expander, and the mass flow rate of at least one of the compressor and the expander. Given the large number of applications in which the system in accordance with the invention can be used, it is important to be able to optimize the system to ensure best performance. Varying the ratio of the mass of gas to the mass of liquid makes it possible to adjust how much heat is removed from the compressor and expander after compression and expansion, respectively, as the liquid generally serves as the main means for removing or adding heat. Adjusting the mechanical volume ratio, typically by mechanical means, can be used to avoid over- and under compression or expansion, respectively, thereby improving the efficiency of the cycle. Changing the mass flow rate, i.e., the combined mass of gas and liquid of the cycle can be used to affect the overall power of the system.

[0014] According to one embodiment, the thermodynamic system operates in a forward sense so that a net power output is achieved. Similar to conventional cycles, operating the system in a forward sense to achieve a net power output makes the system versatile for a wide range of practical applications, such as waste heat to power, micro-Concentrated Solar Power systems, and external heat engine electrical generators.

[0015] According to one embodiment, the thermodynamic system operates in a reverse sense so that a heat pump effect is achieved. Similar to conventional cycles, operating the system in a reverse sense to achieve a heat pump flow with net power input makes the system versatile for a wide range of practical applications, refrigeration systems, coolers, high temperature heat pumps, steam generators.

[0016] According to one embodiment, the compressor is a closed compressor. A closed compressor refers to a compressor where the compression takes place within the volume, isolated by valves or other means. Closed compressors are common in the art, which makes it easy to build the system using conventional components.

[0017] According to one embodiment, the closed compressor is one of: a scroll compressor, a screw compressor, and a piston compressor. All of these are various types of closed compressors that are familiar to those having ordinary skill in the art, thus facilitating integration of the inventive system into practical applications, without any need for specialized compressor components.

[0018] According to one embodiment, the expander is a closed expander. Similar to closed compressors, a closed expander refers to an expander in which the expansion takes place within the volume, isolated by valves or other means. Closed expanders are common in the art, which makes it easy to build the system using conventional components.

[0019] According to one embodiment, the closed expander is one of: a scroll expander, a screw expander, and a piston expander. Again, all of these are various types of closed expanders that are familiar to those having ordinary skill in the art, thus facilitating integration of the inventive system into practical applications, without any need for specialized expander components.

[0020] According to one embodiment, the compressor is an open compressor. An open compressor refers to a compressor that compresses its volume and that is open to the low pressure side of the cycle. In this way, the pressure ratio is maintained by the respective fluid (gas/liquid) mass being transferred and compressed and that being expanded and transferred. A major advantage of this type of compression, such as is used in the FeTu compressor, is that there are no valves, meaning volumetric efficiency is maximized with minimal flow restriction, and fewer mechanical parts, which lowers the risk of mechanical problems.

[0021] According to one embodiment, the expander is an open expander. Similar to open compressors, an open expander refers to an expander that expands its volume and that is open to the high pressure side of the cycle, again to maintain the pressure ratio by the respective fluid (gas/liquid) mass being transferred and expanded and that being compressed and transferred. Similar advantages are associated with open expanders as with the open compressors discussed above.

[0022] The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description below. Other features and advantages of the invention will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] FIG. 1 is a schematic diagram showing a thermodynamic system 100, in accordance with one embodiment.

[0024] FIG. 2 is a schematic diagram showing a thermal energy storage system 200, in which the thermodynamic system 100 of FIG. 1 is incorporated, in accordance with one embodiment.

[0025] FIG. 3 is a schematic diagram showing a ground source heat pump 300, in which the thermodynamic system 100 of FIG. 1 is incorporated, in accordance with one embodiment.

[0026] Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

Overview

[0027] As was described above, a goal with the various embodiments of the invention is to provide a new thermodynamic system with improved efficiency compared to existing systems. This is accomplished, at least in part, by a thermodynamic system that uses the general concept of liquid flooding, similar to what is described in the LFEC system above. The system has a closed gas cycle and a closed liquid cycle. However, in contrast to the LFEC system, in the inventive system, only the liquid cycle undergoes recuperation, and the gas cycle does not have any recuperation. This thermodynamic system, in various embodiments lends itself very well to different types of heat engine and heat pump applications, respectively.

[0028] *Heat Engine* - The system can operate as an external heat engine converting heat into shaft power, typically to a generator. The heat sources can be essentially any known or future heat external heat source applied to the system. The heat can be applied, for example, through heat exchangers to the gas or liquid, or to the exterior of the expander. Cooling can be similarly applied to the elements on the compressor side of the system, for example, through heat exchangers to the gas or liquid, or to the exterior of the compressor. The advantage of using external heat is that any heat source can be used, in contrast to internal combustion where the process is much more complicated. Various implementations of heat engines will be described in further detail below with reference to specific applications.

[0029] *Heat Pump* – The system can also operate in the reverse direction of the heat engine, and in a fashion similar to the reverse Ericsson cycle. In this mode of operation, the expander takes in heat and the compressor expels heat. When the thermodynamic system is operated as a heat pump, it can operate down to cryogenic temperatures yet temperatures can also be reached that are well above the maximum temperatures of current vapor compression cycles (max of approximately 150 degrees Celsius). The maximum cycle temperature is typically limited by the materials of the compressor and expanders (bearings, seals, metals, etc.) and the temperatures of the flooding liquid. For high temperature applications, the flooding liquid can be, for example, thermal oils of concentrated solar power systems, which currently are able reach temperatures of up to approximately 600 degrees Celsius. Various implementations of heat pump applications will be described in further detail below with reference to specific applications.

[0030] FIG. 1 shows a schematic diagram of a thermodynamic system 100 in accordance with one embodiment of the invention. The thermodynamic system 100 will be referred to interchangeably as “system” or “cycle” herein. As can be seen in FIG. 1, the thermodynamic system 100 includes a closed gas cycle (outer loop, formed by components 102, 110a, Hx3, Hx4, 108b, 106, 110b, Hx1, Hx2 and 108a) and a closed liquid cycle (inner loop, formed by components 102, 110a, Hx7, 104, Hx8, 108b, 106, 110b, Hx5, Hx6 and 108a). As was mentioned above, the cycle 100 includes a compressor 102, an expander 104, a liquid recuperator 106. In the embodiment shown in FIG. 1, there are also two liquid-gas mixers 108a-b, and two liquid-gas separators 110a-b. FIG. 1 further shows several heat exchangers, labeled Hx1 through Hx8.

[0031] The flooding liquid can be essentially any type of high heat capacity liquid, such as Duratherm LT, OmniSol, and even water or glycol, depending on application. In principle, the main limitations on the types of liquids that can be used are set by the liquid's freezing/boiling points, such that they remain in liquid phase throughout the cycle. In some embodiments, the flooding liquid can also serve the purpose of assisting sealing in clearance seals, lubricate bearings, lubrication seals, etc. As will be described in further detail below, the flooding liquid may also be used as a heat transfer fluid in systems exterior to the cycle 100. Such exterior systems include solar collectors (trough or concentrated), waste heat sources, tubes or the like in water (or other liquid) tanks, battery thermal conditioning, electric motor, cooling, electronics cooling, jacket around combustion chambers, etc., just to mention a few examples.

[0032] The working gas can be any pure gas or any mixture of gases. Some examples include nitrogen, argon, xenon, helium, hydrogen, and air. Many combinations are familiar to those having ordinary skill in the art, and similar to the flooding liquid, the type of gas or the ratio of gases can be varied depending on the particular implementation and use case at hand.

[0033] The compressor 102 and expander 104 can be a closed compressor/expander or an open compressor/expander, respectively. A combination of a closed and open compressors/expanders can also be used. A closed compressor/expander refers to common compressors/expanders where the compression/expansion takes place within the volume, isolated by valves or other means. Some examples of closed compressors/expanders include scroll compressors/expanders, screw compressors/expanders, liquid ring compressors/expanders, all of which are well known and familiar to those having ordinary skill in the art.

[0034] An open compressor/expander refers to a compressor/expander that compresses/expands its volume and that is open to either the low/high pressure side of the cycle 100. In this way, the pressure ratio can be maintained by the respective fluid (gas/liquid) mass being transferred and compressed/expanded and that being expanded/compressed and transferred. This is essentially what a turbine system does and is also demonstrated by FeTu closed cycle system. This concept can be advantageously used in the closed cycle 100. The major advantage of this type of compression and expansion is that there are no valves, meaning volumetric efficiency is maximized with minimal flow restriction.

[0035] The liquid recuperator 106 is configured to transfer heat between the flooding liquid received from the compressor 102 and the flooding liquid received from the expander 104, such that heat does not go back from the compressor 102 to the expander 104, as will be described in further detail below. Liquid recuperators are well known to those having ordinary skill in the art, and in essence they work as counter flow heat exchangers. The liquid recuperator 106 of FIG. 1 is designed to accommodate a small amount of gas, as may be needed depending on the particular implementation at hand.

[0036] The liquid-gas mixers 108a-b mix the gas and liquid prior to compression in the compressor 102 or expansion in the expander 104. It should be noted that while the liquid-gas mixers 108a-b are shown as separate components, the mixing can actually occur in the compressor 102 or expander 104 itself. There are various ways to mix liquids and gas, such as pumping (e.g., by a gear or diaphragm type pump), wicking, or spraying the liquid into the gas at a predetermined rate and to get the proper mix between liquid and gas in the compressor 102 or expander 104, just to mention a few examples. Many others can be envisioned by those having ordinary skill in the art.

[0037] The liquid-gas separators 110a-b separate the liquid from the gas after the compressor 102 and the expander 104, respectively. The liquid-gas separators 110a-b can be specifically designed devices or can use simple gravity separation, in which the liquid drops down and the gas flows normally. This may mean that some amount of gas could enter the liquid recuperator 106, so the liquid recuperator 106 is designed to accommodate a small amount of gas. This system eliminates the complete separation of the gas-liquid required in prior art systems, where absolute minimum liquid may enter the gas recuperator.

[0038] The system 100 shown in FIG. 1 includes eight heat exchangers, labeled Hx1 through Hx8. However, it should be noted that in most implementations, only the heat exchangers needed for an optimum cycle in that particular implementation are present and used. It should also be noted that FIG. 1 merely shows one possible arrangement of liquid and gas heat exchangers for the heat pump and heat engine uses, and that heat exchangers can be located at different locations within the system. For example, a typical heat pump only includes heat exchangers Hx5, Hx6, Hx3, Hx7. Heat engines may have any combination of the heat exchangers as needed. The specific type of heat exchangers may also vary, and the system 100 can include heat exchangers of several types. Choices relating to the type, number and location of the heat exchangers generally depend on the particular use case at hand and can be made by a person having ordinary skill in the art.

[0039] As will be described in further detail below, the cycle can be that of a heat pump or external heat engine. For the heat pump, the expander is at a low temperature, with Hx1, Hx4, Hx5, Hx8 at the low temperature, and the compressor at a high temperature, with Hx2, Hx3, Hx6, and Hx7 at the high temperature. For an external heat engine, the low and high temperatures of the heat pump are swapped.

[0040] The system 100 has a high pressure side and low pressure side. The high pressure side is after compression and prior to expansion (i.e., components 110a, Hx7, 104, Hx8 and 108b for the liquid loop, and 110a, Hx3, Hx4 and 108b for the gas loop, respectively). The low pressure side is the upper section of FIG. 1, after expansion and prior to compression (i.e., components 110b, Hx5, 104, Hx6 and 108a for the liquid loop, and components 110b, Hx1, Hx2 and 108a for the gas loop, respectively). In some embodiments, small pumps (not shown) are also included in the system 100 to pump liquid out of the recuperator 106 to the compressor 102 or expander 104, respectively. These pumps can be, for example, gear pumps or similar.

[0041] In operation, a mixture of gas and flooding liquid is expanded in the expander 104 and proceeds to the liquid-gas separator 110b, where it is separated into a gas stream 17 and a liquid stream 8. The expansion lowers the temperature of the liquid and gas, so heat exchangers Hx5 and Hx1 will typically take in heat from the environment (or external system). The gas and liquid then continues in separate circuits to liquid-gas mixer 108a, where they are combined into a liquid-gas mix that enters the compressor 102. Compression makes the gas hotter, so the liquid-gas mix exiting the compressor 102 at 1 has a higher temperature. Similarly, a liquid-gas separator 110a separates the gas and liquid into two separate streams. Most of the expulsion of the heat occurs in heat exchanger Hx7 (liquid), but also in Hx3 (gas) if the cycle is optimized. That is, these heat exchangers expel heat to the environment (or an external system). The liquid recuperator 106 prevents heat from flowing back to the expander 104, and then the cycle repeats itself.

Example Applications

[0042] The system 100 is very scalable and can be used for applications that range in size from micro engines through industrial cooling units, or that ranges in thermal power from approximately 200W to 50kW. As such, the system 100 lends itself to a number of heat engine and/or heat pump applications, which will now be described in further detail.

Thermal Energy Storage

[0043] FIG. 2 shows a schematic diagram of a thermal energy storage system 200, in which the system 100 of FIG. 1 is used as a heat pump to upgrade heat from flat panel rooftop solar panels (typically about 50 degrees Celsius) to thermal salts for thermal energy storage (typically about 400 degrees Celsius).

[0044] In a conventional setup, there are typically three fluid loops:

1) A roof top solar thermal fluid (typically water with some kind of anti-freezing additive, such as glycol),

2) Heat pump loops of a vapor compression cycle, and

3) A hot fluid loop from the heat pump to the thermal salts.

[0045] Each of these fluid loops typically has its own pump, and there are heat exchangers between each loop, incurring approximately a 10% loss of heat between each loop.

[0046] In contrast, the thermal energy storage system 200 of FIG. 2 only requires a single fluid, a single pump, and no heat exchangers to transfer heat between different loops. As can be seen in FIG. 2, in the system 200, heat exchangers Hx5 and Hx8 form part of solar thermal collectors 205, where heat is absorbed into the liquid of the system 200, and subsequently released through heat exchangers Hx6 and Hx7 inside a thermal energy storage 210. The simplified design of the system 200 allows for reduced costs associated with manufacturing, installation, repair, etc. Further, it avoids losses associated with heat exchangers, and thereby produces a better efficiency compared to conventional systems.

Ground Source Heat Pump

[0047] FIG. 3 shows a schematic diagram of a ground source heat pump 300, in which the system 100 of FIG. 1 is used to upgrade the temperature of a ground loop fluid to a hot water tank. As can be seen in FIG. 3, in the system 300, heat exchangers Hx5 and Hx8 form part of ground loop 302, where hoses or other conduits are placed in the ground and heat is absorbed into the liquid of the system 300. The heat absorbed by the liquid is subsequently released through heat exchangers Hx6 and Hx7 inside the hot water tank. Glycol or similar fluids are commonly used for ground source heat pumps, so this fluid can also serve as the liquid flooding fluid in the system 300. Similar to the thermal energy storage system 200 discussed above, the ground source heat pump in accordance with this invention eliminates two pumps and two heat exchangers, and carries many of the same benefits that were discussed above. Further, the inventive ground source heat pump 300 also eliminates the HFC/CFC greenhouse gas that is used in most conventional vapor compression heat pumps, and therefore also provides a much more environmentally friendly alternative to most existing systems.

Electrical Vehicle Heat Pump

[0048] In this application, the cycle 100 can be used as a heat pump for cooling and heating of an electrical vehicle (EV). Pre-heating the battery and cabin heating are two significant draws/issues with batteries of an EV. The heat pump described herein can alleviate many of these issues. For example, the cycle 100 can operate as a heat pump using ambient air to preheat batteries of the EV. The cycle 100 can use the same flooding liquid, typically glycol, that is used for battery heating/cooling in the EV. Similarly, the cycle 100 can operate as a heat pump to heat the cabin of the EV, by drawing heat from ambient air, battery and/or motor-generator/electronics cooling. The cycle 100 can also operate as a heat pump to cool the motor-generator and battery in the EV by pumping heat from these elements into the ambient air.

Thermal Energy Storage and Power

[0049] This application combines a heat engine and a heat pump, either as two units or as a reversible unit (since the cycle and the components are reversible). In this application, the heat pump upgrade solar thermal to the Thermal Storage Salts to store the solar energy, similar to what was described above. Then, to convert the stored heat to electricity, the system 100 operates as a heat engine, taking the fluid from the thermal storage salts to the heat engine, and then to the cool side, typically a hot water heater or other use for the heat (with a temperature of approximately 90 degrees Celsius).

Tuning cycle

[0050] Variable compression and expansion ratios (coupled Compressor, Expander or independent), and variable gas-liquid ratio can be used to tune the cycle 100 to various conditions and/or system needs. This is addition to the revolutions per minute (RPM) of the compressor and expander. In some embodiments, the RPM of the compressor and expander are the same, in other embodiments the RPMs are independent of one another.

[0051] In order to optimize the cycle 100 for various conditions and system demands, one or more of the following parameters can be adjusted:

[0052] *System pressure* – adjusting the gas pressure, as is well known with Stirling systems, will vary the power density of the system 100.

[0053] *Overall system RPM* – adjusting the overall system RPM this will vary the mass flow (combined liquid and gas) and thus the system power.

[0054] *Mass ratio of gas to liquid* - Since the liquid is essentially incompressible, the liquid in the compressor or expander effectively changes the maximum gas volume and thus the volume ratio (since the same mechanical volumetric change is taking place). This can be accomplished, for example, with a reservoir of fluid pumped into or removed from the cycle as needed. The change in effective volume ratio with liquid flooding is detailed in the literature incorporated by reference above, describing the LFEC.

[0055] *Volume ratio* – adjusting the volume ratio (compression ratio and/or expansion ratio) by mechanical means, such as is known in piston engines, varying the inlet/exit port exposure time, etc., changes the volume ratio and can be used to avoid over/under compression/expansion, thereby improving the efficiency of the cycle 100.

[0056] Further, while generally the compressor 102 and expander 104 are driven through the same drive system and at the same RPM, in some embodiments, the respective RPMs of the compressor 102 and expander 104 can be varied. This can be accomplished by mechanical means, such as one or both having a variable drive system (there are numerous continuously variable drive systems), or the compressor 102 and expander 104 can each be driving independently by their own motor (generator or motor-generator). Having independent RPMs is useful when tuning the system to various conditions. The respective volumes of the compressor 102 and expander 104 for the cycle 100 are determined by the nominal temperatures of the heat source and heat sink (as is done in Ericsson and Stirling cycles). And change in these would result in off optimum operation.

[0057] By allowing independent RPMs, the mass flows of the compressor 102 and expander 104 can be matched with the temperature changes and thus the density of the compressor and expander fluids. The adjusting of the volume ratios can then be used to match the desired compression or expansion ratios and avoid over/under compression. The volume ratio can be adjusted for one or both of the compressor 102 and expander 104. The varying of the liquid flooding ratios may also be used to affect the volume ratios.

[0058] In this way the system 100 can be tuned for a wide variety of heat sink and heat source temperatures. This is be useful, for example, in an Air Source Heat Pump (ASHP) application where the outside ambient air temperature varies. Or for the desired ASHP outlet temperature. As the skilled person realizes, this concept can also be applied to other cycle applications, both as a heat pump and heat engine.

Concluding comments

[0059] It will be appreciated that a person skilled in the art can modify the above-described embodiments in many ways and still use the advantages of the invention as shown in the embodiments above.

[0060] Thus, the invention should not be limited to the shown embodiments but should only be defined by the appended claims. Additionally, as the skilled person understands, the shown embodiments may be combined.

CLAIMS

What is claimed is:

1. A thermodynamic system, comprising:

a compressor configured to compress a liquid-gas mixture;

an expander configured to expand the liquid-gas mixture;

a first liquid-gas mixer in fluid communication with the compressor and expander, configured to mix liquid and gas into a liquid-gas mixture prior to or during compression;

a second liquid-gas mixer in fluid communication with the compressor and expander, configured to mix liquid and gas into a liquid-gas mixture prior to or during expansion;

a first liquid-gas separator in fluid communication with the compressor and expander, configured to separate gas from liquid after compression;

a second liquid-gas separator in fluid communication with the compressor and expander, configured to separate gas from liquid after expansion; and

a liquid recuperator in fluid communication with the compressor and expander, configured to transfer heat between liquid received from the compressor and liquid received from the expander;

wherein the gas moves in a closed gas cycle, the liquid moves in a closed liquid cycle, and the gas does not undergo recuperation.

2. The thermodynamic system of claim 1, further comprising at least one heat exchanger configured to expel heat from at least one of the gas, the liquid, and the liquid-gas mixture, prior to or after compression.

3. The thermodynamic system of claim 1, further comprising at least one heat exchanger configured to expel heat from at least one of the gas, the liquid, and the liquid-gas mixture, prior to or after expansion.

4. The thermodynamic system of claim 1, wherein the compressor and the expander are configured to operate at different mass flow rates.

5. The thermodynamic system of claim 4, wherein the compressor and the expander are configured to drive by independent drives.

6. The thermodynamic system of claim 4, wherein the compressor and the expander are configured to be driven by the same drive, and wherein at least one of the compressor and expander comprises variable transmission means.

7. The thermodynamic system of claim 1, wherein one or more of the following parameters are variable to achieve a closed optimum cycle operation:

the ratio of mass of gas to the mass of liquid in the liquid-gas mixture,

the mechanical volume ratio of at least one of the compressor and the expander, and

the mass flow rate of at least one of the compressor and the expander.

8. The thermodynamic system of claim 1, operating in a forward sense so that a net power output is achieved.

9. The thermodynamic system of claim 1, operating in a reverse sense so that a heat pump effect is achieved.

10. The thermodynamic system of claim 1, wherein the compressor is a closed compressor.

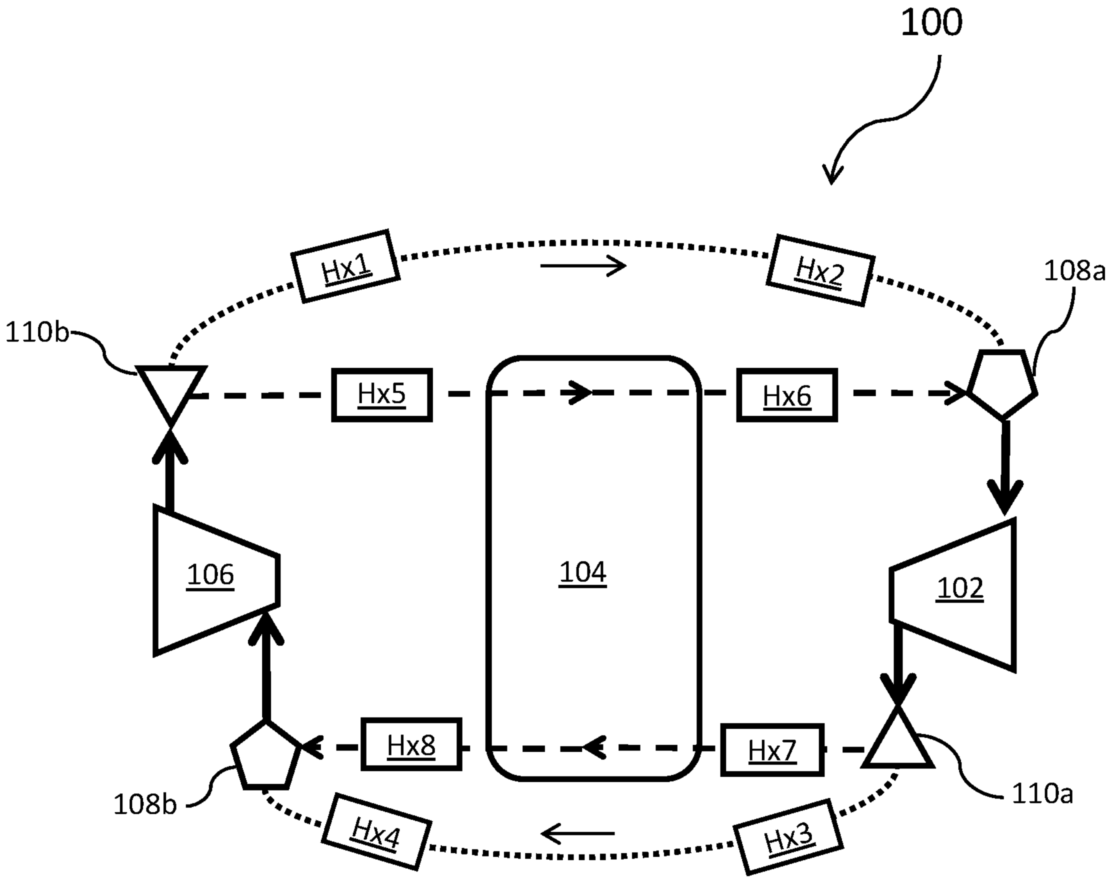
11. The thermodynamic system of claim 10, wherein the closed compressor is one of: a scroll compressor, a screw compressor, and a piston compressor.

12. The thermodynamic system of claim 1, wherein the expander is a closed expander.

13. The thermodynamic system of claim 12, wherein the closed expander is one of: a scroll expander, a screw expander, and a piston expander.

14. The thermodynamic system of claim 1, wherein the compressor is an open compressor.

15. The thermodynamic system of claim 1, wherein the expander is an open expander.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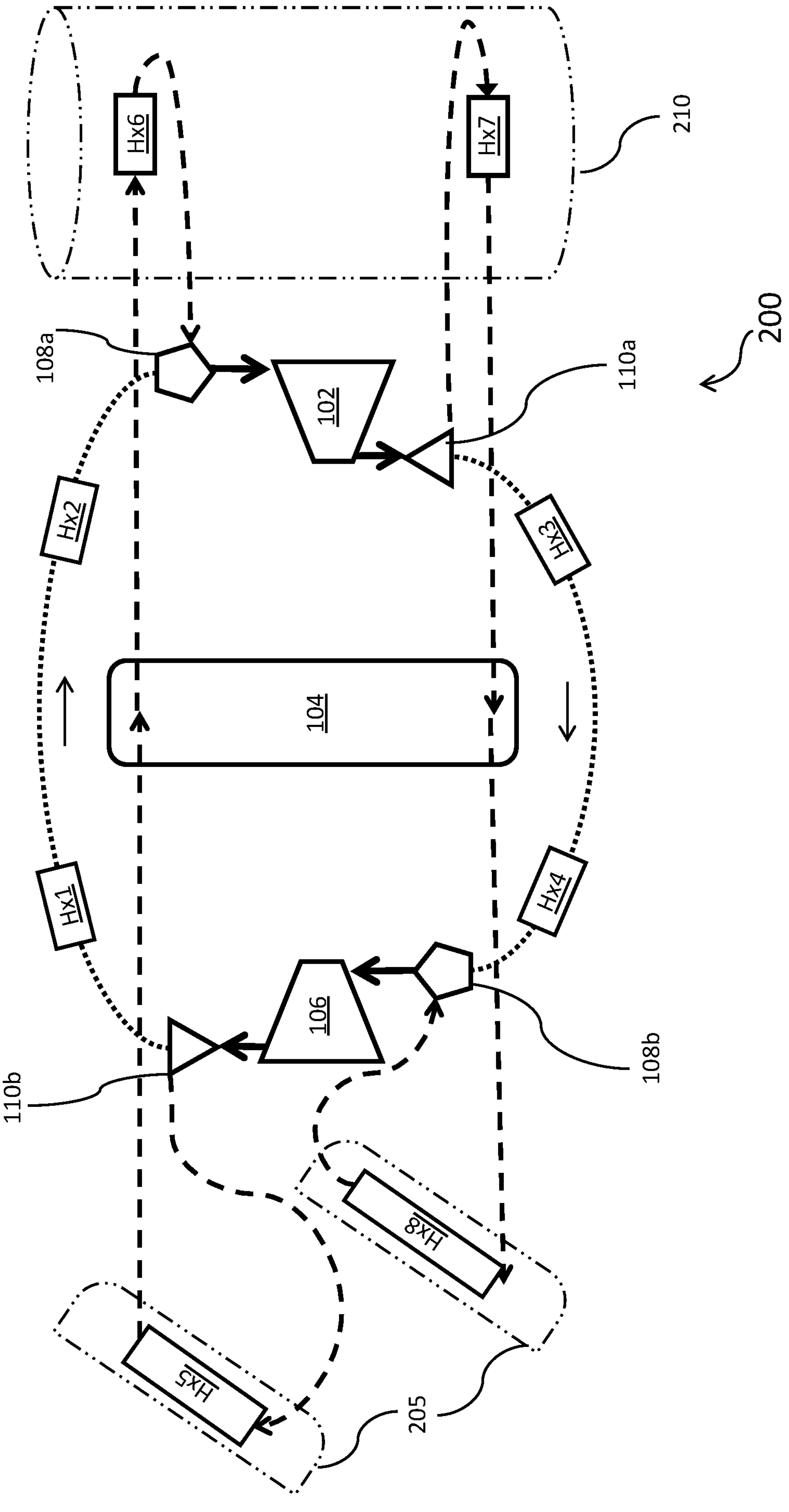
Hx5
Hx6
106
104
102
Hx8
Hx7
108b
110a
Hx4
Hx3

FIG. 1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Hx3
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Hx1
Hx4
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110b
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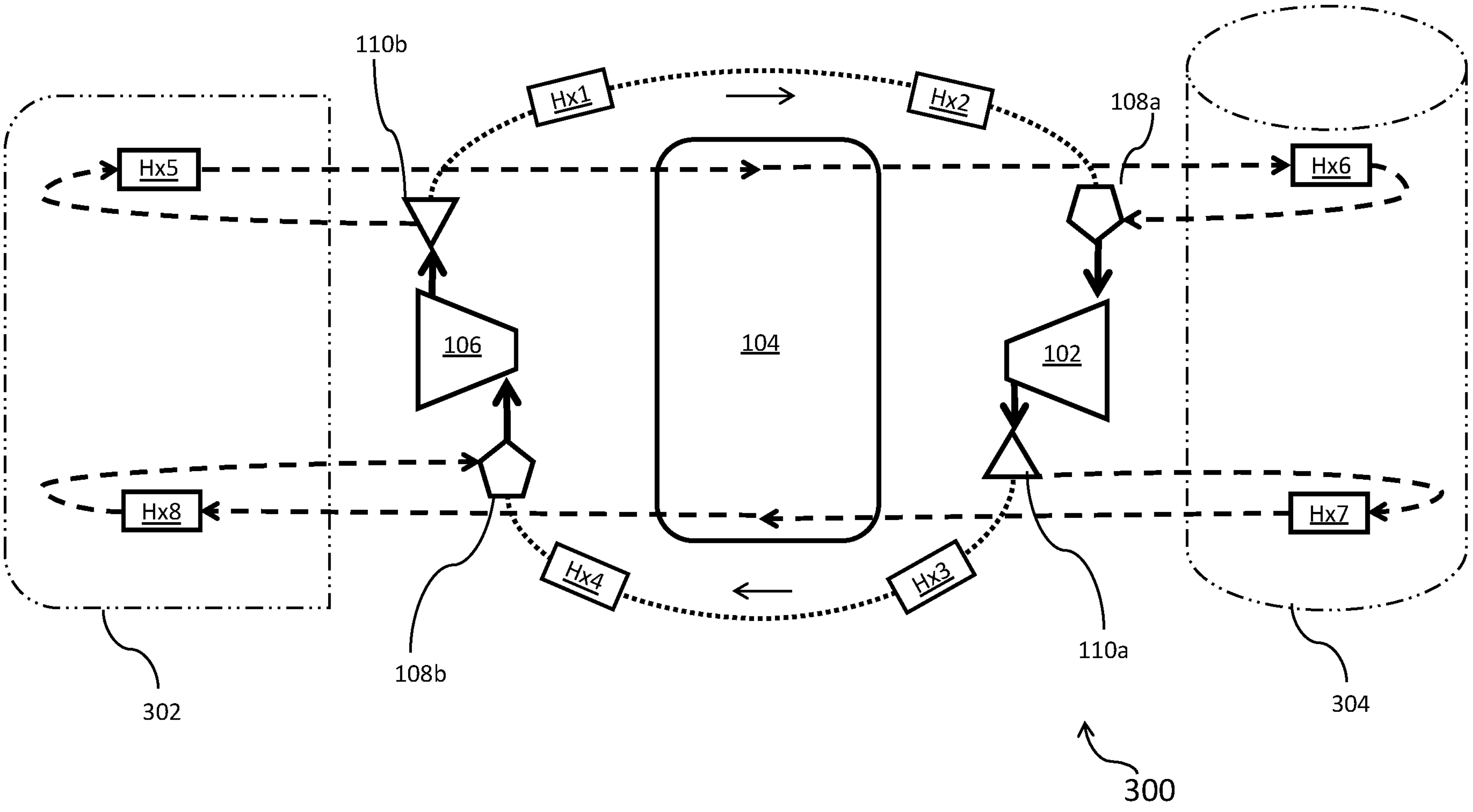
Hx8
Hx5
205

FIG. 2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Hx5
Hx6
106
104
102
Hx8
Hx7
Hx4
Hx3
110a
108b
302
304
300

FIG. 3

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2021/070049

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - F01K 25/10; F01K 7/32; F02G 5/02 (2021.01)
CPC - F01K 25/10; F01K 7/32; F02G 5/02 (2021.02)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
see Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
see Search History document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
see Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2017/0234266 A1 (DOOSAN HEAVY INDUSTRIES & CONSTRUCTION CO., LTD.) 17 August 2017 (17.08.2017) entire document	1-15
A	KR 10-2017-0094581 A (DOOSAN HEAVY INDUSTRIES & CONSTRUCTION CO., LTD.) 21 August 2017 (21.08.2017), see machine translation	1-15
A	US 2016/0003108 A1 (HELD et al) 07 January 2016 (07.01.2016) entire document	1-15
A	US 2015/0076831 A1 (GIEGEL) 19 March 2015 (19.03.2015) entire document	1-15
A	US 2014/0102101 A1 (ECHOGEN POWER SYSTEMS, LLC) 17 April 2014 (17.04.2014) entire document	1-15

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"D"	document cited by the applicant in the international application	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"E"	earlier application or patent but published on or after the international filing date	"&"	document member of the same patent family
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)		
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search 12 March 2021	Date of mailing of the international search report APR 23 2021
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, VA 22313-1450 Facsimile No. 571-273-8300	Authorized officer Blaine R. Copenheaver Telephone No. PCT Helpdesk: 571-272-4300