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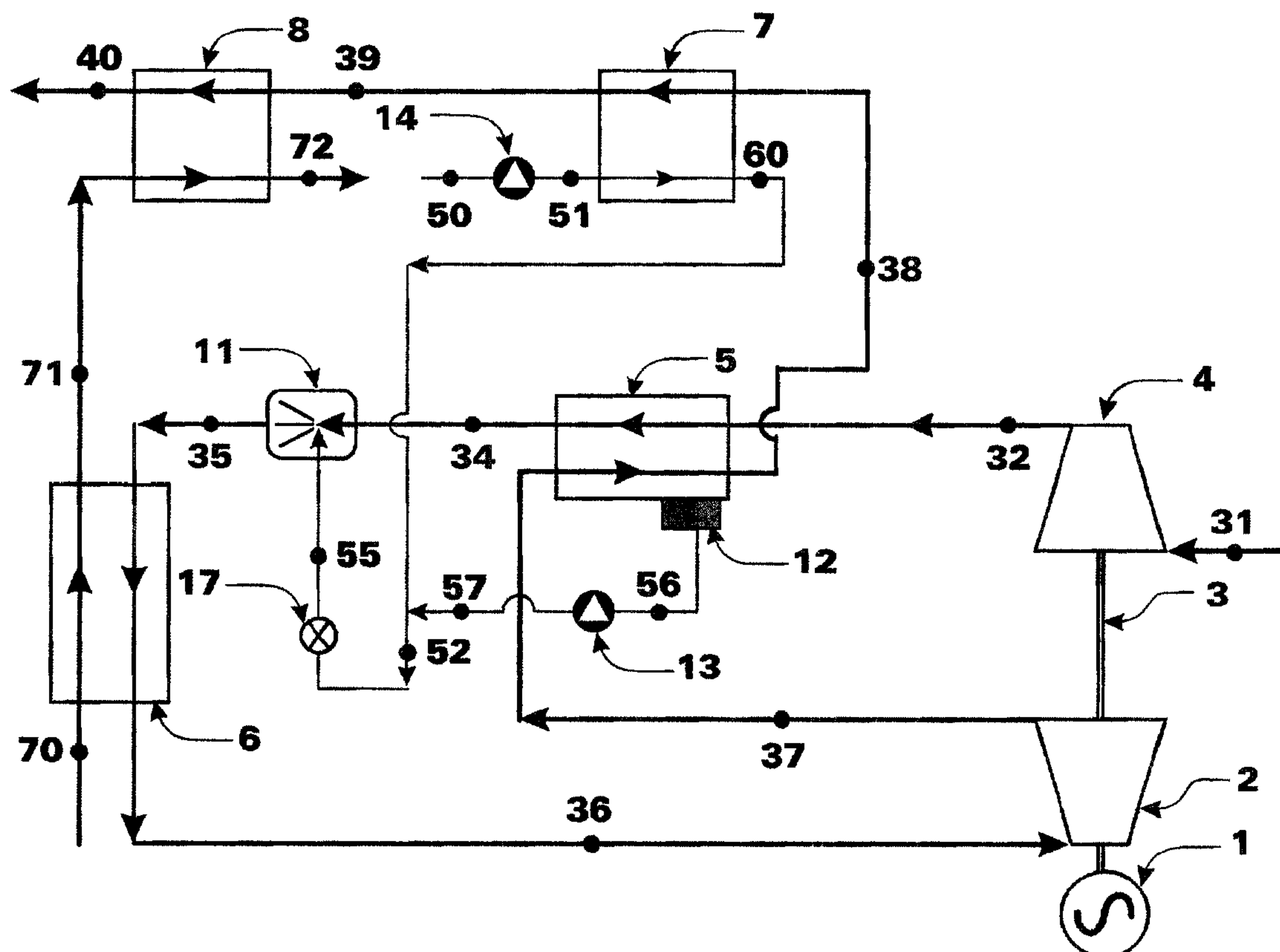
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(71) **Demandeurs/Applicants:**  
BIBEAU, ERIC L., CA;  
SMITH, DOUG W., CA

(72) Inventeurs/Inventors:  
BIBEAU, ERIC L., CA;  
SMITH, DOUG W., CA

(54) Titre : SYSTEME AMELIORE DE CONVERSION ENERGETIQUE A PARTIR D'UN FLUX DE FLUIDE THERMIQUE

(54) Title: ENHANCED ENERGY CONVERSION SYSTEM FROM A FLUID HEAT STREAM



(57) **Abrégé/Abstract:**

An improved method and system to convert thermal energy into electrical energy using an indirect-fired Brayton cycle is presented. A recuperator within the cycle transfers heat from the working fluid exiting the turbine into the working fluid exiting the compressor. Water is injected into the gaseous working fluid after the recuperator and, optionally, before the recuperator to (1) extract additional

**(57) Abrégé(suite)/Abstract(continued):**

thermal energy from a fluid heat stream, (2) increase the mass of working fluid passing through the turbine, (3) improve recuperation of heat, (4) allow use of a higher operating pressure, (5) reduce parasitic compression work, and (6) increase the ratio of turbine work to compressor work. This improved method and system will increase overall efficiency by recovering additional thermal energy from a fluid heat stream and increasing conversion efficiency within the cycle. Means to extend the method and system by closing the conversion loop are also presented.

## ENHANCED ENERGY CONVERSION SYSTEM FROM A FLUID HEAT STREAM

### ABSTRACT OF THE DISCLOSURE

An improved method and system to convert thermal energy into electrical energy using an indirect-fired Brayton cycle is presented. A recuperator within the cycle transfers heat from the working fluid exiting the turbine into the working fluid exiting the compressor. Water is injected into the gaseous working fluid after the recuperator and, optionally, before the recuperator to (1) extract additional thermal energy from a fluid heat stream, (2) increase the mass of working fluid passing through the turbine, (3) improve recuperation of heat, (4) allow use of a higher operating pressure, (5) reduce parasitic compression work, and (6) increase the ratio of turbine work to compressor work. This improved method and system will increase overall efficiency by recovering additional thermal energy from a fluid heat stream and increasing conversion efficiency within the cycle. Means to extend the method and system by closing the conversion loop are also presented.

## BACKGROUND OF INVENTION

### 1. Field of Invention

The present invention relates to a method and system for converting thermal energy from a fluid heat stream into electrical energy, mechanical energy, and useful thermal energy.

More particularly, the present invention which relates to a method and system for converting thermal energy from said fluid heat stream is composed of an indirect-fired Brayton cycle with a recuperator to transfer heat from low-pressure working fluid exiting the turbine into high-pressure working fluid exiting the compressor and uses water introduced to the working fluid within the cycle. Water is first added after said recuperator to extract more energy from said fluid heat stream, to add mass to said working fluid to increase the amount of energy extracted from said turbine and obtain added recuperation without increasing pressure at the exit of said turbine. Water can also simultaneously be introduced before said recuperator to recover more energy in the form of sensible and latent heat from said low-pressure working fluid exiting said turbine.

### 2. Description of the Prior Art

The Rankine cycle minimises compressor parasitic work by compressing a liquid rather than a gas but generates a significant amount of unrecoverable latent heat. The Brayton cycle uses gas as the working fluid which overcomes the unrecoverable latent heat issue but requires higher compressor parasitic work compared to the Rankine cycle. The direct-fired Brayton cycle uses air as the working fluid and mixes fuel with the compressed working fluid in a combustion chamber, creating a high temperature working fluid and resulting in higher electrical conversion efficiency as compared to the Rankine cycle. Since the direct-fired Brayton cycle uses its working fluid as combustion air, the energy input is incremental to and independent of the temperature of its compressed working fluid. The indirect-fired Brayton cycle replaces the fuel and combustion

chamber of the direct-fired Brayton cycle by said fluid heat stream containing thermal energy that is transferred to said working fluid by a heat exchanger. Energy input to the indirect-fired Brayton cycle is dependent on the relationship between the temperature of said fluid heat stream and the temperature of said working fluid in its compressed state. The indirect-fired Brayton cycle approach has the advantage of being able to convert the energy from a relatively dirty fluid stream. Furthermore, said working fluid of the indirect-fired Brayton cycle is at relatively low pressure and does not change phase as in a Rankine cycle, making this energy conversion system simple, safe and easy to maintain. Safety requirements and certified operator requirements are lessened compared to the Rankine cycle system. These aspects are particularly important for small energy conversion systems. The indirect-fired Brayton cycle does not require using air as a working fluid to support combustion and any gas combination can be used for said working fluid to further optimise the system when configured in a closed cycle.

The indirect-fired Brayton cycle directs said working fluid in gaseous form sequentially through several pieces of equipment. Said working fluid, as a relatively cool, low-pressure gas, (1) is passed through a compressor to increase pressure and, consequently, temperature; (2) is directed as high-pressure working fluid through the cool side of a recuperator, an indirect heat exchanger, to increase its temperature further by recovering some energy from the low-pressure working fluid exiting the turbine; (3) is directed as said high-pressure working fluid through a heater, an indirect heat exchanger, wherein external heat is added to said high-pressure working fluid and increases the temperature of said high-pressure working fluid to its highest level; (4) is directed through said turbine wherein work is extracted from said working fluid reducing pressure and temperature; (5) is directed as said low-pressure working fluid through the hot side of said recuperator to release some of the energy not extracted in said turbine and to cool said low-pressure working fluid further; (6) is rejected to atmosphere or to other equipment.

The advantage of the Brayton cycle over the Rankine cycle is diminished for the indirect-fired Brayton cycle because the inlet temperature of said turbine is reduced when

direct combustion is not used. Indirect firing requires a temperature difference for energy transfer and thus the inlet temperature of said high-pressure working fluid entering said turbine must be less than the combustion temperature. In addition, restricting the high temperature side of said heater due to metallurgical constraints significantly limits efficiency of the indirect-fired Brayton cycle, making it no longer as efficient as the Rankine cycle. To overcome this reduced cycle efficiency, prior art has focused on increasing operating temperature of said heater by using specialized metallic or high temperature ceramic materials but at a considerable increase in system cost. The overall energy efficiency of the indirect-fired Brayton cycle is also limited by the temperature increase occurring during gas compression of said working fluid which reduces the mean temperature difference across said heater, thus decreasing the amount of heat that can be extracted from said fluid heat stream. When said recuperator is used, the temperature increase caused by gas compression makes said recuperator less effective by reducing the mean temperature difference across said recuperator. Furthermore, using said recuperator increases the temperature of said working fluid entering said heater thereby reducing the mean temperature difference across said heater and reducing the amount of heat that can be extracted from said fluid heat stream. The effectiveness of said recuperator can be increased by increasing the outlet pressure of said turbine but this is not advisable as this decreases energy extraction by said turbine. Therefore, the temperature increase of said working fluid in said compressor and in said recuperator limits the amount of energy that can be removed from said fluid heat stream, limits the usefulness of recuperation, and thus limits the overall energy conversion efficiency, especially when the temperature of said heater is limited by metallurgical constraints.

Humidification Air Turbines (HAT) for enhancing the conversion efficiency of the direct-fired Brayton cycle have been investigated, especially for applications where costs cannot justify a combined cycle system. Variations of HAT using a humidification tower before a recuperator have been developed resulting in efficiencies that can rival combined cycles. Various methods and systems have been proposed to inject water before a recuperator to increase the amount of heat recuperated, as in U.S. Patent Nos. 6,560,957, 4,610,137, 4,448,018, and inject water into the turbine to increase power, cool

the blades, and reduce NOx emissions, as in U.S. Patent Nos. 6,378,284, 5,160,096. For the indirect-fired Brayton cycle, prior art for example by Farnosh 2003, Yan 1995, Rao 1991, Parsons 1991, and Ruyck 1996 have also investigated humidification of the air and shown efficiency improvements. In all prior art, water is injected after the compressor independent of whether or not a recuperator is used in the system and never after a recuperator. In a direct-fired Brayton cycle there is no thermodynamic advantage injecting water after a recuperator instead of before a recuperator. The prior art does not address how to maximize the heat extracted from a fluid heat stream when a recuperator is used in an indirect-fired Brayton cycle, especially when the heater wall temperature is limited by metallurgical constraints. In addition, prior art does not teach us how to solve the competing criteria that the temperature of the high-pressure working fluid at the exit of the recuperator needs to be as high as possible as a result of maximizing heat recovery in the recuperator and the cycle efficiency, and this same temperature needs to be as low as possible to maximize heat extraction from a fluid heat stream in the heater to improve the overall energy conversion efficiency of the regenerative indirect-fired Brayton cycle system.

Traditional efforts in indirect-fired Brayton cycles have looked at ways to increase the conversion cycle efficiency and especially in ways to increase the inlet temperature of said turbine by overcoming temperature constraints of said heater. However the authors have addressed the overall energy recovery as a combination of heat recovery from said fluid heat stream and conversion cycle efficiency. System modelling by the authors has shown that the optimum system uses a relatively low maximum pressure and temperature with a recuperator in preference to a higher maximum pressure and temperature without a recuperator. The higher maximum pressure and temperature system precludes the use of a recuperator due to a lack of heat transfer temperature difference.

Further modelling has shown that injection of water after said recuperator, and optionally before said recuperator, increases the amount of heat that can be extracted from said fluid heat stream and improves the cycle efficiency to increase the overall

energy conversion efficiency. This arrangement overcomes the negative effect said recuperator has on the amount of heat that can be extracted from said fluid heat stream and the negative effect said compressor has on the amount of heat that can be extracted from said recuperator. The benefits of the disclosed method and system have not been previously understood and the disclosed method and system has not been previously identified, especially when applied to smaller power conversion systems that cannot justify the use of expensive high temperature heat exchangers. The disclosed invention improves the indirect-fired Brayton cycle for a wide range of temperatures, including temperatures above metallurgic limits where ceramic heat exchangers must be used. The advantage of the disclosed method and system is also to use water in liquid and vapour phase to recuperate sensible and latent heat from said low-pressure working fluid exiting said turbine without the implication of the latent heat efficiency penalty associated with the Rankine system.

#### SUMMARY OF INVENTION

The present invention provides a method and a system for implementing an indirect-fired Brayton cycle where one of the novel features is to provide a first water injection into said high-pressure working fluid following heat recuperation. Said first water injection substantially improves both the amount of heat recovered from said fluid heat stream and the conversion cycle efficiency to produce improved overall energy conversion efficiency. The total heat recovery from said fluid heat stream is increased due to the reduced temperature of said high-pressure working fluid which allows said fluid heat stream to be brought to a lower temperature in said heater. The conversion cycle efficiency is increased due to the greater mass of working fluid passing through said turbine. Another novel feature of this method and system is also to provide a second water injection into said high-pressure working fluid before recuperation to further increase the cycle efficiency and recuperate latent heat of the injected water from said low-pressure working fluid exiting said turbine.

The method of the present invention provides implementation of a novel adaptation of the indirect-fired Brayton cycle to convert thermal energy contained in a fluid heat stream into electrical and mechanical energy. The method uses a working fluid comprised of a gas or gas mixture containing preferably air. Said fluid heat stream is normally composed of a mixture of gases, vapours, and particulate and may also be in liquid state. Water composed of preferably deionised liquid water, which can also contain additives, alcohols, glycol and the like is first injected into said high-pressure working fluid after recuperating heat from low-pressure working fluid that is normally rejected after work has been performed. Said first water injection reduces the temperature of said high-pressure working fluid before receiving heat from said fluid heat stream. Because said fluid heat stream has a fixed upper temperature value and because said fluid heat stream reduces temperature as it gives up energy, the means remaining to maximize energy transfer to said working fluid from said fluid heat stream include reducing the temperature of said working fluid before it interacts with said fluid heat stream, increasing the mass flow rate of said working fluid, and increasing the heat capacity of said working fluid. All of these functions are accomplished by said first water injection. In addition, said first water injection allows recuperating more heat from said low-pressure working fluid exiting said turbine before heat is rejected. Improved recuperation is possible because said first water injection also allows the temperature of said high-pressure working fluid after recuperation to be as high as possible to maximise recuperation while ensuring that the temperature of said high-pressure working fluid is as low as possible before heat extraction from said fluid heat stream to maximize heat extraction from said fluid heat stream. These conflicting objectives during optimization are successfully addressed by said first water injection resulting in an increase in energy recovery from said fluid heat stream and in an increase in the conversion cycle efficiency to produce an increase of the overall energy conversion efficiency of the regenerative indirect-fired Brayton cycle system.

In addition, it is another novel feature of this method to also implement a second water injection into said high-pressure working fluid before recuperation while also injecting water after recuperation in said first water injection to further increase the cycle

efficiency. Said second water injection is used to decrease the temperature of said high-pressure working fluid before recuperation to offset the temperature increase of said working fluid that occurs during gas compression, thereby increasing the mean temperature difference across said recuperator. If the temperature of said low-pressure working fluid exiting said turbine is reduced during recuperation to below its dew point temperature, then latent heat from the vaporization of injected water can be recovered, improving cycle efficiency even further. Said second water injection results in an increase in cycle efficiency which is in addition to the benefits obtained using said first water injection.

Furthermore, the present invention provides a system to implement a novel adaptation of the indirect-fired Brayton cycle to convert more thermal energy contained in said fluid heat stream into electrical and mechanical energy. The system uses a working fluid composed of a gas or gas mixture and preferably air, said fluid heat stream that contains thermal energy obtained from an external heat source, and water composed of a clean source of liquid water, preferably deionised and filtered which may also contain additives, alcohols, and glycol and the like. The system can be operated in a closed or open cycle configuration. When configured as a closed system, a fluid coolant and cooler is required prior to the compressor to extract heat and decrease the temperature of said working fluid to the desired inlet temperature of said compressor.

Said working fluid is passed through said compressor to increase pressure to the highest value within the conversion cycle and consequently increases the temperature of said working fluid during this process. The high-pressure working fluid is directed through said recuperator to recover some of the heat contained in the low-pressure working fluid exiting said turbine. Water is then injected into said high-pressure working fluid after exiting said recuperator. Said water mixes with said high-pressure working fluid such that said water vaporizes to add mass to said working fluid and said high-pressure working fluid is reduced in temperature. Said high-pressure working fluid then enters said heater to extract heat from said fluid heat stream and bring said high-pressure working fluid to its highest temperature within the conversion cycle. The decrease in

temperature of said high-pressure working fluid due to said water allows more heat to be transferred from said fluid heat stream to said high-pressure working fluid to improve overall energy conversion efficiency. Said first water injection also allows more heat to be recovered in said recuperator since this recovered heat no longer limits the heat transfer from said fluid heat stream and a higher temperature of said high-pressure working fluid exiting said recuperator can be tolerated. Said high-pressure working fluid enters said turbine and is reduced in pressure and temperature as it performs work and exits as a relatively high-temperature, low-pressure working fluid. Said low-pressure working fluid enters said recuperator and transfers some of its remaining heat to said high-pressure working fluid exiting said compressor. Said first water injection results in both (1) an increase in cycle efficiency due to the added mass flow through said turbine and the additional energy transfer in said recuperator, and (2) an increase of the overall energy conversion efficiency due to the additional energy transfer in said heater from said fluid heat stream.

The system also provides a means for a second water injection into said high-pressure working fluid located before said recuperator. This allows the temperature of said high-pressure working fluid to decrease before it enters said recuperator and offset some of the temperature increase of said working fluid that occurred in said compressor. The temperature of said low-pressure working fluid exiting said turbine can be decreased below dew point temperature in said recuperator to allow recovery of latent heat by condensing entrained water vapour. Said second water injection results in an increase in the cycle efficiency by retaining further energy in the conversion cycle which is in addition to benefits obtained using the first water injection.

#### BRIEF DESCRIPTION OF THE ILLUSTRATED EMBODIMENTS

FIG. 1 depicts a preferred embodiment of an apparatus for implementing the method and system to improve the overall energy efficiency conversion for an indirect-fired Brayton cycle in an open cycle configuration;

FIG. 2 depicts the temperature and entropy diagram for part of the process for preferred embodiment of the present invention illustrated in FIG. 1;

FIG. 3 depicts an alternative embodiment of an apparatus for implementing the improved overall energy conversion efficiency for the indirect-fired Brayton cycle in an open cycle configuration;

FIG. 4 depicts the temperature and entropy diagram for part of the process for embodiment of the present invention illustrated in FIG. 3; and

FIG. 5 depicts an alternative embodiment of an apparatus for implementing the improved thermodynamic efficiency for the indirect-fired Brayton cycle in a closed cycle configuration.

#### DETAILED DESCRIPTION OF THE ILLUSTRATED EMBODIMENTS

The present invention is an adaptation of the regenerative indirect-fired Brayton cycle that provides a method and system to humidify the working fluid at strategic points during the conversion cycle to generate a gas-water mixture to increase the amount of energy recovered from a fluid heat stream and to improve the efficiency of conversion of energy in a working fluid into electrical and mechanical energy and useful thermal energy. Said working fluid is a gas or gas mixture which is preferably comprised of air, helium, carbon dioxide, nitrogen, hydrocarbons, Freon, or other gas or any combination to which water is added during the conversion cycle. Said working fluid gas can also be a mixture composed of a combination of gases and vapours, which can also contain water vapour prior to injection of water into said working fluid. Said water that is injected in said working fluid is preferably filtered and deionised, and as much as possible free of contamination that could wear turbine blades, foul heat exchangers, and increase corrosion rates in the system. Furthermore, said water can also be a mixture composed of water, glycol, alcohols and the like to increase the specific enthalpy of said water, prevent icing, lubricate, prevent corrosion or have other desirable properties. A demineralization system, an acid system, and caustic system or any other system can be added to treat said water to further prevent corrosion and wear of system components. Said fluid heat stream is composed of gases, and may also contain vapours, particulate, tars and the like

and can also be composed of substances that remain in liquid state at high temperatures. Alternatively, said fluid heat stream may be liquid or a mixture of liquids and may also contain impurities, particulates, solids, or gas inclusions. Said fluid heat stream may be produced by being heated by an external energy source using for example biomass, geothermal heat, solar energy, nuclear fuel, various fossil fuels, and the like. Said fluid heat stream may be a stream of waste heat occurring in many industrial processes or be the exhaust of a gas turbine. Said fluid heat stream may be from a combination of energy sources.

FIG. 1 shows a preferred embodiment of the present invention where the method and system will be described in terms of its primary components and its main mode of operation. The indirect-fired Brayton cycle illustrated in FIG. 1 is configured as an open system and said water is introduced into said working fluid after recuperator 5 to obtain a method and system that both improves the amount of heat recovered from said fluid heat stream and introduced to the conversion cycle in heater 6 and improves the cycle efficiency defined by the ratio of the net work produced to the heat transferred into said working fluid by heater 6.

Said working fluid having fluid properties 31 flows into compressor 4 which increases pressure and consequently increase temperature of said working fluid. Recuperator 5 is a non-contact counter-flow heat exchanger with a low temperature side through which said working fluid exiting compressor 4 passes and a high temperature side through which said working fluid exiting turbine 2 passes. Upon exiting compressor 4, said working fluid having fluid properties 32 flows into low temperature side of recuperator 5. Said working fluid exiting turbine 2 having fluid properties 37 flows through high temperature side of recuperator 5 where said working fluid loses sensible heat and loses latent heat if the dew point temperature is reached, whereupon further heat loss will result in condensation of water from vapour to liquid. Said condensation makes latent heat available to heat up said working fluid entering low temperature side of recuperator 5. Condensed water in recuperator 5 is accumulated in recuperator water tray 12 and removed using recuperator boost pump 13 or by some other alternative means.

Upon exiting recuperator **5**, said working fluid having fluid properties **34** flows into first spray **11** where said water is injected. First spray **11** is adapted to humidify said working fluid which can be done using any of a plurality of known methods and systems. Said water having fluid properties **55** flows into first spray **11** with the flow rate controlled by first spray valve **17** to minimize said water accumulating in liquid form in first spray **11** and heater **6**, and maximize the temperature decrease, the specific humidity increase and the enthalpy increase of said working fluid from properties **34** to properties **35**. After exiting first spray **11**, said working fluid having fluid properties **35** flows into low temperature side of heater **6**. Heater **6** is a non-contact counter-flow heat exchanger with a low temperature side through which said working fluid exiting recuperator **5** passes and a high temperature side through which said fluid heat stream passes. Said fluid heat stream having fluid properties **70** flows into high temperature side of heater **6** where said fluid heat stream loses energy to said working fluid. Said fluid heat stream exits heater **6** having fluid properties **71**.

Said working fluid having fluid properties **36** exits heater **6** and flows into turbine **2**. Turbine **2** turns shaft **3** which powers compressor **4** and electrical generator **1**. Said working fluid having fluid properties **37** exits turbine **2**, flows through high temperature side of recuperator **5** and exits recuperator **5** having fluid properties **38**. Economiser **7** is a non-contact counter-flow heat exchanger with a high temperature side through which said working fluid exiting high temperature side of recuperator **5** passes and a low temperature side through which said water to be injected passes. Preheater **8** is a non-contact counter-flow heat exchanger with a high temperature side through which said fluid heat stream exiting heater **6** passes and a low temperature side through which said working fluid passes. Said working fluid enters high temperature side of economiser **7** to transfer energy to heat said water to be injected into said working fluid through first spray **11**. Said working fluid exits economiser **7** having fluid properties **39** and enters low temperature side of preheater **8**. Said working fluid gains energy in preheater **8** from said fluid stream flowing through high temperature side of preheater **8** to increase the temperature and decrease the relative humidity of said working fluid. Said working fluid exiting preheater **8** is unsaturated, has fluid properties **40** and can be used productively to

supply combustion air to a combustion device, to heat and provide moisture to a greenhouse, to dry and condition wood in a wood drying kiln, or in any other cogeneration application (these items not shown in FIG. 1).

Said fluid heat stream exiting heater 6 having fluid properties 71 flows into high temperature side of preheater 8 and exits with fluid properties 72. Thermal energy remaining in said fluid heat stream can be further used, for example, to control said fluid heat stream temperature 70 to protect tube wall temperatures in heater 6 thereby also increasing the mass flow rate of said fluid heat stream flowing through heater 6 (not shown in FIG. 1).

Said water having fluid properties 50 is pressurised using water pump 14, and exits water pump 14 having fluid properties 51. Said water with properties 51 flows through low temperature side of economiser 7 and exits having fluid properties 60. Said water with properties 60 is mixed with said water from recuperator booster pump 13 having fluid properties 57. After being mixed, said water now having fluid properties 52 is fed to first spray valve 17. Said water flow rate is controlled using first spray valve 17 to optimise cycle efficiency and overall energy conversion efficiency.

FIG. 2 shows an illustration of the temperature and entropy diagram of said working fluid for preferred embodiment in FIG. 1 and for the process between compressor 4 inlet and heater 6 outlet. In this illustration, it is assumed that gas compression is isentropic and that injecting said water to humidify said working fluid causes the entropy to decrease as it is assumed that the entropy decrease caused by the decrease in temperature is more significant than the entropy increase due to mixing of two fluids. There may be some operating conditions for this invention where the entropy can increase after water injection or remain constant depending on the working fluid and optimal operational conditions.

The temperature increases across compressor 4 between fluid properties 31 and fluid properties 32 and the temperature and entropy increases across recuperator 5

between fluid properties 32 and fluid properties 34. The temperature and entropy decreases across first spray 11 between fluid properties 34 and fluid properties 35 and the temperature and entropy increases across heater 6 between fluid properties 35 and fluid properties 36. Heat transfer constraints require temperature at fluid properties 34 of said working fluid exiting recuperator 5 be lower than temperature at fluid properties 37 of said working fluid exiting compressor 2, as shown in FIG. 2. Heat transfer constraints require temperature at fluid properties 35 of said working fluid entering heater 6 be lower than temperature at fluid properties 71 of said fluid heat stream exiting heater 6, as shown in FIG. 2. Heat transfer constraints require temperature at fluid properties 36 of said working fluid entering turbine 2 be lower than temperature at fluid properties 70 of said fluid heat stream exiting heater 6, as shown in FIG. 2. FIG. 2 shows the advantage of injecting said water after recuperator 5 between fluid properties 34 and fluid properties 35. Lower temperature at fluid properties 35 allows temperature at fluid properties 71 of said fluid heat stream to be lower and allows more heat to be transferred to said working fluid as it flows through heater 6. Lower temperature at fluid properties 35 also allows more heat to be recovered across recuperator 5 as allowing temperature at fluid properties 34 to increase does not affect the amount of heat input from heater 6. In addition, working fluid enthalpy at fluid properties 36 increases without having to compress said water vapour resulting in decreased work input by compressor 4 relative to work output by turbine 2. All these advantages contribute to improving both the conversion cycle efficiency and the overall energy efficiency.

FIG. 3 shows an alternative embodiment of the present invention where the indirect-fired Brayton cycle is configured as in FIG. 1 with an additional water injector by adding second spray 10 and second spray valve 16. In this embodiment, said working fluid upon exiting compressor 4 having fluid properties 32 now flows into second spray 10 where said water is also injected. Second spray 10 is adapted to humidify said working fluid which can be done using any of a plurality of known methods and systems. Said water having fluid properties 54 flows into second spray 10 and the flow rate is controlled by second spray valve 16 to minimise said water accumulating in liquid form in second spray 10 and recuperator 5, and to maximize the temperature decrease, the

specific humidity increase, and the enthalpy increase of properties 32 of said working fluid to properties 33 of said working fluid. After exiting second spray 10, said working fluid having fluid properties 33 flows into low temperature side of recuperator 5 as embodied in FIG. 1 but with lower temperature, higher specific humidity, and higher enthalpy, to further improve cycle efficiency for similar operating conditions.

FIG. 4 shows an illustration of the temperature and entropy diagram of said working fluid for embodiment in FIG. 3 and for the process between the inlet of compressor 4 and the outlet of heater 6. FIG. 4 is similar to FIG. 2 except that the diagram now shows the effect of adding second spray 10. The temperature and entropy of properties 32 of said working fluid decrease to properties 33 of said working fluid across second spray 10. The lower temperature of properties 33 allows more heat to be transferred to said working fluid as it flows through recuperator 5. Second spray 10 contributes to further improve the cycle efficiency.

FIG. 5 shows an alternative embodiment of the present invention where the indirect-fired Brayton cycle is configured as in FIG. 3 with water injection before and after recuperator 5, but configured as a closed system. Cooler 18, cooler water tray 19, and cooler boost pump 20 are added to the energy conversion system of FIG. 4 to form a closed cycle. Cooler 18 is a non-contact heat exchanger with a low temperature side through which coolant passes and a high temperature side through which said working fluid entering compressor 4 passes. Said working fluid having fluid properties 40 flows through high temperature side of cooler 18 and exits with a reduced temperature of fluid properties 31. Water vapour in said working fluid condenses as the temperature falls below the dew point temperature. Said condensed water is collected in cooler water tray 19 and said condensed water having fluid properties 58 is pumped using cooler boost pump 20. Said condensed water having fluid properties 59 is mixed with said water to be injected through first spray 11 and second spray 10. Said coolant having fluid properties 80 flows through low temperature side of cooler 18. Said coolant exits cooler 18 with fluid properties 81 after having cooled said working fluid to the desired temperature at fluid properties 31 before entering compressor 4. The closed cycle configuration allows a

gas or a mixture of gases to be used continuously within said energy conversion system. Condensation of said water injected into said working fluid allows for minimum make-up water addition to the system through pump 14.

It is understood that injection of water through first spray 11 before heater 6 may result in vaporization occurring in the flow channel conveying said working fluid to heater 6 and may also include vaporization in a region within heater 6, as it is not a requirement for said water to be fully vaporized before entering heater 6. Similarly, it is understood that injection of water through second spray 10 before recuperator 5 may include vaporization in the flow channel conveying said working fluid to recuperator 5 and may also result in vaporization occurring in a region within recuperator 5, as it is not a requirement for said water to be fully vaporized before entering recuperator 5. In addition, injection of said water must take into consideration icing that may arise from a decrease in temperature of said working fluid below ice formation temperature of said water for applications in cold climates. Furthermore the injection flow rate of said water must be controlled as to avoid accumulation of said water in liquid phase inside heater 6, turbine 2, compressor 4, cold temperature side of recuperator 5, cold temperature side of gas heater 6, second spray 10, first spray 11, and channels conveying said working fluid.

The energy conversion system can be designed with a single or multistage turbine 2, a single or multistage compressor 4, more than one turbine 2, or more than one compressor 4 without changing the intent of the disclosed invention. Furthermore, the operating pressures of said working fluid can be biased to operate at a lower maximum pressure to restrict turbine 2 to a single stage. The operating pressures of said working fluid can be biased to operate at a lower maximum pressure to restrict compressor 4 to a single stage. In addition, turbine 2 can also provide mechanical work by connecting shaft 3 to a different work consuming device other than generator 1 to operate for example fans, a gas compressor, a refrigeration system compressor, and the like. Operating the cycle in a closed or open configuration does not change the intent of the invention. Removal of economiser 7 or preheater 8, and the addition of other heat exchangers into the energy conversion system, or alternative use of said fluid heat stream with properties

**72** or said working fluid with properties **40** other than those proposed does not impact the intent of this invention. During operation of the cycle, the flow rate of injected water can be varied from zero to maximum value by adjusting second spray valve **16** or first spray valve **17**.

The disclosed method and system is not constrained by the method of how said water is injected into said working fluid. Injection of said water can be performed by injecting steam to promote atomization, injecting steam with water, and by injecting steam only. Said water can be injected by pressurizing said water and injecting said water using a single nozzle or a plurality of nozzles in various arrangements and configurations. Furthermore, any method and system that is suitable for humidification of said working fluid can be used. The disclosed method and system can also be modified without changing the intent of the invention by combining functions of recuperator **5** and second spray **10** into one unit, by combining functions of recuperator **5** and first spray **11** into one unit, or by combining functions of second spray **10**, recuperator **5**, and first spray **11** into one unit using for example humidification towers and methods and systems that use direct and indirect evaporative gas cooling.

The invention may be embodied in other specific forms without departing from the spirit and important characteristics of the method and system disclosed. Although the present invention has been described completely, it is understood that the invention may be practiced other than as specifically described and still remain within the scope of the claims. Although the invention has been disclosed in reference to several preferred embodiments, those skilled in the art may appreciate modifications that can be made without departing from the scope and spirit of the invention disclosed herein.

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Yan J., Eidenstan L. and Svedberg G., "An investigation of the heat recovery system in externally fired evaporative gas turbines", ASME paper 95-GT-72, International and Aeroengine Congress and Exposition, Houston, Texas, June 5 to 8, 1995.

Rao A.D., Tanner A.L. and Vu T.H., "Closed cycle gas turbine with humidification of the working fluid", Proceeding of the 26<sup>th</sup> Intersociety Energy Conversion Engineering Conference, Boston, August 4 to 9, 1991

Parsons E.L. and Bechtel T.F., "Performance gains derived from water injections in regenerative, indirect-fired, coal-fuelled gas turbines," ASME, 91-GT-288, June 1991.

Ruyck J.D., Peeters F., Bram S. and Allard G., "An externally fired evaporative gas turbine cycle for a small biomass CHP production," IGTI-Vol 9, ASME COGEN-TURBO 1995, Proceeding of the 9<sup>th</sup> European Bioenergy Conference, Copenhagen, Denmark, June 24-27, 1996.

directing the low-pressure working fluid into the inlet of the compressor.

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THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGED IS CLAIMED ARE DEFINED AS FOLLOWS:

**1. A method for implementing a regenerative indirect-fired Brayton cycle to extract heat from a fluid heat stream containing thermal energy to increase overall energy conversion efficiency comprising of:**

**a working fluid comprised of a gaseous mixture which may include non-condensable gases, condensable vapours, solid particulate, or liquid droplets;**

**means for compressing the working fluid to a predetermined pressure to produce a high-pressure working fluid;**

**means to extract heat from a fluid heat stream that has been externally heated and contains thermal energy;**

**means to extract work to generate electrical or mechanical energy from the high-pressure working fluid to produce a low-pressure working fluid;**

**means of heat recuperation to transfer some of the energy, remaining in the low-pressure working fluid after work extraction, into the high-pressure working fluid, before extracting heat from the fluid heat stream; and**

**means to inject water into the high-pressure working fluid after heat recuperation and before extracting heat from the fluid heat stream.**

**2. The method of claim 1, including the further step of injecting water into the high-pressure working fluid before heat recuperation and after compression of the working fluid.**

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3. The method of claim 1 or 2, including the further step of transferring heat from the low-pressure working fluid after recuperation into the water before injecting the water into the high-pressure working fluid.
4. The method of claim 3, including the further step of collecting condensed water from the low-pressure working fluid during regeneration and reusing the water for injection into the high-pressure working fluid.
5. The method of claim 4, including the further step of transferring heat from the fluid heat stream into the low-pressure working fluid after regeneration to reduce the relative humidity and increase the temperature of the low-pressure working fluid.
6. The method of claim 5, including the further step of:  
  
closing the indirect-fired Brayton cycle by extracting sensible and latent heat from the low-pressure working fluid; including  
  
means to collect and reuse condensed water to inject into the high-pressure working fluid, and  
  
feeding the low-pressure working fluid to the inlet of the means for compressing the working fluid to a predetermined pressure to produce a high-pressure working fluid.
7. The method of claim 5, including the further step of using the low-pressure working fluid to provide combustion air to combustion devices.
8. The method of claim 5, including the further step of using the low-pressure working fluid to provide energy and water vapour for cogeneration applications.

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**9.** A system for implementing an indirect-fired Brayton cycle with a recuperator to extract heat from a fluid heat stream containing thermal energy to increase overall energy conversion efficiency comprising of:

a working fluid comprised of a gaseous mixture which may include condensable vapours, solid particulate, or liquid droplets;

a compressor for compressing the working fluid supplied thereto to a predetermined pressure to produce a high-pressure working fluid;

a turbine for generating electrical or mechanical energy by reducing the pressure of the working fluid;

a heater to transfer heat to the high-pressure working fluid from a fluid heat stream that has been externally heated;

a recuperator to transfer sensible and latent heat from the low-pressure working fluid exiting the turbine to the high-pressure working fluid exiting the compressor; and

a water injection system to humidify the high-pressure working fluid after the recuperator.

**10.** The system of claim 9, including an additional water injection system to humidify the working fluid before the recuperator.

**11.** The system of claim 9 or 10, including the addition of an economiser to transfer heat from the low-pressure working fluid to the water before injection into the high-pressure working fluid.

**12.** The system of claim **11**, including the addition of a water tray to collect condensed water from the low-pressure working fluid in the recuperator and reusing the water for injection into the high-pressure working fluid.

**13.** The system of claim **12**, including the addition of a preheater to reduce the relative humidity and increase the temperature of the low-pressure working fluid after the recuperator or after the economiser.

**14.** The system of claim **13**, including the addition of:

a gas cooler to remove sensible and latent heat from the low-pressure working fluid; and

a tray to collect the condensed water and reuse the water to inject into the working fluid,  
and

directing the low-pressure working fluid into the inlet of the compressor.

