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(54) **METHOD TO INTEGRATE REGENERATIVE RANKINE CYCLE INTO COMBINED CYCLE APPLICATIONS**

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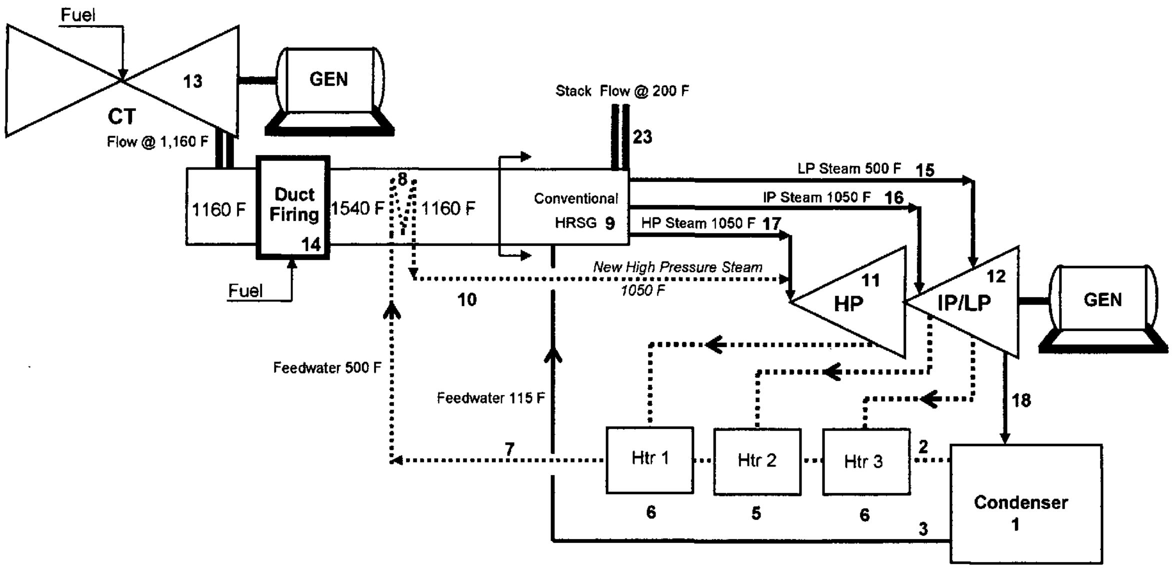
(57) **ABSTRACT**

A system is disclosed that incorporates a regenerative Rankine cycle integrated with a conventional combined cycle. An added duct firing array, typically located after the combustion turbine exhaust and before the conventionally designed Heat Recovery Steam Generator (HRSG), is used to boost enthalpy of said exhaust. An added heating element downstream of the firing array provides sufficient heating for sensible heating, evaporation and superheating of feedwater that has been previously heated by feedwater heaters as part of a regenerative Rankine cycle. In practice, the condensate stream from the condenser is bifurcated such that a dedicated feedwater flow is directed to feedwater heaters. After further heating in the added heating element, the superheated steam, at the same pressure and temperature as the main steam, is now mixed with the main steam prior to turbine entry. The condensate is directed to the HRSG to be heated in conventional fashion.

Method To Integrate Regenerative Rankine Cycle Into Combined Cycle Applications



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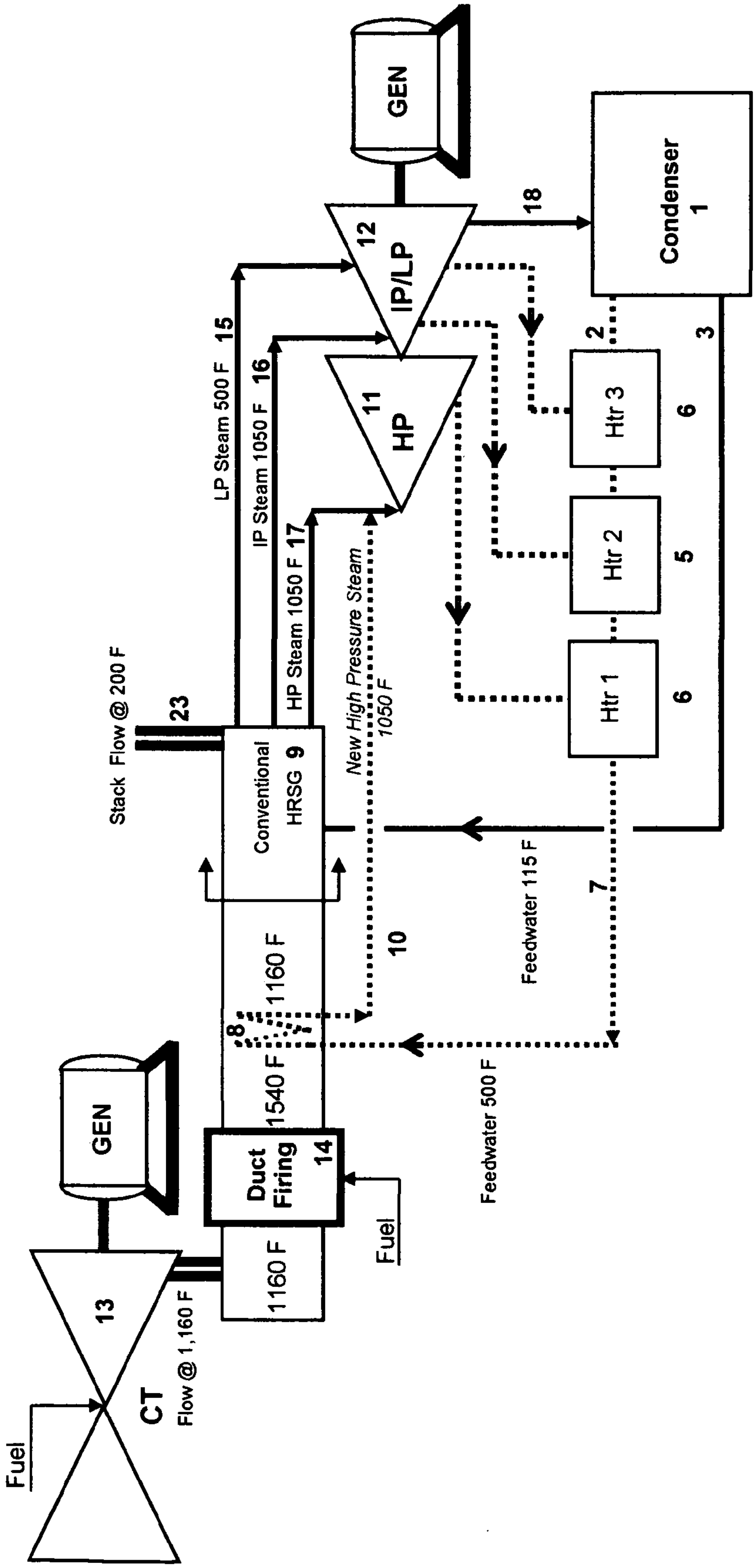
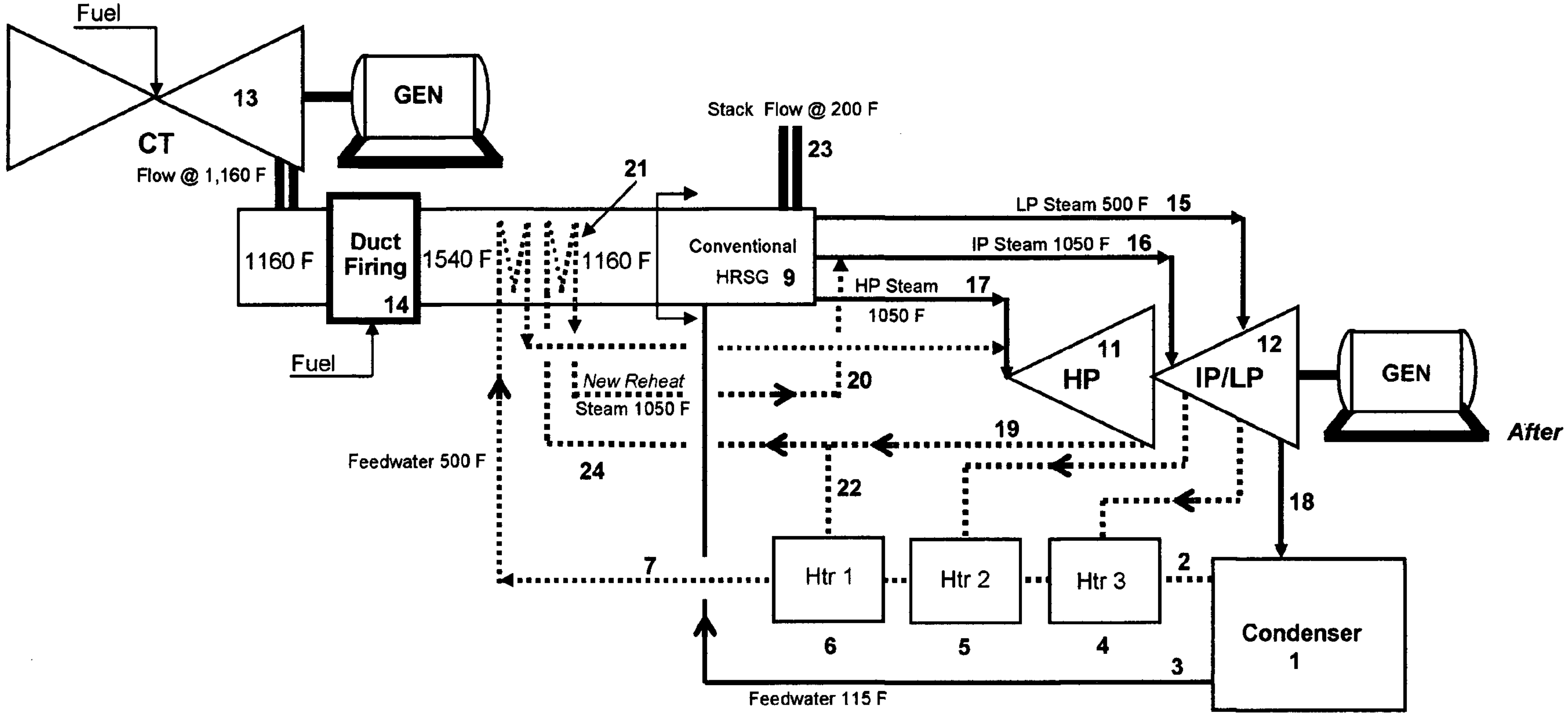


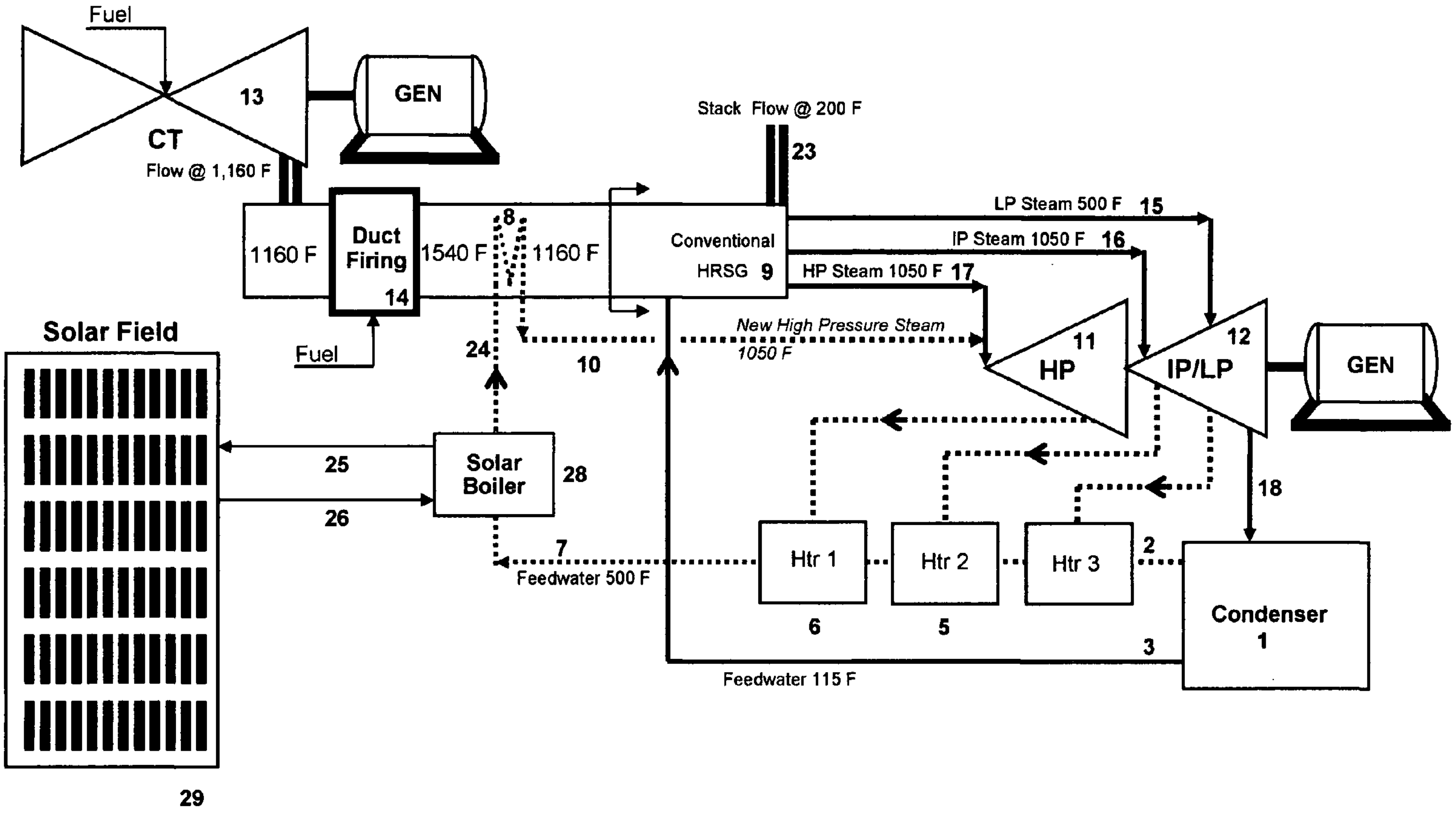
Drawing 2

Method To Integrate Regenerative Rankine Cycle Into Combined Cycle Applications



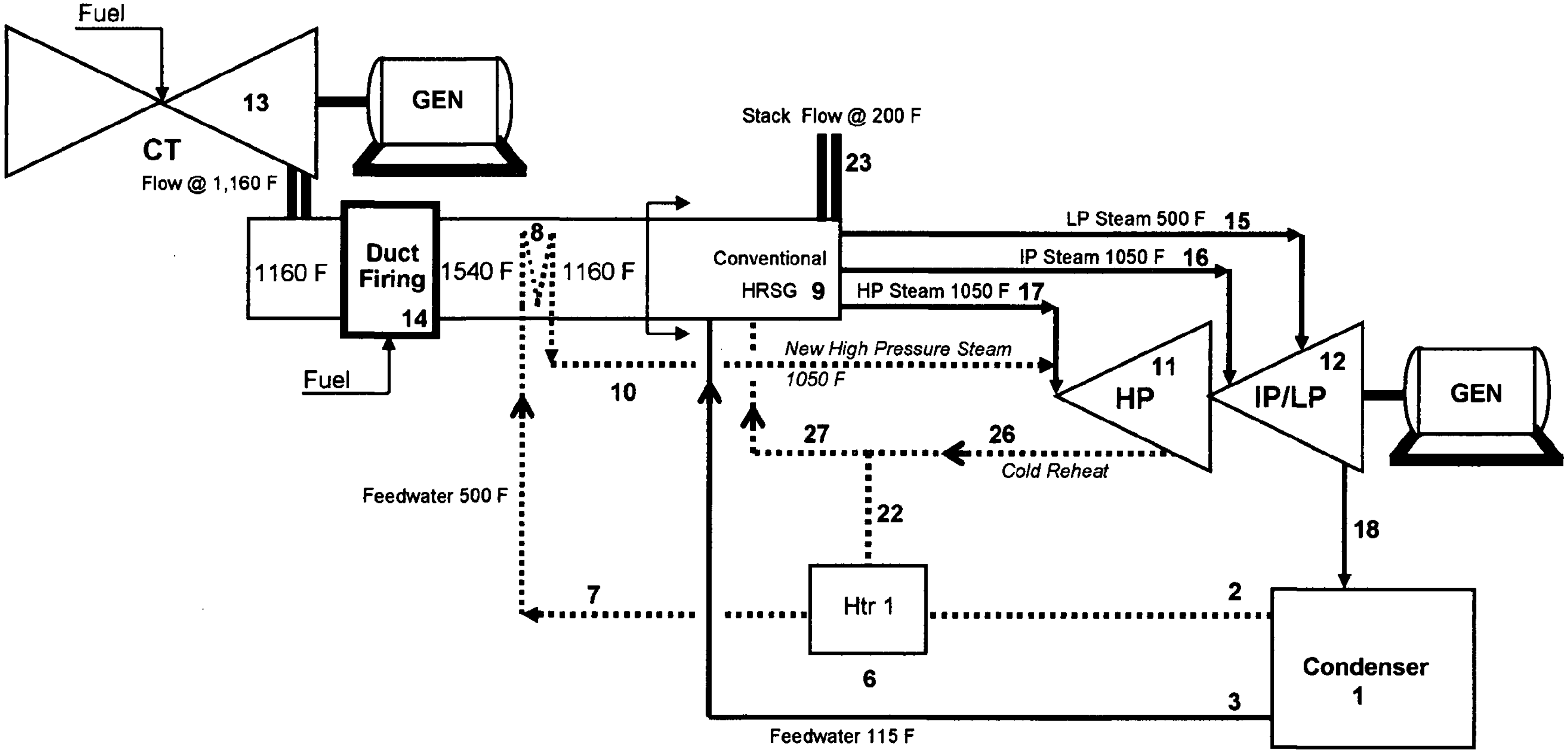
Drawing 3

Method To Integrate Regenerative Rankine Cycle Into Combined Cycle Applications



Drawing 4

Method To Integrate Regenerative Rankine Cycle Into Combined Cycle Applications



METHOD TO INTEGRATE REGENERATIVE RANKINE CYCLE INTO COMBINED CYCLE APPLICATIONS

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CROSS-REFERENCE TO RELATED APPLICATIONS

[0006] This application claims the benefits of the U.S. Provisional Patent Application Nos. 61/741,800 entitled "Method to integrate regenerative rankine cycle into combined cycle applications" filed on Jul. 27, 2012 and 61/741,997 filed on Aug. 1, 2012 entitled "Method to integrate regenerative rankine cycle into existing combined cycle applications" and 61/742,633 entitled "Method to integrate solar regenerative rankine cycle into combined cycle applications" filed on Aug. 14, 2012. These provisional applications are incorporated by reference herein in their entirety.

BACKGROUND OF THE INVENTION

[0007] Combined cycle power plants have come of age due to the advances in combustion turbine technology and, most recently, due to the new natural gas recovery technology of "fracking". Fracking has significantly increased the gas reserves of the United States and has significantly lowered the cost of gas recovery. The state of the combustion turbine technology and the availability of long term and relatively low cost natural gas has made the combined cycle the prominent choice for both future generation needs to serve new loads and to replace coal generation in the near and mid-term future.

[0008] Early applications for combustion turbines were aero derivative models which were, essentially, modified jet engines originally designed for aircraft and modified for land base use. However, the design of this type of technology, i.e. combustion turbines, gradually became specific to the needs of the electric utility industry such that by the **1970**'s specific combustion turbines with characteristics specifically designed to optimize performance in combined cycle operation were commercially available.

[0009] A combined cycle can be described in two parts; the "top" cycle which is the combustion turbine utilizing a Brayton cycle, and the "bottom" cycle which is the Rankine cycle. Shaft power is initially generated through the use of combustion turbines; the turbine section of the combustion turbine used for land base power generation is designed such that there is no thrust as all developed power is recovered in the shaft; however, there is still significantly high exhaust temperature which, in standalone applications, is wasted. The "bottom" cycle of a combined cycle is a Rankine cycle which uses the waste heat from the combustion turbine. The turbines used in combine cycle applications have not been designed necessarily to be the most efficient in a standalone configuration, but rather to be the most efficient when used in tandem with a bottoming Rankine cycle. Typically, these types of combustion turbines normally have a low pressure ratio which results in a high exhaust temperature. The high exhaust temperature is beneficial to the Rankine cycle which, in tandem use with the combustion turbine, can produce combined overall efficiencies in the 60% range.

[0010] Increasing the efficiency of a combustion turbine typically requires higher firing temperatures at the turbine inlet and higher pressure ratio to use the higher thermodynamic availability resulting from the higher firing temperature. However, while increasing the firing temperature without a commensurate increase in the pressure ratio may minimally increase the efficiency of the turbine, the higher exhaust temperature resulting from the higher firing temperature can significantly increase the efficiency of the Rankine cycle. In accordance with the second law of thermodynamics, the efficiency of any heat cycle can be expressed as:

$$\text{Efficiency}=1=(T_L/T_H)$$

Where T_L is the low temperature of the working fluid, i.e. the low temperature of the steam in the cycle, where heat is exhausted to the heat sink. T_H is the high temperature of the working fluid, in our case, steam, and is the point where expansion of the working fluid is used to produce work.

[0011] Consequently, it is always thermodynamically preferable to have the working fluid to be expanded at the highest possible temperature. In order to achieve a high steam temperature, typically around 1050 F, a high exhaust temperature is required; this exhaust temperature must be higher than the operating steam temperature in order to affect heat transfer. It is also noted that for a high Rankine cycle efficiency, the steam must be expanded to the lowest possible temperature and pressure. Typically the temperature is around 115 F at about 1.5 psia or so. However, herein lays a problem for an efficient combined cycle.

[0012] By expanding and condensing the steam to a low temperature, a regenerative Rankine cycle is not possible for a conventional combined cycle configuration. In order to achieve a low stack gas temperature, low feedwater temperature must be supplied to the waste heat boiler. For example, if the feedwater is heated through regeneration to a temperature of, say, 500 F then it is impossible for the stack gas temperature to be lower than 500 F and, in fact, since a temperature difference must be maintained in order to achieve heat transfer (usually a minimum of 50 F or so), then the stack temperature must exit at around 550 F and this hot gas represents an enthalpy loss to the overall cycle. Therefore, feedwater heating, if any, can only be used sparingly in order to maintain a sufficiently low feedwater temperature in order to ensure there is no unreasonable stack loss.

[0013] To date, turbine manufacturers have concentrated on increasing firing temperatures of the combustion turbines for increased efficiencies; but high firing temperature requires enormous research and development costs as well as costly material and blade cooling methods. The novelty proposed herein goes back to the basics and proposes an alternative that increases the efficiency of the Rankine cycle not through higher operating working fluid temperatures but employing regenerative heating to increase the Rankine cycle efficiency.

[0014] Overall, the energy consumption in the United States has declined slightly over the last 5 years and much of this decline can be attributed to the overall economic decline of the past several years. However, domestic production has still increased by about 3% per year due to a decrease in the importation of electricity from Mexico and Canada. Overall, in the next ten years, electric consumption in the United States is expected to grow incrementally at about 1 to 1.5% per year. Even though this is a small number, the total installed capacity in the United States in 2010 was about 1,140 GW's. Therefore, even a 1% increase would require construction of about twenty 500 MW power plants every year. And this does not include the replacement capacity due to aging plants, and, in particular, aging coal plants.

[0015] There is a significant market driven by the aging coal plants in this country. Over the next 10-15 years, dozens of coal units will be replaced with gas-fueled combined cycle units. It is unlikely that the power plant operators will walk away from an existing power plant site which has high value infrastructure including transmission and water rights as well as a certain ease of permitting since development would occur on an already despoiled plant site. There is significant difficulty in developing a new coal plant since coal has increased in price and natural gas has decreased. In addition, the combined cycle is about 40-45% more efficient than a coal plant and the capital cost is about ⅓ the cost of a coal plant. And this price differential does not include the cost of greenhouse gas (CO_2) clean up which would add considerably to the cost of coal generation.

[0016] Greenhouse gases will be a significant driver not only for renewable energy resources but also for combined cycle plants as well. Combined cycle plants emit less than 50% greenhouse gas than a similar size coal plant operating at the same capacity factor. Green house gas reduction is a significant driver for the construction of combined cycle power plants. Consequently, a low cost and highly efficient Regenerative cycle integrated in a combined cycle novelty will be received favorably in the commercial markets.

SUMMARY OF THE INVENTION

[0017] This novelty firstly adds an additional duct firing array into the CT exhaust stream and before the Heat Recovery Steam Generator (HRSG). Then, additional heating elements are placed into the duct immediately downstream of the added duct firing array and before the HRSG. With this additional ability to add and extract heat, this novelty supplies the necessary and separate enthalpy to a separate regenerative cycle. This is accomplished by creating a separate and designated stream of feedwater mass flow rate by dividing the flow from the condenser hotwell (condensate/feedwater) to allow harvesting of the additional enthalpy resulting from proposed additional duct firing array. This fractional flow from the condenser is preheated with extraction steam from the steam turbine and then the heated feedwater captures the additional enthalpy provided by the additional duct firing array to provide main and reheat steam. Steam is produced commensurate with the pressure and temperature of the steam produced by the HRSG such that said steam can be mixed with the HRSG produced steam.

[0018] The remaining fractional flow from the condenser is pressurized to feedwater and directed to HRSG in conventional manner. Consequently, in a conventional arrangement of feedwater flow to the HRSG, the feedwater flow must be kept at low temperature prior to entering the HRSG in order to ensure that the stack gas temperature does not rise. The fractional flow that is pre-heated by extraction steam is a separate feed and is not impacted and does not affect the low temperature feedwater flow to the HRSG.

[0019] Thus, full regeneration of the Rankine cycle loop through the use of turbine steam extraction and feedwater heaters can be achieved with high temperature feedwater being directed to the additional heating elements for main and reheat steam production. Typically, in a standalone regenerative Rankine cycle, the mass ratio of the total steam extraction flows to the main throttle steam flow is in the order of 0.35 or so (depending on the number of extraction ports and commensurate number of feedwater heaters) to fully utilize regeneration and to pre-heat the feedwater as much as possible.

[0020] While separate steam turbines could be used for the non-regenerative and regenerative steam produced, the common configuration would be to utilize a common turbine and co-mix the two steam flows. Only that portion of the steam flow generated through the regenerative process would be part of the regenerative Rankine cycle; the feedwater flow through the feedwater heaters would be equal to the amount of regenerative steam produced. Accordingly, this dedicated flow of feedwater could be raised close to the saturation temperature of the operating pressure of the HRSG. Limitations would ensue based on amount of total flow of main steam throttle flow to the dedicated feedwater flow for duct firing. In traditional regenerative cycles, regeneration is normally limited by the amount of heat that can be transferred from the main throttle steam flow; in this novelty, the limitation can be the amount of heat absorbed by the feedwater stream. In any case, the heating of the independent feedwater flow for duct firing closer to the point of saturation may result in a gain in thermodynamic efficiency.

[0021] This invention also benefits from the operational duality of the traditional duct fired concept using condensate, pressurized to feedwater, fed directly to the HRSG and the dedicated feedwater regenerative stream, pressurized to feedwater, fed to the additional heating elements located downstream in the CT exhaust and upstream of the HRSG. By switching from this novelty's concept during plant operation and running the additional heating surfaces "dry" or with minimal cooling steam flow in the additional heating elements, the traditional method of duct firing can be implemented with concurrent increase in condensate flow, which would yield higher capacity although at lower efficiency. Accordingly, when efficiency is preferred, the plant can be operated in the enhanced regenerative mode as described herein; when higher capacity is required the switch can be made to traditional duct burning.

[0022] Another variation or additional embodiment of this novelty is to add reheat with the regeneration feature. In this manner, a dedicated duct burner array and heating element are used for reheating. This technique allows for reheating back to the original main steam temperature without impacting the stack gas temperature or design parameters in the HRSG.

[0023] It is noted that this novelty can be applied to new installation or to existing regenerative Rankine cycle installations. In particular, coal plants that are near end of life operation could be repowered utilizing the existing steam turbine generator, feedwater train and associated piping, and equipment as well as the indigenous infrastructure such as site and transmission. In this embodiment, at least one combustion turbine with at least one HRSG could be used to incorporate the existing coal plant's equipment.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] Drawing **1** is a sketch that diagrammatically shows the proposed concept. The drawing shows an inner feedwater loop, shown in dotted lines, employing feedwater heaters supplying additional feedwater flow in a designated flow path such that additional heating elements and added duct firing results in a separate regenerative Rankine cycle. The duct firing shown is an added array and is not to be confused with conventional duct firing used to increase the steaming capacity of the HRSG. The novelty's added duct firing array does not impact or impede the operation of the conventional duct firing and can be used in tandem with the proposed novelty. The novelty's proposed additional duct firing does not increase the feedwater flow rate from the condenser directly to the HRSG to produce more steam; this novelty proposes a separate loop method allows the feedwater to be preheated in a separate loop using extraction flows from the steam turbine with additional enthalpy added for steam production using a dedicated duct burner array.

[0025] Drawing **2** is similar to Drawing **1** but shows the additional embodiment of reheating that would be available, if deployed, under this novelty. In this scheme, the cold reheat steam is bifurcated with the majority of steam flowing to the separate and designated heating elements and the remaining steam flow used for regenerative heating in the first point heater.

[0026] Drawing **3** is similar to Drawing **1** but shows the additional embodiment of adding solar thermal energy to the fuel mix which is used to generate steam in the regenerative portion of the overall cycle.

[0027] Drawing **4** is a sketch that diagrammatically shows the application of the regenerative ranking cycle integrated with a combined cycle having a non-extraction steam turbine.

DETAILED DESCRIPTION OF THE INVENTION

[0028] The numbers and data shown are general approximations only in order to more fully delineate the principles of the proposed novelty and the overall flow schematic should not be construed as a final thermodynamic analysis. Referring to Drawing **1**, if we assume a closed operating Rankine cycle, condenser **1** condenses the steam flow **18** from the low pressure steam turbine **12**. This novelty separates that amount of condensate into two streams **2** and **3** where stream **2** is the additional mass flow rate used for regeneration and absorbs the heat from steam extractions from appropriate ports in the extraction turbine. In practice, the fraction dedicated to the regenerative portion of the condensate flow **2** from the condenser is, typically, about 40-45% of total condensate flow. However, these values can be adjusted for cycle optimization. The pre-heated feedwater **7** is shown in Drawing **1** as a dedicated feed to the separately fired heating element **8**. The amount of condensate **3** used for non-regenerative cycle operation is fed directly to the HRSG **9** for feedwater heating, evaporating and superheating and then directed to the High Pressure (HP) steam turbine **11**. Condensate **2** flows through the regenerative heater #**3** **4**, then through heater #**2** **5** and then completes its pre-heating through heater #**1** **6**. Typically, in traditional Rankine regenerative reheat cycles that are non-critical, the first point heater (heater #**1**) **6** receives steam extraction from the cold reheat line; this embodiment of reheat is described further under other embodiments. The herein embodiment description assumes that the first point heater **6** receives its extraction flow from the cold reheat line from the HP turbine **11**. For simplicity, boiler feed pumps and other associated flow lines, such as feedwater drip lines, have not been shown.

[0029] The amount of reheating, and the number of feedwater heaters, is an economic evaluation whereby the cost of preheating is evaluated against the gain in efficiency; typically large coal plants use **7** or **8** heaters; if a new facility is used, an economic evaluation will determine the number of feedwater heaters used. Drawing **1** shows only three for simplicity. While this novelty permits heating close to the saturation point, it is assumed here for illustrative purposes that the pre-heated feedwater **7** is heated to approximately 500 F. Heating elements **8** provide sensible heating, evaporation and superheating required for production of main steam. All three elements **8** are shown as a single heating element for simplicity and would be located upstream of the HRSG **9** and downstream from the added duct firing **14**.

[0030] While the exhaust of the combustion turbine **13** is shown as **1160** F, the additional duct firing **14** adds heat such that the overall gas temperature is now 1540 F. The amount of heat required to eventually generate steam from the feedwater **7** would then bring down the combustion turbine's exhaust gas temperature to approximately the temperature as before (1140 F). This is the same temperature that the exhaust gas would need to produce the enthalpy to run the combined cycle without duct firing **14**. In other words, the total flow enthalpy to HRSG **9** is essentially reset to its original enthalpy value and the many heating elements in the HRSG **9** (which are not shown in Drawing **1** or Drawing **2**) are not impacted and the stack temperature remains unchanged.

[0031] Referring again to Drawing **1**, the feedwater **7** is heated in the additional heating element **8**, the feedwater stream which is now superheated steam **10** is directed to the inlet of the HP steam turbine **11** where it is mixed with the main steam produced by the CT exhaust flow in the HRSG **9** at the same pressure and enthalpy for expansion in the HP turbine **11**. It is noted that this example depicts a three pressure combined cycle and that the low pressure steam **15**, and the intermediate pressure steam **16** are directed to the IP/LP steam turbine **12** as appropriate. The main steam **17**, the intermediate pressure steam **16** and the low pressure steam **15** have all been generated with essentially no changes to the HRSG **9**. The primary design parameter proposed in this novelty is that the heating of the separated and designated regenerative feedwater **7** is performed solely with the added heating elements **8** and the added duct firing **14** in the duct upstream of the conventionally designed HRSG **9** where the said HRSG design is, essentially, unaltered and the stack temperature **23** remains, essentially, unchanged.

[0032] Referring to Drawing **2**, the addition of a reheat section is shown in conjunction with the production of main steam produced by the previously described regenerative Rankine cycle in Drawing **1**. The cold reheat working fluid **24** is a separate loop used to reheat that portion of the main steam that has been generated through a regenerative Rankine cycle. It is noted that the main steam produced by the HRSG using solely the waste heat of the CT **13** is reheated through the HRSG operation only. Drawing **2** is the same as Drawing **1** except for the addition of the specific equipment and lines required for reheating of the main steam. In Drawing **2**, we follow the assumption that most non-critical Rankine cycles take the first point heater steam extraction **22** from the cold reheat line **19**. The remaining fraction of the cold reheat **24** is then directed to an additional heat element **21** to be reheated located upstream of the HRSG **9** such that the reheat steam **20** is reheated to the temperature of the Intermediate pressure steam (IP) produced by the HRSG **9**. The reheated steam **20** is directed to the intermediate steam line **16** and mixed with the combined cycle's production of intermediate steam and directed to the IP/LP steam turbine **12**. The reheating process does not impact the stack temperature **23**.

[0033] The novelty described can, with minor variation, also be used to incorporate solar thermal energy into the regenerative Rankine cycle in conjunction with a combined cycle. Referencing Drawing **3**, the method to incorporate solar thermal is described. In this embodiment, solar heat energy is used to further heat the feedwater **7** after heating is completed through feedwater heating using extraction steam. From Condenser **1** the feedwater stream **2** is preheated in the feedwater heaters using extraction steam; the heated feedwater **7** is directed to the solar boiler **28** where, depending on the amount of solar energy supplied by the solar field **29**, sensible or sensible and latent heat is added. Under maximum solar heating supplied, dry steam at the saturation pressure can be directed to the additional heating element **8**. In heating element **8**, further heat is added such that superheated main steam **10** at throttle pressure is produced for eventual mix with the main steam **17** produced by the HRSG **9**. This method reduces the amount of heat that duct firing **14** is required to add.

[0034] This novelty can also be employed to retrofit existing combined cycle power plants. However, the retrofit design is less efficient than the preferred embodiment since the amount of extraction heating is reduced; in addition, said heating is added at a greater temperature difference that increases the entropy losses in the cycle process. But, by using the existing infrastructure at an existing plant, cost can be reduced and extra capacity may be added economically. Referring to Drawing **4**, the designated feedwater **2** to be pre-heated by extraction steam is directed to Heater **1 6** where steam from the cold reheat **26** is used as the said extraction steam **22**. This steam line **26** is already in existence and tapped to provide a fractional steam **22** flow to the feedwater heater **6**. The heated feedwater **7** is then directed to the separately fired element **8** where further enthalpy is added and the rest of the cycle is processed as described in the preferred embodiment.

1. A method for generating electric power that incorporates the use of a regenerative Rankine cycle with a combined cycle, the method comprising the steps of:

Bifurcating the condensate from a condenser into two or more separate condensate feed streams whereby the condensate in at least one condensate feed stream is pressurized to feedwater and sent directly to a heat recovery steam generator and the condensate in at least one condensate feed stream is pressurized to feedwater and sent to at least one separately fired heating element first being preheated by a one or more feedwater heaters utilizing extraction steam from an extraction turbine;

generating steam in at least one separately fired heating element and transferring the steam to an extraction steam turbine having one or more extraction ports;

converting the steam into electricity through the use of an extraction steam turbine and generator and extracting some of the steam for heating feedwater.

2. The method of claim **1**, wherein additional heat enthalpy is supplied to the separately fired heating element and used to boost the temperature and enthalpy of the combustion turbine exhaust flow such that there is additional enthalpy in said combustion turbine exhaust flow to generate steam for use in a regenerative Rankine cycle.

3. The method of claim **1**, wherein the separately fired heating element is placed downstream of the combustion turbine inside the combustion turbine exhaust ducting.

4. The method of claim **1**, wherein the separately fired heating element may be configured in a "once through" or drum design.

5. The method of claim **1**, wherein the method may be utilized in conjunction with a single pressure or multiple pressure heat recovery steam generator.

6. The method of claim **2**, wherein some or all of the additional heat enthalpy supplied to the separately fired heating element is generated from combusting fuel in at least one duct burner.

7. The method of claim **2**, wherein the additional heat enthalpy supplied to the separately fired heating element may be generated from fossil fuel or non-fossil fuel or a combination of both.

8. The method of claim **2**, wherein substantially all of the additional heat enthalpy supplied to the separately fired heating element is utilized to generate steam.

9. The method of claim **2**, wherein some or all of the additional heat enthalpy supplied to the separately fired heating element is supplied through the use of one or more duct burners placed in the combustion turbine exhaust ducting and before the separately, fired heating element.

10. A method to generate reheated steam utilizing a separately fired heating element in a regenerative Rankine cycle used in conjunction with a combined cycle, the method comprising of:

Partially expanded steam from the high pressure turbine exhaust is sent to an independent fired heating element to boost said steam to a temperature that is compatible with the hot reheat steam produced by the heat recovery steam generator for mixing with total mix directed to the intermediate pressure turbine inlet;

a duct burner to provide for the necessary enthalpy into the separately fired heating element to reheat the steam is placed downstream of the combustion turbine inside the combustion turbine exhaust ducting.

11. A method for generating electric power that incorporates the use of a regenerative Rankine cycle with a combined cycle, the method comprising the steps of:

Bifurcating the condensate from a condenser into two or more separate condensate feed streams whereby the condensate in at least one condensate feed stream is pressurized to feedwater and sent directly to a heat recovery steam generator and the condensate in at least one condensate feed stream is pressurized to feedwater and sent to at least one separately fired heating element first being preheated by a one or more feedwater heaters utilizing cold reheat steam from a non-extraction turbine;

generating steam in at least one separately fired heating element and transferring the steam to a non-extraction steam turbine;

converting the steam into electricity through the use of a non-extraction steam turbine and generator.

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