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Sensitivity analysis of STIG based combined cycle with dual pressure HRSG

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Abstract

Thermodynamic evaluation has been carried out for a combined cycle with STeam Injected Gas Turbine (STIG) having dual pressure heat recovery steam generator (HRSG). Steam from high-pressure steam turbine is injected into the combustion chamber at a pressure higher than the combustion pressure to improve the exergy efficiency of combined cycle. The effect of steam injection mass ratio, deaerator pressure (or temperature ratio), steam reheat pressure ratio, HP steam turbine pressure, compressor pressure ratio and combustion temperature on combined cycle exergy efficiency has been investigated. It has been found that advantage from steam injection to combined cycle is obtained at high steam reheat pressure and high steam turbine inlet pressure. At this condition, the increasing effect of gas cycle output exceeds the decreasing effect of steam cycle output. The major exergetic loss that occurs in combustion chamber decreases with introduction of steam injection in to the combustion.

Keywords: Combined cycle power generation; Steam injection; Exergy; Heat recovery steam generator; Exergy analysis

1. Introduction

The STIG method stands for steam injected gas turbine. The steam from the high-pressure (HP) steam turbine is injected into the combustion chamber. Air from the compressor and steam from the heat recovery steam generator (HRSG) both receive fuel energy in the combustion chamber and both expand inside the same turbine to boost the power output of turbine. In addition, the specific heat of superheated steam is almost double the value of air and the enthalpy of steam is higher than that of air at a certain temperature. Therefore, the STIG method is a very effective way to boost the net power output and increase the overall efficiency of gas turbines. Presently the STIG technology is applied only to the gas turbine cycle and it is not extended to the combined power cycle. The reason may be due to the decreased steam turbine output with steam injection. The combined cycle is now well established and offers superior performance to any of the competing systems. Not much information is reported in the literature about the combined cycle with the steam injection. Steam injection in the combined cycle increases the gas cycle output but the steam cycle output decreases. But proper selection of parameters for combined cycle such that the rise in gas cycle output is more than the drop in steam turbine output; the combined cycle output can be increase with the steam injection.

In 1978, Cheng [1] proposed a gas turbine cycle in which the heat of the exhaust gas of the gas turbine is used to produce steam in a HRSG. This steam is injected in the combustion chamber of the gas turbine, resulting in an efficiency gain and a power augmentation. Rice [2] developed a steam injected gas turbine cycle with a topping in which a HP steam is first expanded in a back-pressure steam turbine, producing power, and then is injected into the combustion chamber of the gas turbine. Borat [3] found that the efficiency and the net output of the gas turbine increased considerably, of the order of 20–40 percent with the steam injection. Poullikkas [4] reviewed the gas turbine technologies and emphasized on various advance cycles involving heat recovery from the gas turbine exhaust, such as, the gas to gas recuperation cycle, the combined cycle, the chemical recuperation cycle, the Cheng cycle, the humid air turbine cycle, etc. Gigliucci et al. [5] pre-

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Nomenclature

e	specific exergy	$kJ\,kg\,mol^{-1}$
h	specific enthalpy	$kJ\,kg\,mol^{-1}$
i	specific irreversibility	$kJ\,kg\,mol^{-1}$
M	molecular weight	
m	mass	$kg\,kg\,mol^{-1}$ fuel
P	pressure	bar
R	universal gas constant	$kJ\,kg\,mol^{-1}\,K^{-1}$
s	specific entropy	$kJ\,kg\,mol^{-1}\,K^{-1}$
T	temperature	K
w	work	$kJ\,kg\,mol^{-1}$
η	efficiency	
ε	specific exergy at ground state	$kJ\,kg\,mol^{-1}$
θ	excess temperature ratio	

Suffix

cc	combined cycle
ch	chemical
de	deaerator
OA	over all
ph	physical
sat	saturation
0	reference point
1	first law
2	second law

Acronyms and abbreviations

CEP	Condensate Extraction Pump
CPH	Condensate Pre-Heater
DSH	Degree of Super-Heat
ECO	Economiser
EVAP	Evaporator
FP	Feed Pump
GT	Gas Turbine
GTCC	Gas Turbine Combustion Chamber
HAT	Humid Air Turbine
HP	High-Pressure
HRSG	Heat Recovery Steam Generator
LP	Low-Pressure
LHV	Lower Heating Value
PP	Pinch Point
RH	Reheater
SH	Superheater
ST	Steam Turbine
STIG	STeam Injected Gas turbine
TTD	Terminal Temperature Difference

sented the main results of thermodynamic analysis of a cogenerative cycle, which deals with a hydrogen-fed, with steam injection in the gas turbine itself to couple high process efficiencies with very low nitrous oxide emissions. Steam injection also allows for a more flexible steam-production to power-production ratio [6]. Wang and Chiou [7] proved that the techniques namely steam injection gas turbine and inlet air-cooling are very effective features that can use the generated steam to improve the power generation capacity and efficiency.

There are many methods developed to improve the efficiency of the combined cycle. Heppenstall [8] described and compared several power generation cycles, which were, developed to take advantage of the gas turbine's thermodynamic characteristics. Chmielniak et al. [9] discussed the effectiveness of various technological configurations with gas turbines, which are to be applied during modernization projects of already existing conventional combined heat and power plants. Pelster et al. [10] presented a thermo environmental methodology to deal the complexity of analysis to the combined cycles. Franco and Casarosa [11] identified the key element to obtain high efficiency of combined cycle, which is the optimization of HRSG with the use of parallel sections and of limit sub-critical conditions (up to 220 bar). Gallo [12] compared the HAT cycle (humid air turbine) with the simple cycle gas turbine, recuperated gas turbine cycles, steam injection gas turbines and also with the combined cycle. Korobistyn [13] overviewed the improvements that can be implemented within the basic and combined cycles. Huang et al. [14] used an exergy analysis for a combination of steam injected gas turbine cogeneration system and forward feed triple effect evaporation process, with and without vapor recompression. Nishida et al. [15] analyzed the performance characteristics of the regenerative steam injected gas turbine system. Araki et al. [16] studied the characteristics of a humidification tower, which is used as a humidifier for the advanced humid air turbine system. Haselbacher [17] investigated the performance differences in terms of thermal efficiency and specific power output of the combined cycle power plants. Bassily [18] modeled a dual pressure reheat combined cycle and optimized.

Introduction of STIG to gas cycle without including steam turbine proves to be economically competitive in power range under 150 MW [19]. The expansion of steam in the gas turbine proceeds to the atmospheric pressure whereas in the combined cycle plant steam leaves the steam turbine at much lower pressures, thus providing more power. Therefore, a gas turbine with steam injection will have a lower efficiency than that in combined cycle operation. But if the increasing effect of gas cycle output is more than the decreasing effect of steam cycle output, the combined cycle efficiency increases with the steam injection.

The main aim of this work is to find the combined cycle system parameters at which the exergy efficiency of overall system improves with introduction of steam injection. For this, a sensitivity analysis has been carried out with the steam injection to fuel mass ratio, deaerator temperature ratio, steam reheat pressure ratio, steam turbine inlet pressure, gas cycle pressure ratio and combustion chamber temperature on exergy efficiency of the combined cycle.

2. Thermodynamic model of the combined cycle with steam injected gas turbine (STIG)

The schematic flow diagram of STIG based combined cycle with the components is shown in Fig. 1. Temperature–entropy diagram for the corresponding combined cycle with steam injection is shown in Fig. 2. A gas cycle with intercooler and gas reheater is selected for topping cycle. For a combined cycle system, the energy recovered from a single gas turbine exhaust is usually insufficient to power a steam turbine. Because the efficiency of steam turbine is steeply declined when it's size (capacity) becomes too small. In order to collect enough recovered energy, the combined cycle system is designed with two gas turbines and a steam turbine. Fig. 3 is the temperature–heat transferred diagram for triple pressure HRSG. The heating devices in the HRSG are arranged with the minimum temperature difference between the flue gas and the water/steam to minimize the exergetic loss in HRSG. Low-pressure (LP) in HRSG is determined with the available exhaust temperature in HRSG section. The pinch point (PP) in HRSG is the minimum temperature difference between flue gas and saturated steam in evaporator. The enthalpy rise between feed water inlet and steam outlet must equal the enthalpy drop of the exhaust gases in the HRSG, and the PP and terminal temperature difference (TTD) cannot be less than about 20 °C if the HRSG is to be of economic size [20]. Steam is injected from HP steam turbine into the combustion chamber at a pressure, 5 percent higher than the combustion pressure. Feed water from deaerator enters into heating zones of LP and HP steam generators after pumping in the LP and HP feed pumps. The make up water is added at outlet of the condenser and before the condensate extraction pump to compensate the steam injection in the combustion chamber.

Steam injection in the gas turbine controls the peak temperature of the combustion chamber. It reduces the excess air required to control the combustion temperature and so the work input to air compressor decreases. Steam injection improves the heating value of the gas at the gas turbine inlet and so the gas turbine output. Steam injection decreases heat rejection in the condenser but it increases the exhaust gas loss. If the increase in the gas cycle output is more than the decrease in the steam cycle output, there is a rise in combined cycle efficiency otherwise; the same will decrease with steam injection. In this work investigation has been carried out to find the parameters such that the gain in gas cycle is more than the loss in steam cycle from steam injection.

3. Thermodynamic analysis of the combined cycle

The assumptions made for the analysis of the combined cycle are tabulated in Table 1. The energy efficiency of the combined cycle is determined based on the lower heating value (802 303 kJ kg mol^{-1}) of the fuel. The available work output of combined cycle (difference between exergy of fuel and total exergetic losses) in percent of standard chemical exergy of the fuel (836 420 kJ kg mol^{-1}) is expressed as exergy efficiency of combined cycle [21].

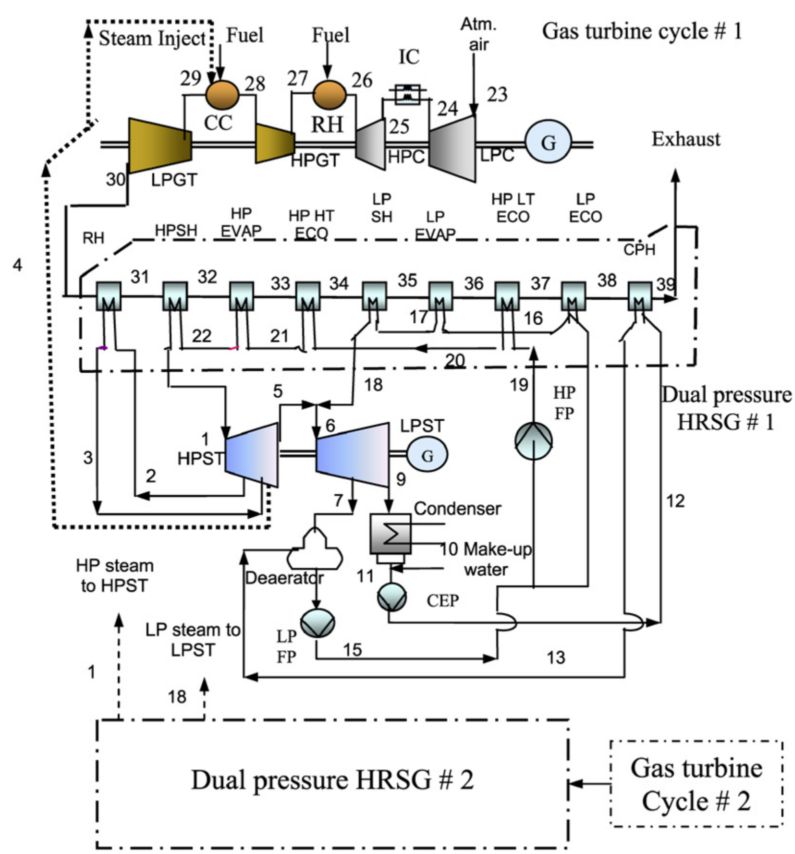

Fig. 1. STIG based combined cycle power plant with dual pressure HRSG.

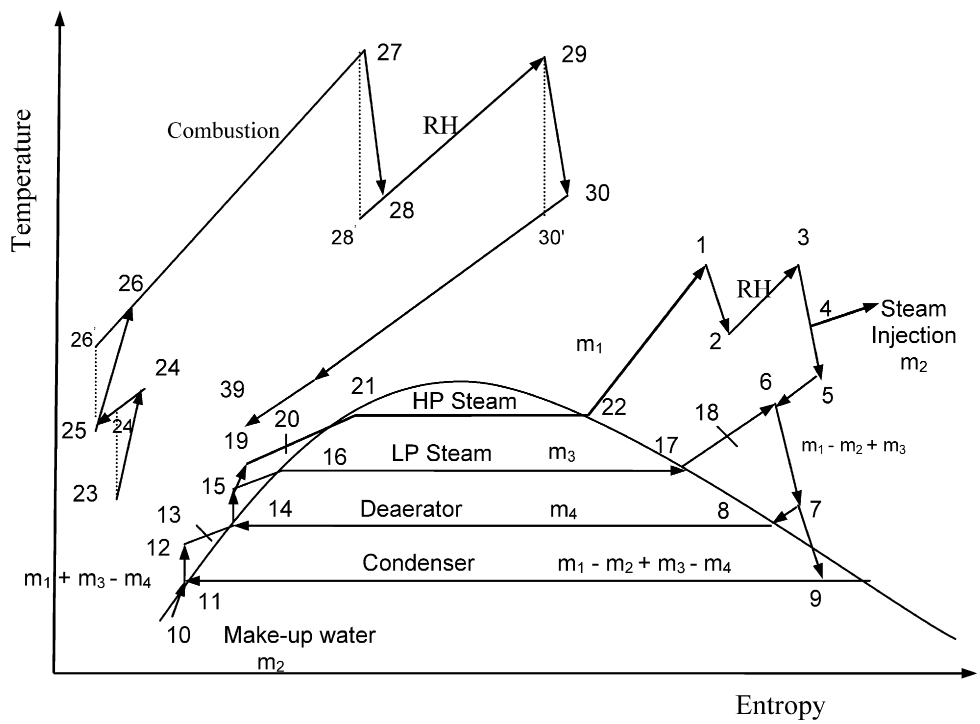

Fig. 2. Temperature–entropy diagram of combined cycle plant with steam injection and dual pressure HRSG.

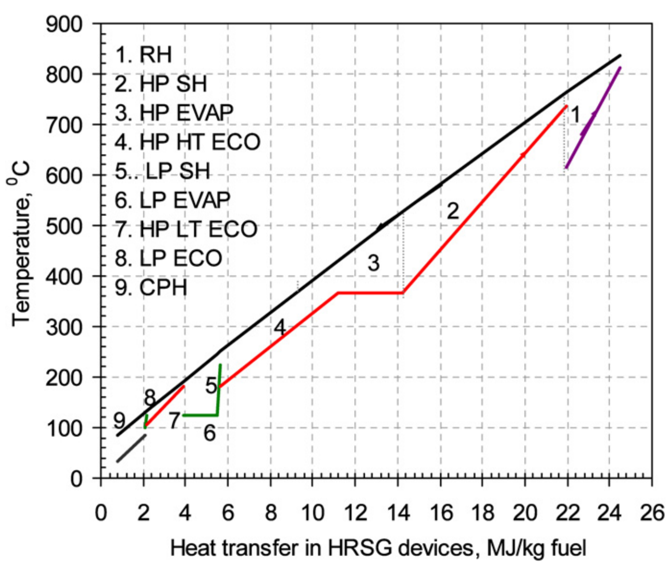

Fig. 3. Temperature-transferred heat diagram for dual pressure HRSG in the combined cycle with steam injection to fuel ratio of 2 kg/kg^{-1} and the pressure ratio of 20.

For 1 kg mol of methane, let 'a' kg mol is supplied to gas turbine combustion chamber and remaining, i.e., $(1-a)$ is supplied to gas reheater. The amount of steam injection (y, kg mol) is determined from the given steam mass ratio (kg steam/kg fuel) in main combustion chamber.

$$\text{Steam injection } (y) = \frac{\text{steam to methane mass ratio} \times M_{CH_4}}{M_{H_2O}} \quad \text{kg mol kg mol}^{-1}\text{fuel} \tag{1}$$

The combustion equation in gas turbine combustion chamber is

Table 1
Assumptions in the steam injected combined cycle with dual pressure HRSG

Atmospheric condition	25 °C and 1.01325 bar
Gas cycle pressure ratio and maximum temperature	20 and 1200 °C
Inlet pressure for HP steam turbine	200 bar
Steam reheater terminal temperature difference (TTD)—temperature difference between gas turbine outlet and reheated steam	25
Condenser pressure	0.05 bar
Deaerator temperature ratio	0.20
Steam reheat pressure	30% of HP pressure
Pinch Point (PP)—minimum temperature differences between the flue gas and the steam in the HP and LP evaporators of HRSG	65
TTD in HP/LP superheater (temperature difference between flue gas inlet and HP/LP superheated steam)	25
Degree of superheat (DSH) in LP superheater	50
Isentropic efficiency of gas turbine	90%
Isentropic efficiencies of compressor and steam turbine	85%
Pressure drop in combustion chamber	8% of combustion chamber pressure
Steam injection pressure	5% more than the combustion chamber pressure
Make-up water is supplied at condensate temperature	
Pressure drop in HRSG, deaerator and condenser is neglected	
Heat loss in HRSG, turbines, condenser, and deaerator is neglected	

$$a[CH_4 + x(O_2 + 3.76N_2) + yH_2O(g)] \rightarrow a[CO_2 + (2+y)H_2O + (x-2)O_2 + 3.76xN_2] \tag{2}$$

In this equation 'x' is the amount of air to be supplied and 'y' is the steam injection per kg mol of methane into gas turbine combustion chamber. $(x-2)$ is the excess amount of oxygen in the products of the combustion. The air requirement for the combustion is obtained by the energy balance of the chemical equation with compressed air temperature, combustion temperature (state 26 and 27 as indicated in Figs. 1 and 2) and steam injection.

The combustion equation in gas reheater is

$$a[CO_2 + (2+y)H_2O + (x-2)O_2 + 3.76xN_2] + (1-a)CH_4 \rightarrow CO_2 + (2+ay)H_2O + (ax-2)O_2 + 3.76xaN_2 \quad (3)$$

By energy balance in the reheater the value of 'a' is determined from the known temperatures of T_{28} and T_{29}, (states in gas reheater in Fig. 1 and 2) which gives the amount of fuel supplied to combustion chamber and reheater. It is observed that 58% of fuel is supplied to gas turbine combustion chamber with the steam injection and the remaining 42% is supplied to the gas reheater. The excess air coming from the combustion chamber is used in the gas reheater for the combustion of the remaining fuel. The excess amount of oxygen in the products of gas reheater is $(ax-2)$.

The steam from the HRSG enters into steam turbine to generate power. The outlet steam from HP steam turbine is mixed with the superheated LP steam.

- Over all temperature difference in the steam cycle,

$$\Delta T_{OA} = T_{HP\ sat} - T_{co} \quad (4)$$

- Excess temperature ratio of deaerator,

$$\theta_{de} = \frac{T_{de\ sat} - T_{co\ sat}}{T_{HP\ sat} - T_{co\ sat}} \quad (5)$$

- Excess temperature ratio of LP steam turbine,

$$\theta_{LP} = \frac{T_{LP\ sat} - T_{co\ sat}}{T_{HP\ sat} - T_{co\ sat}} \quad (6)$$

- At outlet of HP evaporator, the flue gas temperature,

$$T_{33} = T_{HP\ sat} + PP_{HP} \quad (7)$$

From the energy balance in the steam reheater, HP superheater and evaporator, the steam generation in the HP heaters is determined. The energy balance in the HP high temperature economizer gives the enthalpy of the flue gas at state 34 shown in Fig. 1. From this enthalpy the temperature T_{34} is determined with the iterative method.

- The saturation steam temperature in the LP heaters,

$$T_{LP\ sat} = T_{34} - TTD_{LP} - DSH_{LP} \quad (8)$$

- The superheated steam temperature in the LP superheater,

$$T_{18} = T_{34} - TTD_{LP} \quad (9)$$

- At LP evaporator, the outlet temperature of the flue gas,

$$T_{36} = T_{LP\ sat} + PP_{LP} \quad (10)$$

- The amount of steam injected in the gas turbine combustion chamber,

$$m_2 = M_{H_2O}(a \times y)\ \text{kg kg mol}^{-1}\ \text{fuel} \quad (11)$$

The temperature and enthalpy of mixed steam (HP and LP) are obtained from the mass and energy balance of the adiabatic mixing process. The work outputs and inputs are related to the unitary mass flow of fuel.

To determine the exergetic losses, the irreversibilities associated in all the components to be estimated for exergy analysis. In this analysis the efficiency and the losses are determined for 1 kg mol of the fuel.

Mass of the fuel = 1kg mol of the methane

The chemical and physical exergies are determined at each state of the cycle.

- Chemical exergy,

$$e_{ch} = \sum_k n_k \overline{\varepsilon_k^0} + RT_0 \sum_k n_k \ln.[P.x_k] \quad (12)$$

where x_k is the mol fraction of kth component
  - Physical exergy,

$$e_{ph} = h - \sum_k T_0 s_k \quad (13)$$

  - Exergy,

$$e = e_{ch} + e_{ph} \quad (14)$$

- Exergetic loss in the component of combined cycle,

$$i = e_{in} - e_{out} \quad (15)$$

- First law efficiency of combined cycle,

$$\eta_{1,cc} = \left(\frac{w_{net\ cc}}{LHV_{CH_4}}\right) \times 100 \quad (16)$$

- Second law efficiency of combined cycle,

$$\eta_{2,cc} = \left(\frac{\overline{\varepsilon_{CH_4}^0} - \sum i}{\overline{\varepsilon_{CH_4}^0}}\right) \times 100 \quad (17)$$

where $\sum i$ is the sum of exergetic losses in all the components and exergetic loss through exhaust.

4. Results and discussions

The influence of combined cycle parameters on exergy efficiency of STIG based combined cycle has been studied. The examined parameters in this analysis are steam injection mass ratio, deaerator temperature ratio, steam reheat pressure ratio, HP steam pressure, compressor pressure ratio and combustion chamber temperature. For LP and deaerator heaters, the saturation temperature over the condenser is expressed in excess temperature ratio as a fraction of the over all temperature difference between HP evaporator and the condenser. The steam reheat pressure is taken as a ratio of the HP pressure in HRSG.

Fig. 4 presents the effect of steam injection to fuel mass ratio in main combustion chamber on flue gas, air and steam generation flow rates at a gas turbine inlet temperature of 1200 °C. It is assumed that complete combustion takes place in the turbine combustion chamber and gas reheater due to excess amount

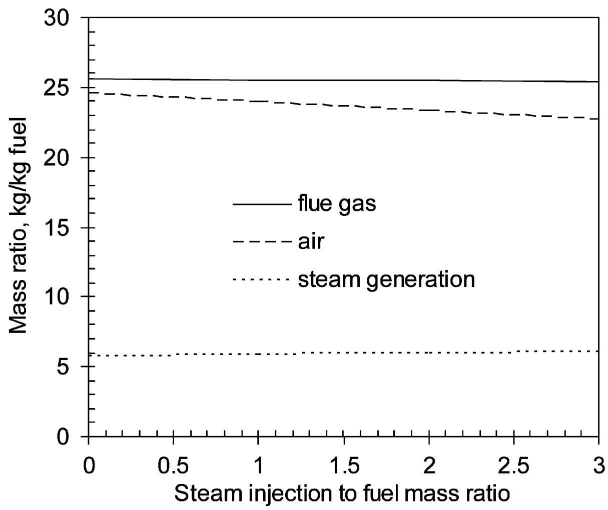

Fig. 4. Effect of steam fuel ratio in main combustion chamber on mass ratio of flue gas, air and steam generation in HRSG at the gas turbine inlet temperature of 1200 °C.

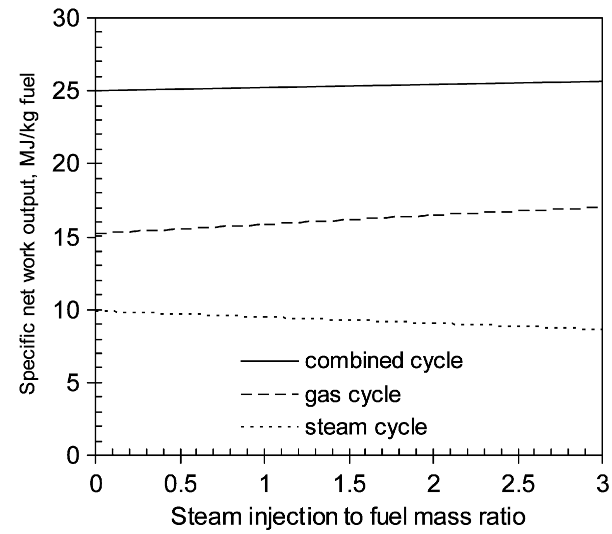

Fig. 5. Effect of steam fuel ratio in combustion chamber on the specific work output of gas, steam and the combined cycle at gas cycle pressure ratio of 20 and HP pressure of 200 bar.

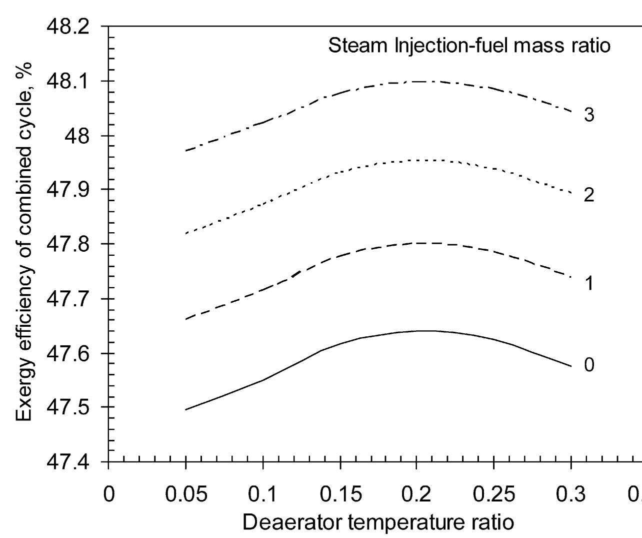

Fig. 6. Effect of deaerator temperature ratio on exergy efficiency of the combined cycle at the HP pressure of 200 bar.

air in the combustion chamber. Steam injection decreases the demand of air to combustion as steam effectively controls the combustion temperature than the air. But the air should not be decrease below a minimum requirement of complete combustion. It implies that the amount of steam injection has a limit depending on actual air quantity in compressor. From the chemical reaction equation in the gas reheater (Eq. (3)), the value of 'ax' should not be less than 2 as the excess oxygen in the gas reheater is $(ax - 2)$. The steam injection to fuel mass ratio in main combustion chamber at this value is 6.0. But to get a stable combustion, steam is injected up to the ratio of 3.0 only. Increase in the steam injection decreases the air and subsequently the exhaust gas. The steam generation rate in HRSG increases with increase in steam injection. Introduction of steam injection in combined cycle improves the efficiency of combined cycle due to decreased work input to air compressor, increased heating value at gas turbine inlet and increased steam generation rate in HRSG.

Fig. 5 depicts the effect of the steam injection rate on specific work outputs of the gas, steam and combined cycle. The diagram also shows the improvement in output of combined cycle with increase in steam injection compared to the case without steam injection (0 kg per kg fuel). The gas cycle net output increases with the increase in the steam injection. But the expansion of steam in turbine decreases with increase in steam injection, and so the steam turbine output decreases. In the plot the increasing effect of the gas turbine cycle is dominated the decreasing effect of the steam turbine output therefore, on overall basis; the combined cycle efficiency increased with the steam injection rate. Decreasing effect of excess air in the combustion chamber reduces the NO_x emission with the steam injection. At the steam injection of 2 $kg\,kg^{-1}$ fuel, the specific work outputs of gas, steam and combined cycle are 16.5, 9.0 and 25.5 MW per kg fuel respectively.

Fig. 6 generates the effect of the deaerator temperature ratio on the exergy efficiency of the combined cycle with the steam injection mass ratio. The efficiency of the combined cycle increased first and then decreased with increase in the deaerator temperature ratio for all ratios of steam injection and also for the case without steam injection. The optimum deaerator temperature ratio, which is independent of steam injection, is observed as 0.2. The exergetic efficiency of the combined cycle at the deaerator temperature ratio of 0.2 (1.0 bar) and at steam injection ratio of 0, 1, 2 and 3 are 47.6, 47.8, 48.0 and 48.1 percent respectively. At this deaerator temperature ratio, LP temperature ratio becomes to 0.30 (2.35 bar).

Fig. 7 generates the effect of steam reheat pressure as a ratio of HRSG HP pressure on exergy efficiency of the combined cycle. The steam injection is varied from 0 to 3 $kg\,kg^{-1}$ fuel in main combustion chamber. The reheat pressure as a fraction of HP pressure (200 bar) is varied from 0.15 (30 bar) to 0.5 (100 bar). At high reheat pressure, the temperature difference between flue gas and steam decreases which improves the

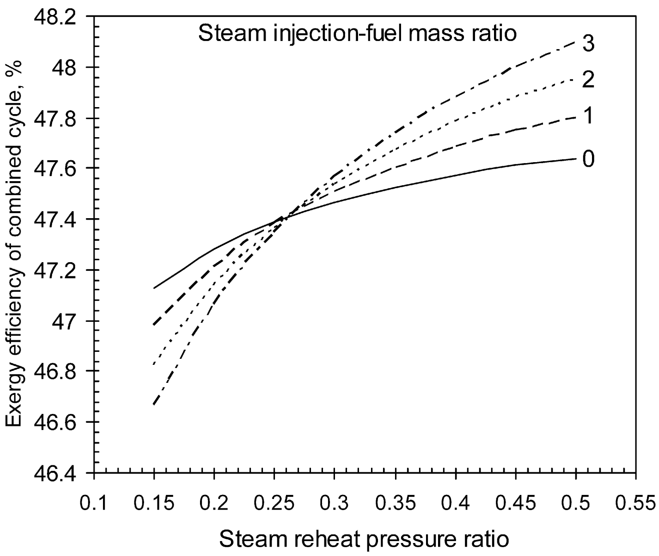

Fig. 7. Effect of steam reheat pressure ratio (fraction of HP pressure) on exergy efficiency of the combined cycle at the HP pressure of 200 bar.

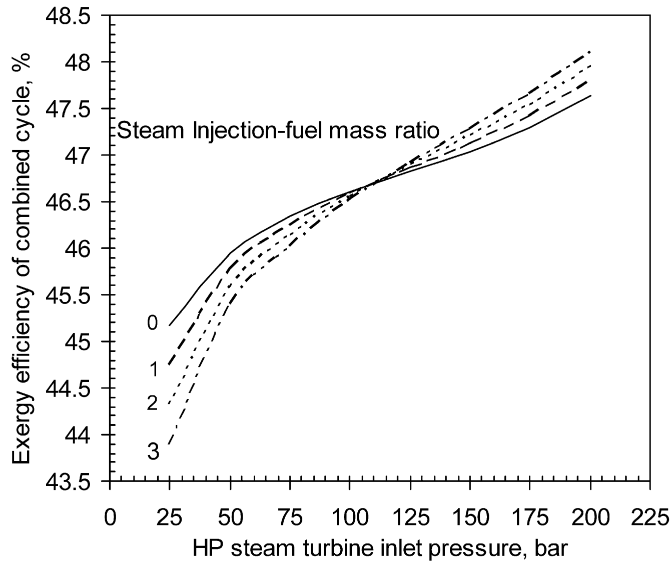

Fig. 8. Effect of HP steam turbine inlet pressure on exergy efficiency of combined cycle.

heat recovery. It increases the steam generation in HP heaters. Therefore efficiency of combined cycle increases with increase in steam reheat pressure. The benefit of steam injection to the combined cycle is obtained from the reheat pressure ratio of 0.25 (50 bar) only. Below this pressure ratio, the steam injection decreases the combined cycle efficiency. It is due to lower efficiency at low reheat pressure. But to overcome erosion of LP steam turbine blades due to wet steam at exit, the reheat pressure ratio is considered at 0.3. The exergy efficiency increases from 47.6 percent (without STIG) to 48.1 percent (with steam injection of 3 kg kg^{-1} fuel) at steam reheat pressure ratio of 0.5. The first law efficiency of the combined cycle at this reheat pressure and with the steam injection (3 kg kg^{-1} fuel) is 51.0 percent, which is not shown in this plot.

Fig. 8 shows the effect of HP steam turbine inlet pressure on exergy efficiency of the combined cycle with different steam mass ratios. The HP pressure is varied from 25 bar to 200 bar and the steam injection ratio increased from 0 to 3 kg kg^{-1} fuel to study the effect of steam injection with the HP pressure on the exergy efficiency of the combined cycle. The efficiency of the combined cycle increases with both HP pressure and steam injection. The effect of steam injection is significant at high-pressure region. The steam injection decreases the combined cycle efficiency at low HP pressures up to around 100 bar. At high HP pressure (from 100 bar), rise in gas cycle output is more than the drop in steam turbine output with the steam injection where as at low-pressure side it is not like that.

To vary the topping cycle parameters, (compressor pressure ratio and combustion temperature) the bottoming cycle parameters are selected such that the steam injection increases the efficiency of the combined cycle. The effect of compressor pressure ratio on efficiency of the combined cycle is generated in Fig. 9. The efficiency of the combined cycle increases with increase in pressure ratio reaches to maximum and decreases with further increase in the pressure ratio of the gas cycle. The optimum pressure ratio of the gas cycle is varied around 16 to 20 for all steam injection ratios. At optimum pressure ratio, the exergy efficiency of the combined cycle maximizes to 48.1 percent at 3-steam injection ratio. The effect of the combustion chamber temperature i.e. gas turbine inlet temperature on the efficiency of the combined cycle is developed in Fig. 10. The cycle efficiency increases with increase in the gas cycle temperature. The linear variation of cycle efficiency with the combustion temperature shows that the effect of temperature is more compared to other parameters. But this temperature should be kept in limit with the metallurgical properties of the materials. The exergy efficiency of combined cycle increases from 48.1 to 49.1 with increase in the combustion temperature from 1200 to 1250 °C at the steam injection of 3 kg kg^{-1} fuel and gas cycle pressure ratio of 20.

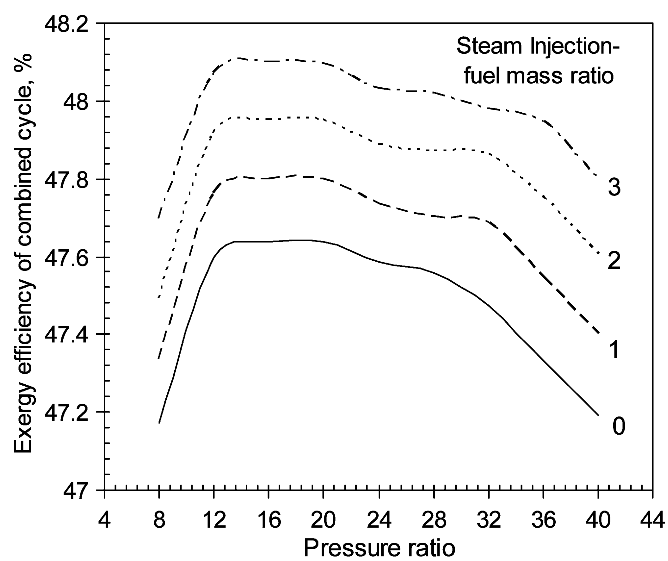

Fig. 9. Effect of gas cycle pressure ratio on exergy efficiency of STIG based combined cycle at the combustion temperature of 1200 °C.

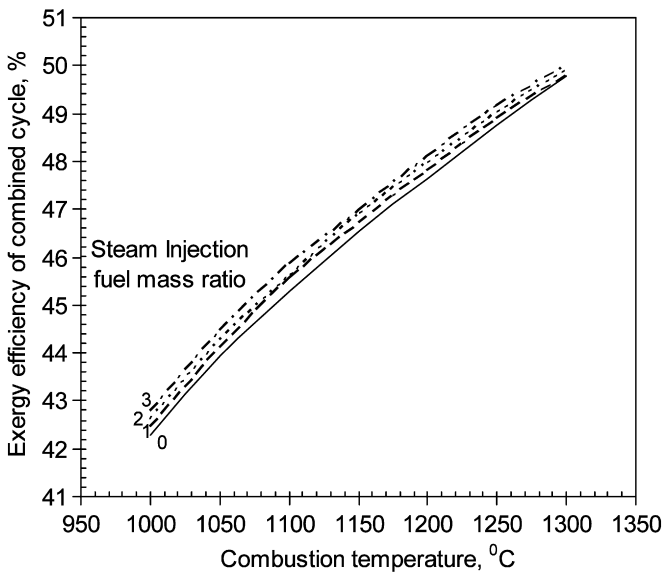

Fig. 10. Effect of combustion chamber temperature on exergy efficiency of combined cycle at the gas cycle pressure ratio of 20.

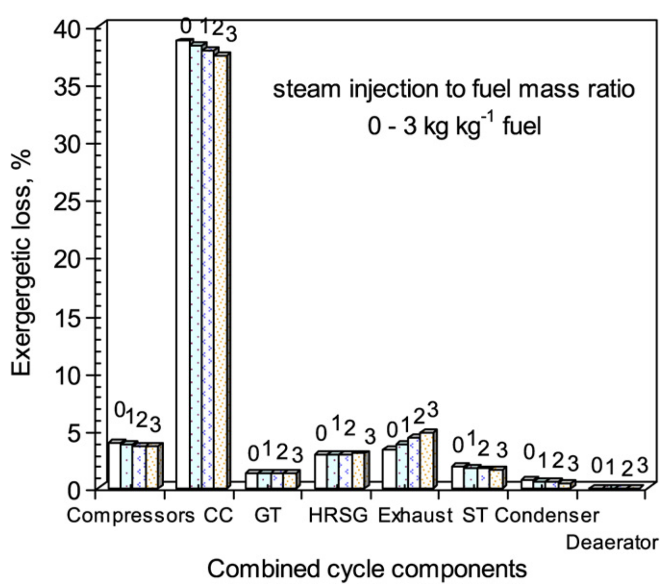

Fig. 11. Comparison of the effect of steam injection on exergetic loss of the cycle components in percent of exergy input of fuel.

Fig. 11 compares the exergetic loss in the combined cycle components with and without the steam injection in the gas turbine combustion chamber. The steam injection is varied from 0 to 3 kg kg^{-1} fuel. The exergetic loss in the compressors, combustion chamber (including gas reheater), steam turbines and condenser decreases with increase in stem injection and compared to the case without steam injection. The exergetic loss in the remaining components i.e. gas turbine, HRSG, exhaust and deaerator increases with the steam injection. The exergetic loss in air compressors decreases with the steam injection due to the decreased airflow. The major part of the exergetic loss occurs in the gas turbine combustion chamber and gas reheater, which is 38.5 percent without steam injection. The steam injection in the combustion chamber decreases this exergetic loss to 37.4 percent with the steam injection of 3 kg kg^{-1} fuel. The exergetic loss in the chemical reaction is the difference of the availability between reactants and products. The steam injection in combustion increases the availability of both reactants and the products of the combustion but the increase in the products availability is more than the increase in the reactants. So the exergetic loss in combustion chamber decreases with the steam injection. The enthalpy and entropy change in gas turbine increases with steam injection and so a minor increase in exergetic loss in gas turbine with steam injection. The loss of latent heat in the exhaust gas becomes high because a large amount of water vapor is included in the working fluid of the gas turbine. This leads to the increased exergetic loss in the exhaust gas with the steam injection. The quantity of steam for expansion in LP steam turbine and also in the condenser decreases with the steam injection. Therefore the exergetic loss in steam turbine and condenser decreases with the steam injection. The amount of bled steam into the deaerator increases with the steam injection and so the exergetic loss in the deaerator (minor loss) increases. On overall basis the total exergetic losses in combined cycle decreases with steam injection compared to the case without steam injection.

Table 2
Mass flow rates and the enthalpies in and out of HRSG sections with the steam injection of 2 kg kg^{-1} fuel (from single gas turbine unit)

	Mass flow rate of steam kg kg^{-1} fuel	Enthalpy of steam at inlet to heaters kJ kg^{-1} steam	Enthalpy of steam at outlet to heaters kJ kg^{-1} steam
Steam reheater	5.0	3614.5	4081.0
HP heaters	5.0	437.5	3851.0
LP steam	0.75	417.0	2932.5
CPH	5.6	138.0	360.5

Table 2 shows the mass flow rate along with enthalpy of steam in HRSG sections at the steam injection rate of 2 kg kg^{-1} fuel. The mass of steam is tabulated for single HRSG and therefore the steam supply to steam turbine doubles, which comes from two numbers of HRSGs.

5. Conclusion

For complete combustion in the gas turbine combustion chamber and gas reheater the maximum limit for the steam injection mass ratio is identified as 6 kg kg^{-1} fuel. The steam injection increases the gas cycle efficiency and decreases the steam cycle efficiency. But with the selection of bottoming cycle parameters, such that the decreasing effect of steam turbine output is less than the increasing effect of gas cycle output, the combined cycle efficiency can be improved with the introduction of steam injection. Steam injection gives benefits to combined cycle at high steam reheat pressure and high steam pressure. Here increasing effect of the gas cycle output exceeding the decreasing effect of the steam cycle output. The combined cycle efficiency increases with increase in the HP pressure and steam reheat pressure. The optimum deaerator temperature ratio is obtained at 0.2 for the given working conditions. Steam injection decreases combustion chamber and gas reheater exergetic loss from 38.5 to 37.4 percent compared to the case without steam injection in the combustion chamber.

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