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Effects of Steam Injection on the Performance of Natural Gas Combined Cycle Power Genertion System

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Abstract**—**In the present work, combined cycle power generation configuration studies with natural gas as a primary fuel. Steam is injected in main combustion chamber and reheat combustion chamber individually and simultaneously to understand the performance of combined cycle work output and greenhouse gas emissions. The effect of pressure ratio, gas turbine inlet temperature on combined cycle work output, thermal efficiency and exergy efficiency carried out with and without steam injection. It is observed that the steam injection increases gas cycle efficiency and decreases the steam cycle efficiency. Ideal pressure ratio found to be 25 in all different combined cycle power generation system configurations. Maximum CO_2 emission reduction (7.2%) occurs when steam injected in reheater combustion chamber.

Keywords – combined cycle; steam; turbines; energy efficiency; exergy efficiency

I. Introduction

This Research investigations are conducted to study the combined cycle power generation systems with various options to increase efficiency and to reduce carbon dioxide emissions. Srinivas et. al. [1] conducted parametric simulation of steam injected gas turbine combined cycle. Waldyr [2] compared the humid air turbine (HAT) cycle with simple gas turbine cycle, steam injected gas turbine and also with the combined cycle. Nishida et. al. [3] investigated the performance characteristics of the regenerative steam injected gas turbine system. Shukla and Singh [4] conducted thermodynamic analysis of steam injected gas turbine cycle power plant with inlet air cooling. Bahrami et. al., [5] conducted performance comparison between steam injected gas turbine and combined cycle during frequency drops. Korakianititis et. al. [6] conducted performance investigations for combine-cogeneration power plants with performance enhancements. In the present work the effect of steam injection in main and reheat gas turbine combustion chambers and the role of operating variables for different natural gas fired combined cycle power generation systems are investigated.

II. Confriguration and Methodology

A. Natural gas combined cycle configuration

Natural gas fired combined power generation systems are gaining popularity due to their higher combustion efficiency and reduced emission. Different combined cycle power generation configurations are considered in the present work and are listed in Table 1. Fig.ure 1 shows the schematic diagram of these configurations.

The topping cycle consists of air compressor ($C1$) followed by an intercooler (IC). Air is further compressed in second air compressor ($C2$). Compressed air is burned with methane in combustion chamber ($CC1$). In case of configuration #2 and #3 from Table 1, a fraction of a steam (ζ) is injected in the first combustion chamber. Products of first combustion chamber enters main gas turbine ($GT1$) and produced work output. Exhaust gas from main gas turbine further burned with methane in second combustion chamber ($CC2$). In case of configuration #3, a fraction of steam (ω) is injected in reheater combustion chamber. Product of reheater combustion chamber enters the reheater gas turbine ($GT2$) to produce work output. Exhaust gas from gas turbine enters heat recovery steam generator ($HRSG$) which produces steam in the bottoming cycle. The Steam then enters the steam turbine (ST) and produces work output. Fraction of steam (ζ and ω) is taken out at particular pressure and used in topping cycle for power augmentation. Water vapor from steam turbine is then condensed in condenser and recirculates in the bottoming cycle through pump. It is assumed that system is operating at steam state steady flow conditions.

TABLE I. CONFIGURATIONS

Configuration	Description of Study
1	Combustion of air and methane without stream injection
2	Combustion of air and methane with steam injection in main combustion chamber
3	Combustion of air and methane with steam injection in main combustion chamber and reheater combustion chamber

Figure 1 shows the generalized schematic diagram for all configuration listed in Table 1. Air is compressed from ambient condition into air compressor ($C1$) and ($C2$). An intercooler (IC) is used between $C1$ and $C2$ to bring the air temperature down and to reduce overall compressor work. Compressed air [$\phi O_2 + (\theta \times 3.76) N_2$] enters combustion chamber 1 ($CC1$) and burned with methane fuel (α) at constant pressure. Combusted gas has high thermal energy and expanded partially into Gas Turbine 1 ($GT1$) to obtain shaft work ($\dot{W}_{GT1}$). Partially expanded gas enters combustion chamber 2 ($CC2$) and burned with methane fuel (β) to elevate the thermal energy of the gas. Gas coming out of $CC2$ is expanded in Gas Turbine 2 ($GT2$) to obtain shaft work ($\dot{W}_{GT2}$). Gas coming out of $GT2$ is passed through Heat Recovery Steam Generator (HRSG) to generate more steam which passes through Steam Turbine (ST) to obtain shaft work ($\dot{W}_{ST}$). Saturated water flows through pump (P) in order to increase pressure and then passed through HRSG, which then completes the Rankine cycle.

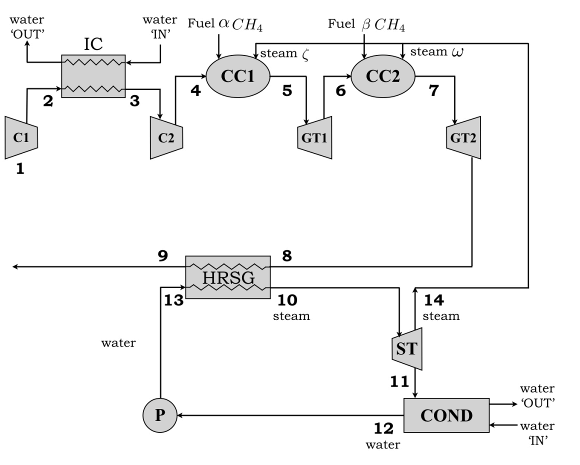

Figure 1. Schematic diagram of configuration 1, 2 and 3 (Listen in Table-1)

The configuration #2 has basic schematic same as configuration #1, except a fraction of steam (ζ) is extracted from ST and injected inside combustion chamber $CC1$ with air and fuel. The fraction of steam ζ is percentage of air mass flow which enters combustion chamber $CC1$ at state 4. The steam ζ is then taken out from steam turbine at the stage where steam pressure is 5% higher than pressure of combustion chamber 1 ($CC1$). The configuration #3 is an extension from configuration #2, where fraction of steam (ω) is injected inside of reheater combustion chamber ($CC2$). Steam is taken out of steam turbine at 5% higher pressure present inside combustion chamber 2 ($CC2$).

TABLE II. FUEL BALANCE ON $CC1$ AND $CC2$ FOR CONFIGURATION #1.

Theo_{air} [%]	α [%]	ζ [%]	TIT1 [^oC]	β [%]	ω [%]	TIT2 [^oC]	η_{th} [%]	W_c [kW]	W_{st} [kW]	W_{net} [kW]
200	40	0	1053	60	0	1222	43.38	250363	146469	348051
200	42.22	0	1074	57.78	0	1217	44.01	250363	145701	353104
200	44.44	0	1095	55.56	0	1213	44.64	250363	144921	358139
200	46.67	0	1116	53.33	0	1208	45.26	250363	144128	363155
200	48.89	0	1137	51.11	0	1204	45.89	250363	143321	368153
200	51.11	0	1157	48.89	0	1199	46.51	250363	142502	373130
200	53.33	0	1178	46.67	0	1194	47.13	250363	141670	378088
200	55.56	0	1198	44.44	0	1189	47.74	250363	140824	383024
200	57.78	0	1218	42.22	0	1184	48.35	250363	139966	387939
200	60	0	1238	40	0	1179	48.96	250363	139094	392832

B. *Thermodynamic Analysis and Methodology*

For the considered configurations energy and exergy analyses are conducted with steam injection in gas turbine combustion chambers. Equations are developed for the configurations and the role of steam injection and effect of operating variables are simulated on performance and carbon dioxide emissions..

TABLE III. FUEL BALANCE ON $CC1$ AND $CC2$ FOR CONFIGURATION #3.

Theo_{air} [%]	ζ [%]	TIT1 [^oC]	ω [%]	TIT2 [^oC]	η_{th} [%]	W_c [kW]	W_{GT} [kW]	W_{st} [kW]	W_{net} [kW]
200	1	1173	1	1169	46.93	250363	491503	136722	376533
200	2	1162	2	1146	46.52	250363	492837	132014	373246
200	3	1152	3	1123	46.08	250363	493950	127296	369729
200	4	1142	4	1102	45.62	250363	494858	122566	365996
200	5	1132	5	1081	45.13	250363	495575	117824	362060
200	6	1122	6	1061	44.61	250363	496115	113068	357934
200	7	1112	7	1042	44.08	250363	496490	108297	353627
200	8	1103	8	1023	43.52	250363	496710	103510	349152
200	9	1094	9	1005	42.94	250363	496787	98707	344516
200	10	1085	10	987.5	42.34	250363	496729	93886	339730

All simulations have been conducted using Engineering Equation Solver (EES).

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III. RESULTS AND DISCUSSIONS

A. Effects of pressure ratio on combined performance with fraction of steam injection

The effects of pressure ratio on combined cycle for both thermal and exergy efficiency is shown in Fig 2. It can be seen from Fig. 2 that there is a sharp increase in thermal efficiency for initial pressure ratio range from 5 to 25. For configuration #1, there is a reduction in thermal efficiency corresponding to pressure ratio of 25 to 40 whereas for configurations #2 and #3, there is no such noticeable reduction in thermal efficiency after optimum pressure ratio has reached. Furthermore it can be seen from Fig. 2 that there is an increase of 1.57% exergy efficiency corresponding to 5% steam injection in $CC1$ and $CC2$.

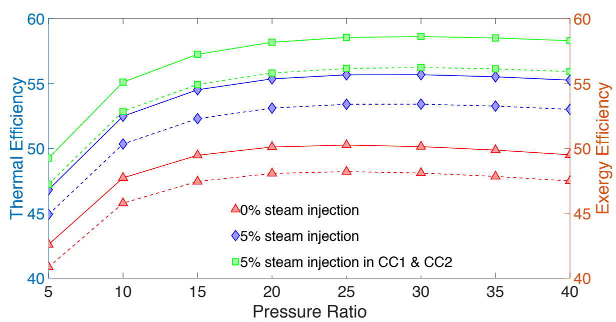

Figure 2. Effects of pressure ratio on combined cycle for both thermal (solid line) and exergy efficiency (broken line)

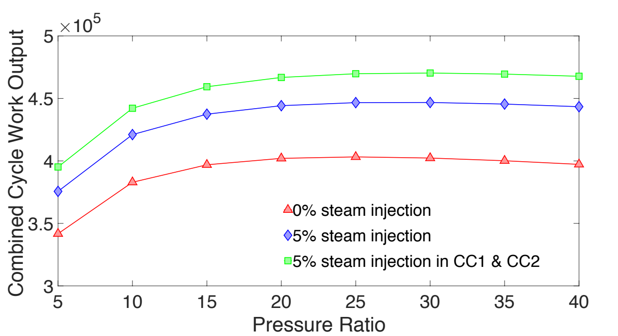

Figure 3. Effects of pressure ratio on the combined cycle work output

B. Effects on CO_2 emission with fraction of steam injection

Amount of fuel reduction with steam injection has direct impact on CO_2 emissions. The operating parameters of the combined system are set as pressure ratio = 25, Ambient temperature = $25\ ^oC$, Ambient pressure = 1 bar, Steam temperature = 500 ^oC and Steam pressure = 100 bar. The effects of steam injection on CO_2 emission is shown in Fig. 4. When steam ζ is injected to $CC1$, a constant $TIT1$ is maintained through reduction on air mass flow, thus reduction in compressor work. At this flow rate, combined cycle net work output increase by 3.2%, because of increase in mass flow of the steam from 0% to 10% in $GT1$. In order to maintain constant combined cycle work output, fuel (α) consumption reduces. And when steam ω is injected in $CC2$ only, mass flow rate affects only $GT2$ and through reduction of fuel β in $CC2$, 7.2% of CO_2 emission reduction observed. However, when steam ζ and ω were injected in $CC1$ and $CC2$ together, only 0.9% of CO_2 emission was observed. The results indicates that injecting steam in $CC2$ alone has greater effects on reduction of CO_2 emissions.

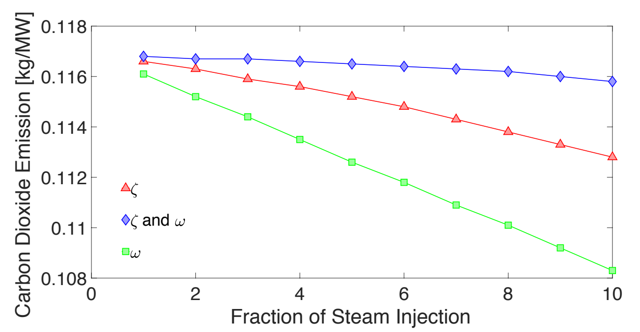

Figure 4. Effects of steam injection in $CC1$ and $CC2$ on Carbon Dioxide Emission.

C. Performance analysis on fuel ratio for combined cycle with fraction of steam injection

Table II shows fuel supply ratio between $CC1$ and $CC2$.At pressure ratio of 25 and Theo_{air} of 200%, ideal fuel supply is $\alpha = 54\%$ and $\beta = 46\%$. At this fuel supply $TIT1$ and $TIT2$ are very close to each other, which then becomes and important factor to gas turbine efficiency. Furthermore, Table III shows steam ζ and ω injected at $CC1$ and $CC2$ respectively. As steam ζ injected in $CC1$, there is a reduction in TIT1 due to increased mass from the steam, which further resulting in reduction of flame temperature. There is a sharp reduction in TIT1 of 88 ^oC with 10% steam injection in $CC1$. Further addition of steam ω in $CC2$ resulting further reduction of TIT2. Work output of the gas turbines are increased about 5MW but sharp decline in the net work output (37MW) due to work output lost from the steam turbine. Furthermore Table III shows ideal theoretical air input at different steam injection to maintain the same net work output. Theoretical air is reduced by 32%. It is assumed that complete combustion takes place in both $CC1$ and $CC2$. Steam injection decreases the amount of excess air in the combustion chamber, which also supports in controlling the temperature. The amount of steam injection has a limit depending on the air quality on the compressor. As a result of decreased fuel mass, the flue gas from the combustion chamber decreases resulting reduction in CO_2 and NO_2 emission (Fig. 4).

D. Exergy destruction in combined cycle system

Figure 6 shows exergy destruction in each individual component in combined cycle compared to overall exergy destruction in the cycle. These results corresponds to fixed turbine inlet temperature of 1200 ^oC and pressure ratio of 25. The main source of exergy destruction in the combined cycle unit are the main combustion chamber ($CC1$), reheat combustor

($CC2$) and heat recovery steam generator (HRSG) which are responsible for 37%, 20% and 16% respectively of the total exergy destruction. It can be seen from the Fig. 6 that the combustors of topping cycle have the highest exergy destruction. Moreover, reducing the destruction in the combustors of topping cycle will lead to a significant improvement in the exergetic efficiency and also reduced destruction in the combined cycle.

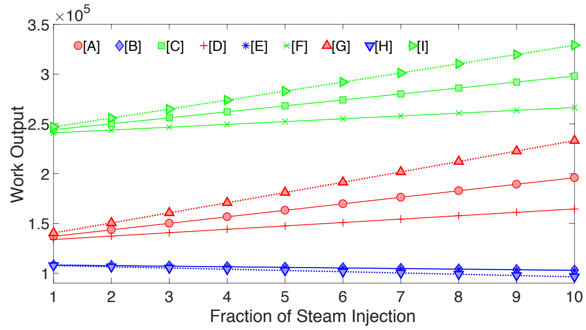

Figure 5. Effects o work output with steam injection for Configuration #1, #2 and #3.

TABLE IV. EFFECTS OF WORK OUTPUT WITH STEAM INJECTION FOR CONFIGURATION #1, #2 AND #3 (FIG. 5).

	Work Output	Steam injection in:
[A]	Gas Cycle Work Output	$CC1$
[B]	Steam Cycle Work Output	$CC1$
[C]	Combined Cycle Work Output	$CC1$
[D]	Gas Cycle Work Output	$CC2$
[E]	Steam Cycle Work Output	$CC2$
[F]	Combined Cycle Work Output	$CC2$
[G]	Gas Cycle Work Output	$CC1$ and $CC2$
[H]	Steam Cycle Work Output	$CC1$ and $CC2$
[I]	Combined Cycle Work Output	$CC1$ and $CC2$

The exergy destruction in the combustion chamber is related to chemical reaction that occurs in combustion process. The exergy destruction ratios that associated with both turbines are less than 10% of total exergy destruction of the power plant. Although the rejected heat in the condenser is considered as tremendous amount from first law of thermodynamics perspective, the exergy destruction ratio associated with the condenser unit is low because the steam at condenser condition does not have potential power to produce useful work. As the fraction of steam (5%) injected in $CC1$and $CC2$, there is a drop of exergy destruction in $CC1$ and $CC2$ by 2.3% and 2% respectively. Steam injection adds more useful work and lowers the requirement of fuel amount in combustion chamber, that further reduces the destruction.

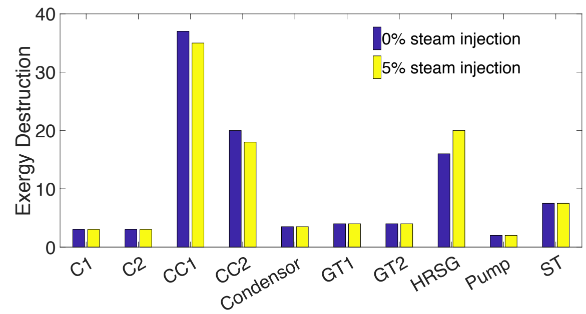

Figure 6. Percentage of exergy destruction in each component as compared to overall destruction on combined cycle with steam injection.

IV. CONCLUSIONS

It is observed that the steam injection increases gas cycle efficiency and decreases the steam cycle efficiency. Ideal pressure ratio found to be 25 for considered combined cycle power generation configurations. Steam injection in main combustion chamber and reheat combustion chamber individually has more benefit than steam injection in both combustion chambers together. Maximum CO_2 emission reduction (7.2%) occurs when steam injected in reheat combustion chamber Thermal efficiency of combined cycle system increased by 8.2% when 10% steam injection in both combustion chambers. The present results and trends on steam injection effect on work output and efficiency are in agreement with results reported in the literature.

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