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Effects of Oxyfuel Combustion on the Performance of Natural Gas Combined Cycle Power Genertion System

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Abstract—In the present work, natural gas combined cycle power generation configurations are investigated with oxyfuel combustion. Steam is also injected in main combustion chamber and reheat combustion chamber to understand the performance of combined cycle work output and greenhouse gas emission. It is observed that the steam injection increases gas cycle efficiency and decreases the steam cycle efficiency. CO_2 emission reduction of 3.2% when steam injection in both combustion chambers for oxyfuel cycle. In oxyfuel combustion, higher ratio of recycle flue gas brings higher thermal efficiency and highest thermal efficiency is achieved when steam is injected in gas turbine main combustion chamber only.

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

I. Introduction

There is growing research investigations conducted on natural gas combined cycle power generation system with oxyfuel combustion approach due to the ability to capture carbon dioxide emissions and for carbon capture and storage. Mietzko et. al. [1] reported comparison of natural gas combined cycle power plants with post combustion and oxyfuel technology at different CO_2 capture rates. Stanger et. al. [2] presented details on oxyfuel combustion for CO_2 capture in power plants. They reported an overview of the current state of the art technology on the development of oxyfuel combustion systems for CO_2 capture. Sammak et. al., [3] reported conceptual mean-line design of single and two-shaft oxyfel gas turbine in a semi closed oxyfuel combustion combined cycle. Thorbergsson and Gronstedt [4] conducted thermodynamic analysis of two competing mid-sized oxyfuel combustion combined cycles. Jericha et. al., [5] presented gas turbine with CO_2 retention for 400MW oxyfuel system Graz Cycle. Woollatt and Franco [6] reported details on conceptual aerodynamic design of turbo-machinery components for natural gas oxyfuel cycles. Mathieu and Bolland [7] presented results on comparison of costs for natural gas power generation with CO_2 capture. In the present work, natural gas combined cycle power generation configurations are investigated with with oxy fuel combustion. Steam is also injected in main combustion chamber and reheat combustion chambers to understand the performance of combined cycle work output and greenhouse gas emissions.

II. Confriguration and Methodology

A. Natural gas combined cycle configuration

Natural gas fired oxyfuel combustion combined power generation systems gaining popularity for carbon capture and storage. In the present work different oxyfuel combined cycle power generation configurations as listed in Table 1 are considered. Figure 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.

In configuration #1, pure oxygen (ϕ) obtained from air separator unit (ASU) is used as oxidizing agent and burned in $CC1$ with main combustion chamber fuel α and in $CC2$ with fuel supply β. Expanded gas after $GT2$ is passed through $HRSG$ and steam is generated to operate bottoming Rankin cycle. Exhaust gas after $HRSG$ contains only CO_2 and water vapor. Water vapor is condensed through water separator (WS) and removed from exhaust gas.

Combustion of methane and pure oxygen produces very high flame temperature, which is not suitable for turbine operation at this stage. A fraction of CO_2, defined as λ is compressed in three compressors ($C3$, $C4$, $C5$) coupled with intercooler between each compression. Highly compressed λCO_2 is removed from the cycle for sequestration. Remaining part of CO_2 defined as $(1-\lambda)$ is compressed in $C1$ and $C2$ and recycled back to $CC1$ to bring the flame temperature down to suitable operative condition.

TABLE I. CONFIGURATIONS

Configuration	Description of Study
# 1	Combustion of oxygen and methane without stream injection
# 2	Combustion of oxygen and methane with steam injection in main combustion chamber
# 3	Combustion of oxygen and methane with steam injection in main combustion chamber and re-heater combustion chamber

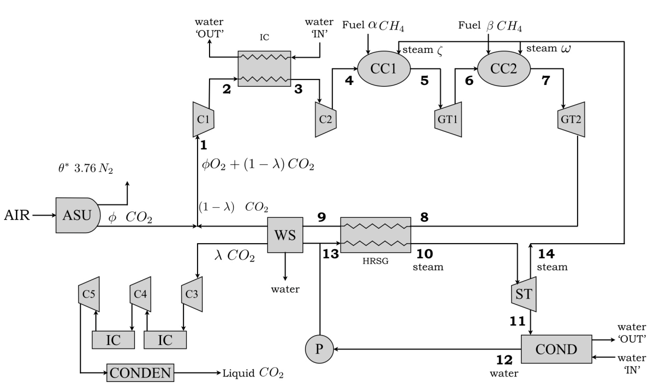

Figure 1. Schematic diagram of configuration 1, 2 and 3 (Listen in Table-1)

Similar to configuration #1, in configuration #2, a fraction of steam ζ is extracted from ST and injected inside $CC1$ with pure oxygen ϕ and fuel α. The $CC2$ is not injected with steam, where steam is taken from steam turbine at 5% higher pressure than pressure present inside the $CC1$. As an extension of configuration #2, in configuration #3, additional steam ω is taken from steam turbine and injected inside of $CC2$. Pressure at which ω is extracted from steam turbine is 5% higher than pressure present at $CC2$.

TABLE II. EFFECTS OF FLUE GAS RECYCLE ON TURBINE INLET TEMPERATURE IN COMBINED CYCLE STEAM – CONFIGURATION #1.

λ [%]	90	80	60	40	20	0
$TIT1$ [°C]	1552	1643	1871	2194	2687	3545
$TIT2$ [°C]	1619	1697	1880	2105	2383	2710

B. *Thermodynamic Analysis and Methodology*

For the considered natural gas oxyfuel combined cycle power generation systems energy and exergy analyses are conducted. Equations are developed and simulations are conducted to investigate the role of flue gas recycle ratio and steam injection on thermal efficiency and CO_2 reduction.

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

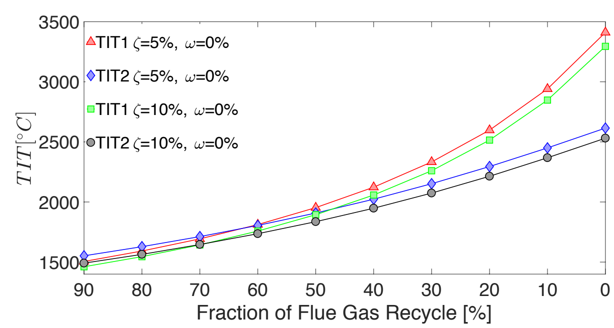

Figure 2. Effects of steam injection on TIT with fraction of flue gas recycle (Configuration #2)

III. RESULTS AND DISCUSSIONS

A. *Effects of flue gas recycle on turbine inlet temperatures*

When fuel is burned with pure oxygen, it produces very high TIT (Turbine Inlet Temperature) which is not desirable for current operational turbine blades.

To bring TIT to operable level, the flue gas λ is recycled to the combustion chamber once all water vapor is isolated. Table 2 shows the effects of λ on $TIT1$ and $TIT2$ when fuel supply is maintained at $\alpha = 54\%$ and $\beta = 46\%$.

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B. Effects of steam injection on TIT with fraction of flue gas recycle

Figure 2 shows the effects of steam injection (with 5% and 10% respectively) only in the $CC1$. Steam addition helps to lower the TIT as it adds mass of steam in combustion chamber. As more steam in injected in $CC1$, additional mass flow from steam reduces the TIT to the operational level of $1000^oC - 1400^oC$ (i.e. configuration #3, figure not shown here). Furthermore fig. 3 shows combined cycle efficiency if maximum when steam injected only in $CC1$ and minimum when steam is injected in $CC1$ and $CC2$ together. Higher efficiency can be obtained from configuration #2 and #3.

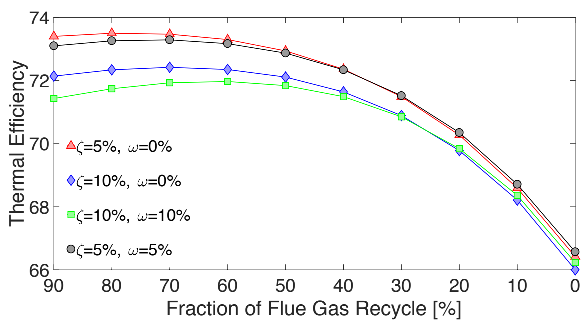

Figure 3. Effects of steam injection on combined cycle thermal efficiency with fractioin of flue gas recycle (Configuration #2 and #3)

C. Effects of pressure ratio on combined cycle work output, efficiencies and CO_2 emission

Various pressure ratio applied to the oxyfuel combustion system at fixed $TIT1$ and $TIT2$ of 1200^oC. Figure 4 shows the effects of pressure ratio on both the topping cycle work output and combined cycle work output for all configuration listed in Table 1.

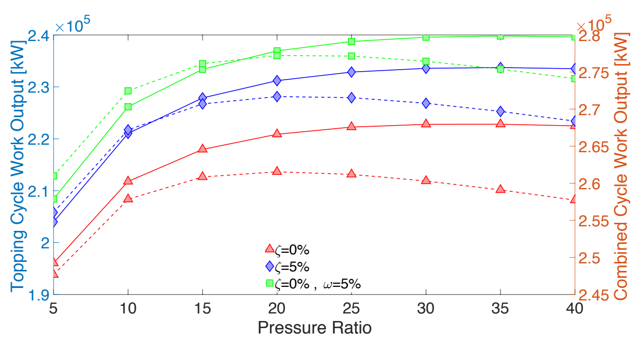

Figure 4. Effects of pressure ratio on topping cycle work output (left axis) and on combined cycle work output (right axis dotted line) for Configuration #1, #2 and #3.

It can be seen from Fig 4 that topping cycle increases work output up to pressure ratio of 25 and then remains constant at higher pressure ratio. Adding 5% steam injection at $CC1$ further increases the topping work output and 5% steam injection at $CC1$ and $CC2$ brings topping cycle work slightly higher. There is an increase of 2.3% work output when steam injected in $CC1$ only and 0.3% further increase when steam is injected in both combustion chambers.

Figure 5 shows the CO_2 emission for all configuration considered here. It can be observed from Fig 5 that, the lowest emission accounts in configuration #3 with corresponding pressure ratio of 25 and steam injection of 5%.

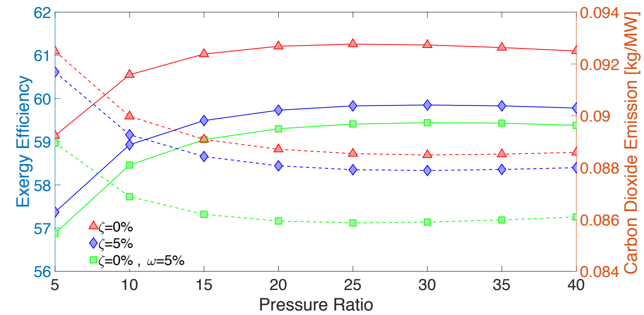

Figure 5. Effects of pressure ratio on exergy efficiency (left axis) and on CO_2 emission (right axis dotted line) for Configuration #1, #2 and #3

IV. Conclusions

CO_2 emission reduction of 3.2% when steam injection in both combustion chambers for oxyfuel cycle. In oxyfuel combustion, higher ratio of recycle flue gas brings higher thermal efficiency and highest thermal efficiency is achieved when steam is injected in main combustion chamber only. More than 10% steam in combustion chamber brings combined cycle thermal efficiency down. The present results and trends on oxyfuel combustion work are in agreement with results reported in the literature.

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