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Energy, Exergy & Environmental Analysis of a Combined Cycle With Pre-combustion CO_2 Capture and N_2 Injected into the Compressor of the Gas Turbine

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ABSTRACT

Power plants are a major source of CO_2 emissions in the environment, which cause global warming; due to this issue, CO_2 capture from hydrocarbon fuels is one of the key technology options to reduce greenhouse gases. Pre-combustion capture of CO_2 in the combined gas and steam turbine cycle has been investigated in this paper. The first step in the pre-combustion method is to react the fuel with oxygen, which comes from the air separation unit and produces a mixture of hydrogen and carbon monoxide. The CO is converted to CO_2 in a water-shift reactor, and a physical absorbent removes the CO_2; a hydrogen-rich fuel is produced, which can be burnt in a gas turbine with minimal CO_2 emissions.

This paper presents a thermodynamic cycle analysis, where pre-combustion CO_2 capture is applied in a combined cycle where the main goal is to reduce the CO_2 emission into the atmosphere. The main parameters are varied to examine the influence on cycle performance. The cycle performance results for the combined cycle with CH_4 as fuel are presented and compared to the combined cycle with precombustion CO_2 capture, both with and without Nitrogen injection into the compressor. An exergy analysis is carried out to determine which case has more exergy destruction. The results indicate that at 45 ^{o}C the combined cycle efficiency is raised by around 3 % when the pre-combustion CO_2 capture without Nitrogen injection into the compressor is used, and the power output has been increased by 29 %. The performance of combined cycle with CO_2 capture can be further enhanced by the N_2 acquired from the air separation process and injected into the compressor's middle stage. The results demonstrate a good improvement in the performance; the power output increases by 48 % and efficiency by 4.2 %. However, exergy destruction is increased when the CO_2 capture, both with and without N_2 injection into the compressor is used. Nevertheless, pre-combustion capture requires large monetary investment for a new-build plant where also the CO_2 emission is reduced by 100 %.

Keywords: CO_2 Capture, gas turbine, combined cycle, N2 injected, energy, and exergy analyses

Nomenclature

Symbol

Cp	specific heat (kJ/kg. K)

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CO_2	Carbon dioxide
N_2	Nitrogen
η	Efficiency
h	Enthalpy (kJ/kg)
I	Irreversibility (kW)
m	mass flow rate (kg/s)
P_G	is the power of the gas turbine.
Q_{in}	inlet heat (kW)
R_g	universal gas constant
s	Entropy (kJ/kg. K)
T_0	Atmospheric temperature (298 K)
φ	exergy (kW)

Subscripts

a	air
ex	exit
in	inlet
f	fuel
g	gas
gen	generation

INTRODUCTION

Gas turbine technology is widely used, the simple gas turbine cycle has low thermal efficiency, especially in hot climatic conditions, but innovation constantly drives new improvements in performance. There are a few different methods that are used to improve a gas turbine's efficiency and power output, the most popular way is the gas and steam turbine combined cycle, in addition, the methods employing steam injected into the gas turbine cycle components show even more success in improving the gas turbine cycle performance [1]. In its most basic configuration, the air in the simple cycle gas turbine is compressed and mixed with the fuel (usually natural gas) and burned in a combustor. The resulting exhaust gases expand through the turbine that drives the compressor and an electric generator. In a combined cycle gas turbine plant, the hot exhaust gases leaving the turbine pass through a heat recovery steam generator, producing steam to generate more electricity with no additional fuel as shown in figure 1**.**

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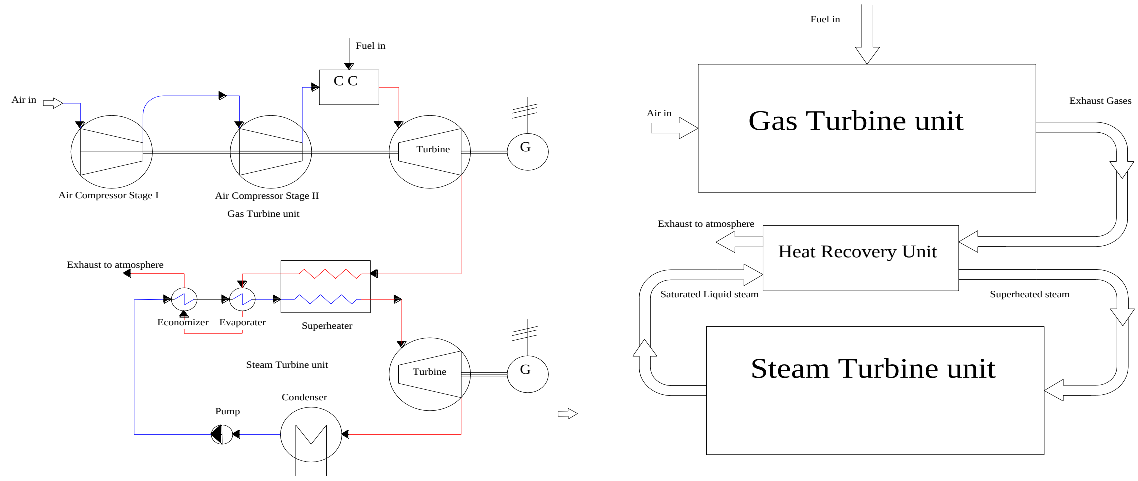

Figure 1 Gas and Steam Combined Cycle

On the other hand, the levels of atmospheric carbon dioxide, and other greenhouse gases are on the rise and are causing global warming. Fossil-fuelled power generation and other man-made greenhouse gas sources mostly emit CO_2, with the power generation sector being the largest emitter of carbon dioxide (International Energy Agency, 2006) [2]. Thus, CO_2 capture in fossil fuel power plants can be used to control and limit the emission of greenhouse gases and thereby reduce the rise in atmospheric temperature.

One of the methods for the capture of CO_2 from fossil fuel power generation is Pre-combustion capture, which is removing CO_2 from the fuel before combustion is completed, this method is an alternative to combusting fuel directly in a combustor. Initially, synthesis gas (syngas), which is a mixture of mainly H_2 and CO with a trace of CO_2, is produced from a fossil fuel, it can be done by adding oxygen that is separated from the air in an air separation plant to the fossil fuel [3]. This process is called partial oxidation and the reaction for this process is given below,

$$C_x H_y + x/2\, O_2 \rightarrow xCO + (y/2)\, H_2$$

This synthesis gas, or syngas, can then undergo the water-gas shift reaction to convert CO and H_2O to H_2 and CO_2 [4].

Water gas shift reaction: $CO + H_2O \leftrightharpoons CO_2 + H_2$.

The CO_2 can then be captured, separated, transported, and ultimately sequestered, and pure H_2 is further used as a fuel for the combined cycle to produce electricity [5].

This study focuses on the pre-combustion approach to control the gas emission by removing the greenhouse gases such as CO_2 to the environment, we first convert the fuel into H_2 and CO_2, subsequently separating CO_2 from the fuel gases (CH_4) which can be stored permanently or reutilized industrially while the hydrogen is used as a fuel. Furthermore, this approach examines how Nitrogen (N_2), after separating it from air and injecting it into the compressor, improves the cycle's performance, it is used to compensate for the fuel mass shortage when the combined cycle runs at full load. The injection of Nitrogen into the compressor has a significant role in improving the combined cycle's performance, increasing efficiency and power

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output. These benefits can lead to the ability to produce more power in peak time and base load operation. The IPSEpro program has been used to model and examine the combined thermodynamic cycles to determine the optimum mode of operation and configuration [6].

SYSTEM ANALYSIS

Another option currently being developed is to utilize hydrogen as a fuel for the power plant using a pre-combustion method. The studies show that the combined cycles with natural gas as a fuel using a pre-combustion method to capture the carbon dioxide improves greenhouse gas control. The main disadvantage of pre-combustion capture is that it requires a chemical plant in front of the turbine. Complicated chemical processes normally cause extra shutdowns of the plant, resulting in lower power output [7]. In this study after using pre combustion capture, H_2 has been obtained and used as a fuel for the combined cycle. A simplified schematic of the combined cycle integrated with pre-combustion capture is shown in figure 2.

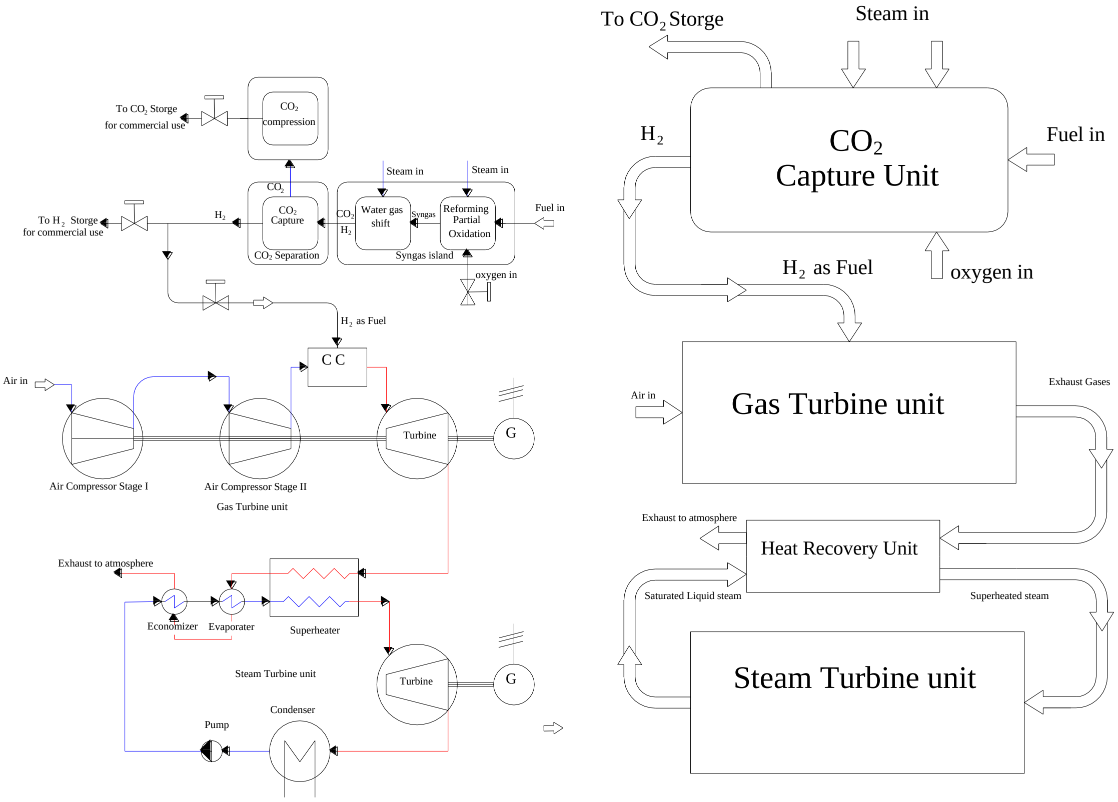

Figure 2 Pre-Combustion Combined Cycle

The system shown in figure 3 represents the combined cycle and the injection of N_2 into the compressor to enhance the cycle's performance. The purpose of the compressor is to compress the inlet air (raise its pressure). After the air- N_2 mixture is discharged from the compressor at high-pressure, it is sent to the combustor, mixed with H_2, and combustion occurs. The hot pressurized gas exits the combustors at a very high temperature up to 1117 °C. This gas then passes through a gas turbine, giving the turbine energy to spin the compressor and the power for a generator to produce electricity and the hot exhaust gases leaving the turbine pass through a heat recovery steam generator, producing steam that is used to generate more electricity with no additional fuel. Based on the first and second laws of thermodynamics, this work examines the combined cycle's performance, using the energy and the exergy analysis in the combined cycle operation.

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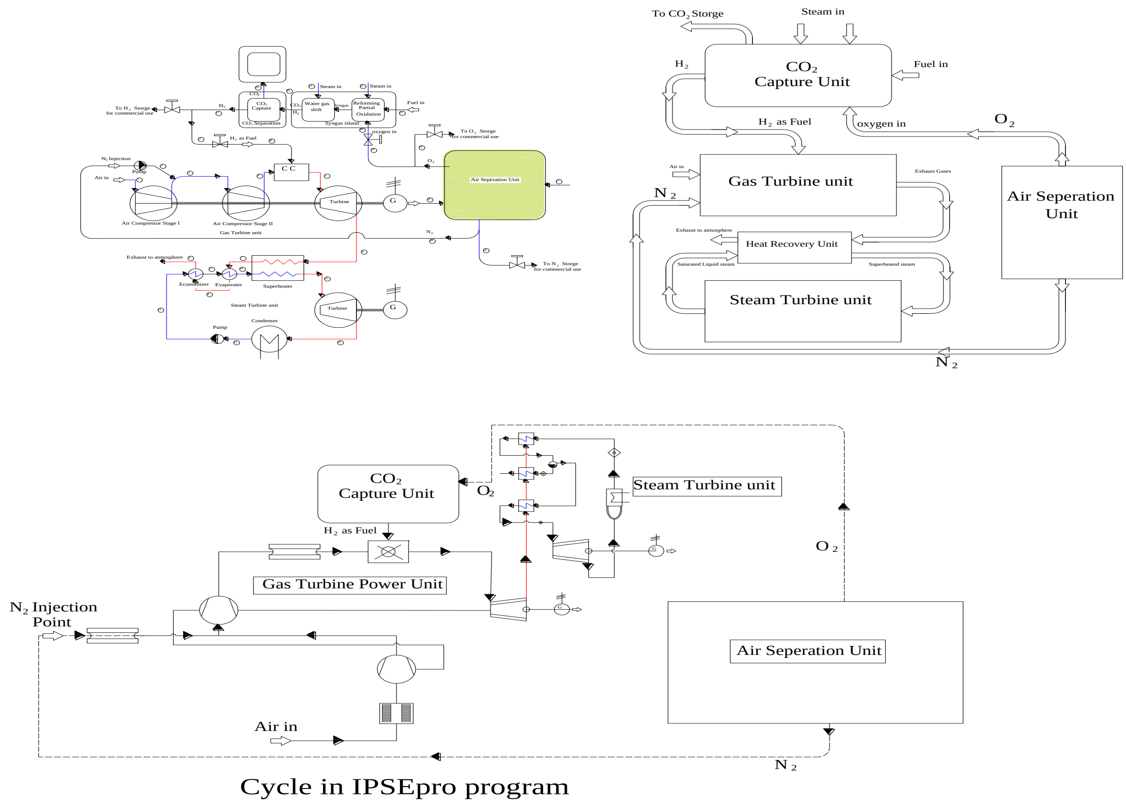

Figure 3 Pre-Combustion Combined Cycle with N_2 Injection

THERMODYNAMIC ANALYSIS

The present study introduces the energy and exergy analysis for the combined cycle with pre-combustion CO_2 capture and N_2 injected into the compressor. The analysis investigated the cycle performance due tochanges in the ambient temperatures.

Assumptions

The following assumptions are made to simplify the calculations; however, they can be refined to reach more real solutions. The main assumptions are:

Hydrogen (H_2) gas enters a steady-flow adiabatic combustion chamber at 25°C and 20 bar.

Mass of air m_{air} = 393kg/s

Design Parameters	
Ambient temperature T_a	15^oC
Inlet pressure P_{air}	1.002 bar
Air Humidity	60 %
The input data for the compressor	
Compressor isentropic efficiency η_s	0.87
Compressor mechanical efficiency η_m	0.99

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Pressure ratio P_2/P_1	11
Pressure drops in the combustion chamber (ΔP)	0.1 bar
The input data for turbine:	
Turbine mechanical efficiency η_m	0.99
Turbine isentropic efficiency η_s	0.9
The characteristics of the heat exchanger are:	
The pressure drops of the hot temperature side	0.1 bar
The pressure drops of the low temperature side	0.1 bar

The temperature increase of the air during the compression is:

$$\left(\frac{dT_{ex-in}}{T_{in}}\right)_{actual} = \left(\left(\frac{P_{ex}}{P_{in}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right) \Big/ \eta_s \quad (1)$$

Where,

$$\gamma = \frac{Cp}{Cv}$$

T_{in}: Compressor inlet Temperature [K]

T_{ex}: Compressor outlet Temperature [K]

$dT_{ex\text{-}in}$: Temperature different between *inlet* and exit

P_{in}: Compressor inlet pressure

P_{ex}: Compressor outlet pressure

Compressor Injected with Nitrogen Analysis

$$\eta c = \frac{\left(\left(\frac{P_{ex}}{P_{in}}\right)^{\frac{\gamma-1}{\gamma}} -1\right)C_p * \dot{m}_a * T_{in} + \left(\left(\frac{P_{ex}}{P_{in}}\right)^{\frac{\gamma-1}{\gamma}} -1\right)C_{pN2} * \dot{m}_{N2} * T_{in,N2}}{(\dot{m}_a + \dot{m}_{N2})C_{p2} * T_{ex} - \left((C_p * \dot{m}_a * T_{in}) + (C_{pN2} * \dot{m}_{N2} * T_{in,N2})\right)} \quad (2)$$

The pressure ratio P_{ex}/P_{in} can be obtained directly from the combustion chamber pressure loss.

$$\frac{P_{ex}}{P_{in}} = 1 - \left[\Delta P / P_{ex}\right] \quad (3)$$

The overall efficiency of the combined cycle (η_{CC}) calculated using the following equation.

$$\eta = \frac{P_G}{m_f * Low\ heating\ vaue} \quad (4)$$

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EXERGY DESTRUCTION IN THE COMPONENTS OF THE COMBINED CYCLE

The complex thermodynamic analysis of the combined cycle is based on the second law of thermodynamics because the conventional first law analysis of any thermodynamic system has the capability to determine the energy distribution across the system boundaries but does not explain the means of energy degradation that cause decreases in the power output of the system. The exergy analyses for the gas turbine components have been conducted to determine the energy loss caused by irreversible processes. Exergy analysis usually predicts an energy system's thermodynamic performance and the system components efficiency by quantifying the entropy generation of the components. This analysis provides a tool for the optimal design and operation of complex thermal systems. The exergy and irreversibility equations for each component are written as follows [8],

Compressor: The exergy and irreversibility in the compressor is given by

$$\Delta\varphi = \left(\left((m_a * h_{in}) + (m_{N2} * h_{N2})\right) - \left((m_{N2} + m_a) * h_{ex}\right)\right) - 298 * \left(\left((m_a * s_{in}) + (m_{N2} * s_{N2})\right) - \left((m_{N2} + m_a) * s_{ex}\right)\right) \quad (5)$$

$$I = T_0 * [\left((m_a + m_{N2}) * s_{ex}\right) - [(m_a * s_a) + (m_{N2} * s_{N2})]] \quad (6)$$

Combustion Chamber: As an approximation, the virtual power is used to calculate the combustor component's exergy. The exergy balance of this component and exergy loss due to irreversibility in the combustion chamber is given by**:**

$$\varphi_{c.c} = Q_{in} + T_o S_{gen} \quad (7)$$

$$I_{c\cdot c} = T_0 S_{gen} \quad (8)$$

Where

$$S_{gen} = (\dot{m}_a + \dot{m}_f)\left(c_p ln\frac{T_{ex}}{T_{in}}\right) - \frac{Q_{in}}{T_{av}} \quad (9)$$

And = average (T_{ex}, T_{in})

Turbine

The exergy loss due to irreversibility in a gas turbine is given by:

$$\varphi_T = m_g(h_{in} - h_{ex}) - T_o m_g(s_{in} - s_{ex}) \quad (10)$$

$$I_{GT} = m_g T_o(s_{ex} - s_{in}) \quad (11)$$

where

$$(s_{ex} - s_{in}) = C_{Pg} ln\frac{T_{ex}}{T_{in}} - R_g ln\frac{P_{ex}}{P_{in}} \quad (12)$$

and

$$R_g = C_{Pg}\frac{(\gamma-1)}{\gamma} \quad (13)$$

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DISCUSSION OF THE RESULTS

Based on the methodology developed and the thermodynamic equations shown in this study, the effect of ambient conditions on the performance and the destruction of exergy due to irreversibility in the gas turbine components is displayed graphically, with and without nitrogen injection into the compressor. The exergy destruction is obtained from the exergy analysis, in addition, the impact of CO_2 capture is shown in the results. The following figures show the change in the combined cycle performance with changing ambient temperature [15-45 ^{0}C].

To improve the power output of the combined cycle, N_2 injection into the compressor is employed. The higher value of LHV "lower heating value" of H_2 means less mass flow rate in the fuel stream which leads to increased efficiency and power output.

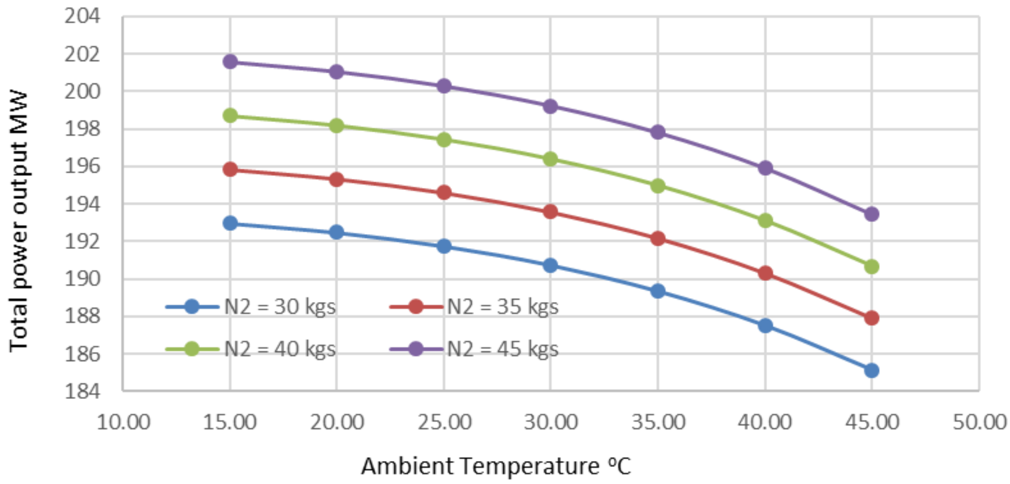

Figure 4: The power output of the combined cycle with injection of different N_2 mass flow rate as a function of ambient temperature

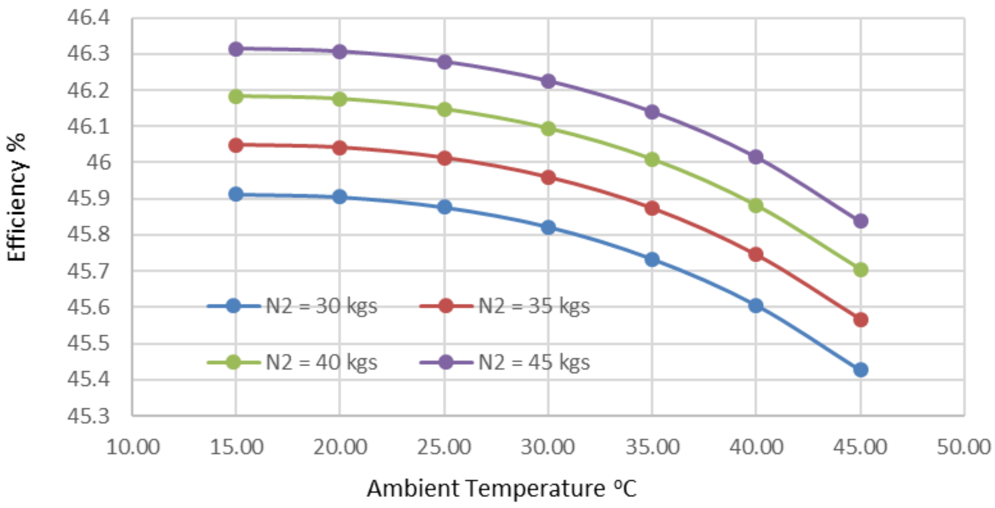

Figure 5: The efficiency of the combined cycle with injection of different N_2 mass flow rate as a function of ambient temperature

Detailed pre combustion combined cycle efficiency and power output analyses are performed on four different N_2 mass flowrate injections (30 kg/s – 45 kg/s), also the effect of ambient temperature for each N_2 mass flowrates is performed. Figures 4 & 5 shows that total power output and the combined cycle efficiency are increases as the mass flowrate of N_2 injected increases, and that indicates that the pre-combustion combined cycle with N_2 injection improves the cycle performance. However, the power output and efficiency are decreases as the ambient temperature increases in all examined N2 flowrates. So that the mass flowrate of (45 kg/s) N2 injected into the cycle is recommended for farther analysis.

The variation of the power output and efficiency against ambient temperature for the three different cases, (normal combined cycle, pre combustion combined cycle without N_2 injection and pre combustion combined cycle with (45 kg/s) N_2 injection) are shown in Figures 6 and 7 respectively.

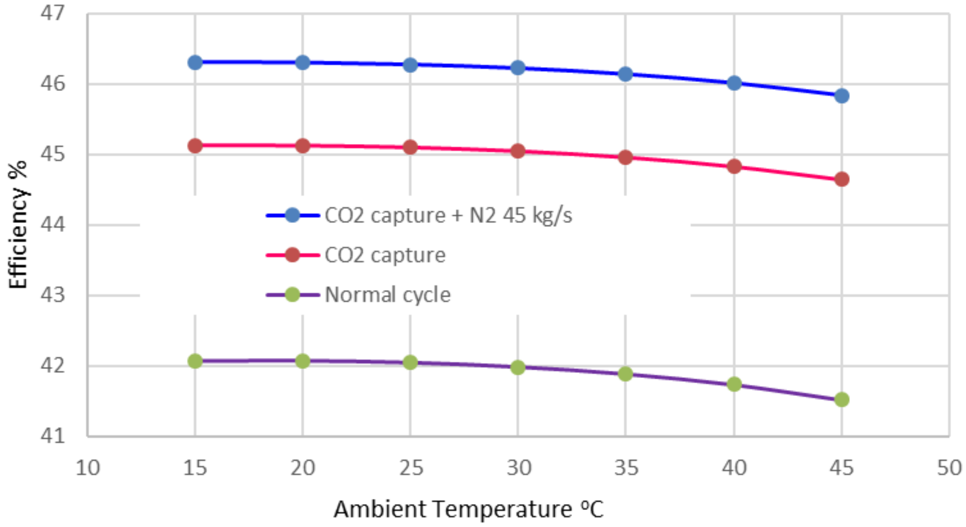

Figure 6: The efficiency of the 3 cases of the combined cycle as a function of ambient temperature

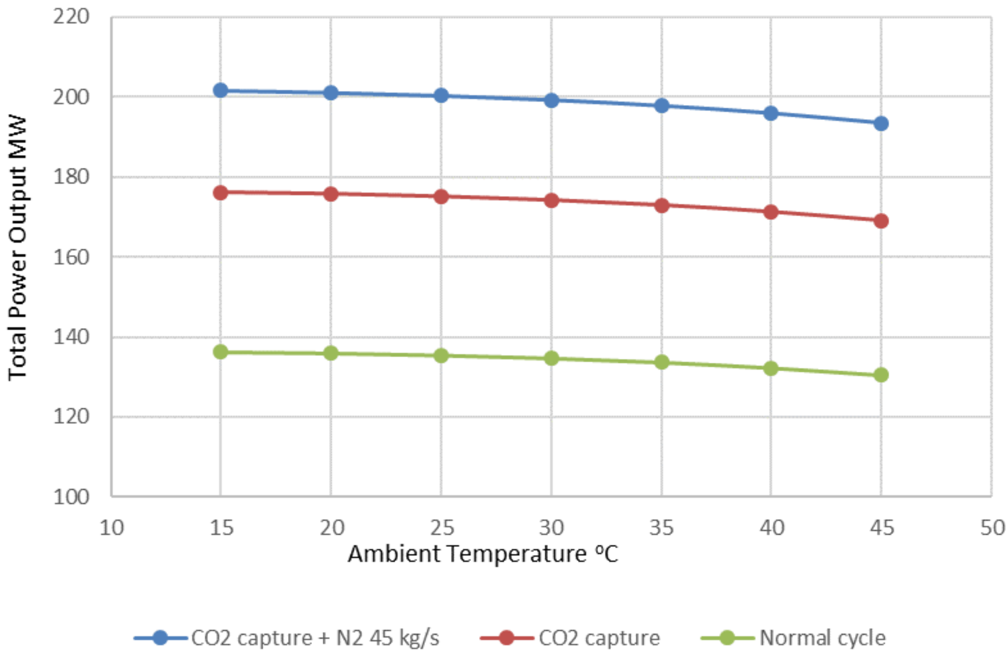

Figure 7: The power output of the 3 cases pf the combined cycle as a function of ambient temperature

Figures 6 and 7, demonstrates the effect of ambient temperature on the efficiency and the power output of the combined cycle for the different 3 cases. The cycle efficiency and the power output does not show much change with ambient temperature between 15 ºC to 45 ºC. The bottom curve in figure 6, represents the efficiency of conventional cycle that uses CH_4 as fuel, where the efficiency is lower compared to the pre-combustion cycles represented by the top 2 curves, the top curve demonstrating that when N_2 has been injected into the pre-combustion cycle, the cycle's performance has further improved, with an increase in efficiency by 4.2 % compared to the normal combined cycle. Figure 7 shows that the combined cycle with CO_2 capture without N_2 injection increases the power output by about 29 % compared to the normal cycle, moreover, the N_2 injected into the compressor achieves the highest power output. And the result shows an improvement in the power output is increased by about 48 % in the combined cycle with N_2 injection and CO_2 capture when compared with the normal combined cycle.

Exergy analysis identifies the causes and locations of thermodynamic losses more clearly than energy analysis. Consequently, exergy analysis can help in improving and optimizing designs. The exergy of the combustion chamber is affected by modifications made to the normal cycle as shown in figure 8. The exergy losses in the combined cycle components in three different cases are presented. The results show that when CO_2 capture is implemented, the exergy loss will be higher than the normal cycle exergy loss, however, as the N_2 is injected into the compressor, the exergy loss will be maximized. Exergy loss in the combustion chamber is the largest of all component losses in the gas turbine cycle. The exergy destruction during the combustion process was different for the different fuels. The exergy loss when using H_2 as a fuel increased by 18 % compared to CH_4. The combustion chamber has the biggest exergy loss in the combined cycle, a loss of around 130 MW, while the air compressor has a loss of roughly 7.5 MW.

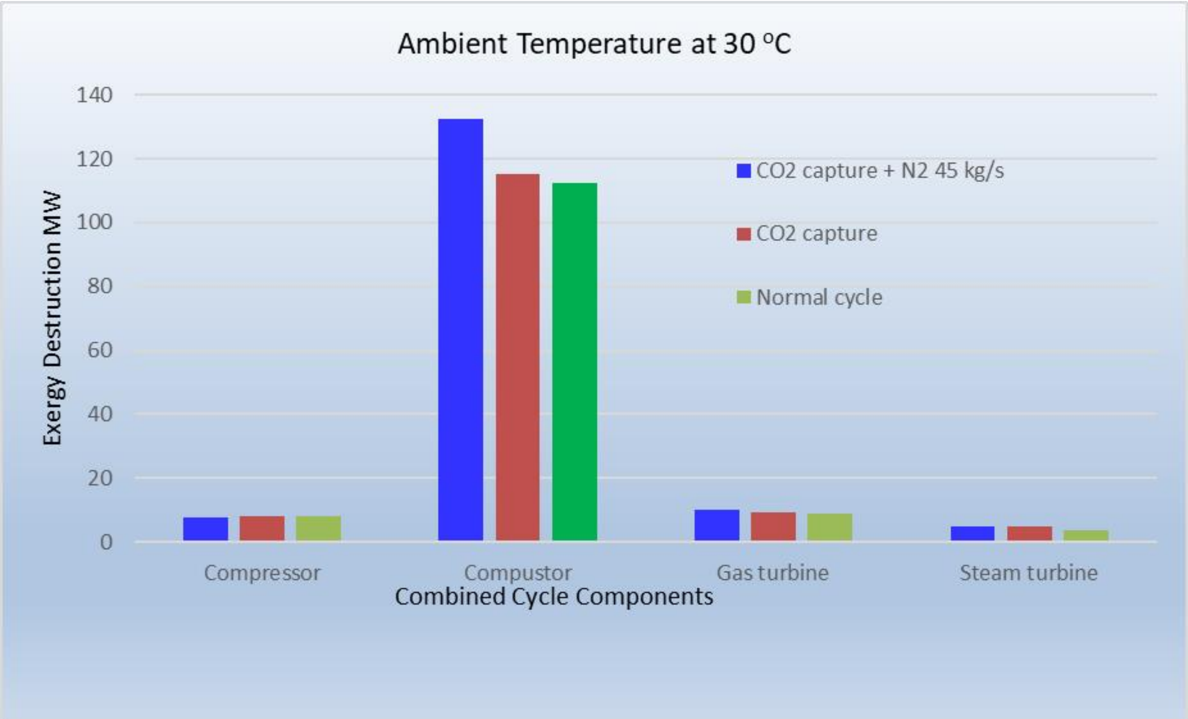

Figure 8: Exergy destruction of the combined cycle components at 15 ^{0}C for the 3 cases

The effect of the environment temperature variation (between 15°C, and 45°C) on the component exergy destruction rate when the pressure ratio stays at 11 bar is shown in figure 9. Clearly, the combustion chamber's exergy destruction decreases as the ambient temperature increases in the case of N_2 injection into the compressor with CO_2 capture, however, the exergy loss for all other components does not change much when the ambient temperature increases. In the combustion chamber, at high ambient temperature, the exergy loss will be lower than the exergy loss at the lower ambient temperature. The exergy loss in the combustion chamber has various causes, mainly due to the chemical reaction and heat transfer occurring inside the combustion chamber.

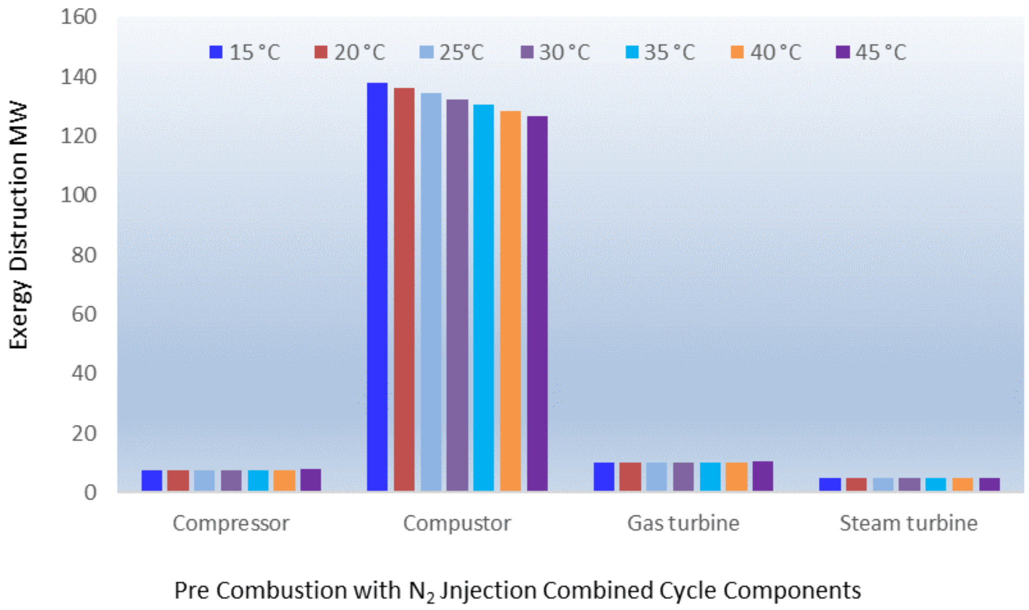

Figure 9: Exergy destruction of the CO_2 capture + (45 kg/s) N_2 injection as a function of ambient temperature

The exhaust gas temperature from the gas turbine in the pre-combustion combined cycle with and without N_2 injection has a favourably high heat content as shown in figure 10, leading to a high exhaust temperaturethat is used to operate the steam turbine cycle, for farther increase in ambient temperature the exhaust gas temperature starts to decrease. On the other hand, upon examining the amount of fuel consumption, it is discovered that the fuel consumption drastically decreases when pure H_2 is used as a fuel because of a veryhigh lower heating value compared with the CH_4 fuel as shown in figure 11.

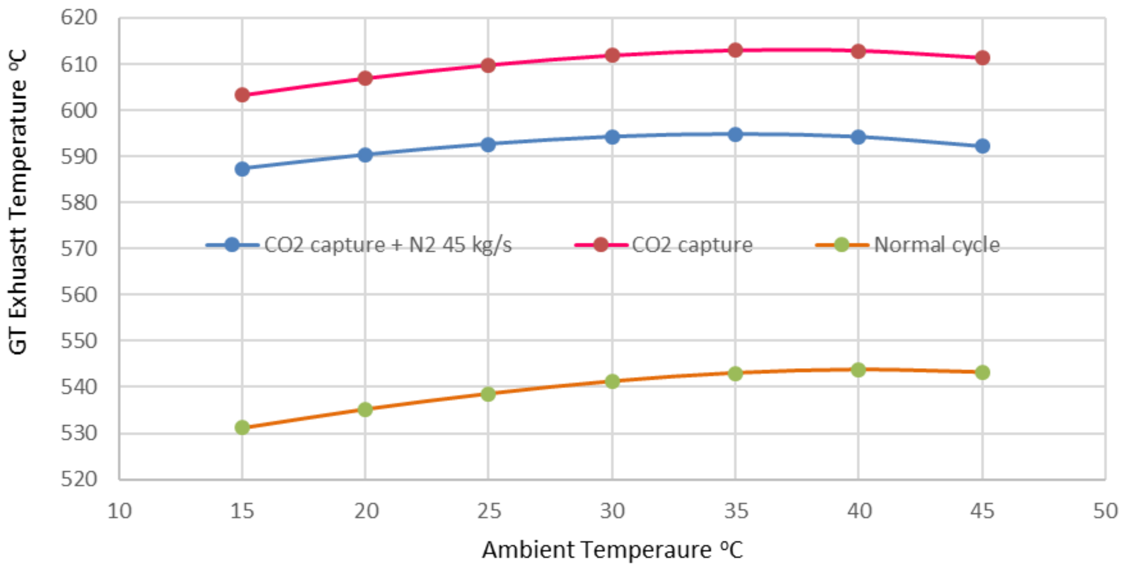

Figure 10: The gas turbine exhaust gas temperature as a function of ambient temperature for the 3 cases

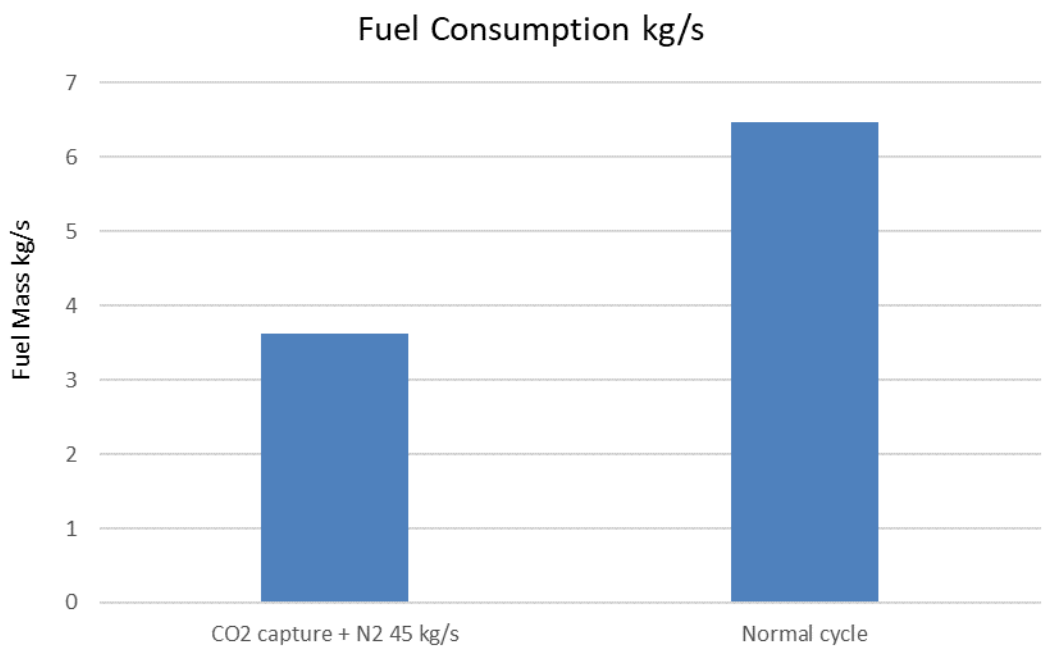

Figure 11: Fuel Consumption for two cases

There was a significant reduction in CO_2 emission when CO_2 capture is applied in the combined cycle as demonstrated in this study as shown in figure 12, where the CO_2 emission is reduced by 100 % also the exhaust gas analysis dose not recorded any amount of NO_x emission, thereby positively reducing climate change.

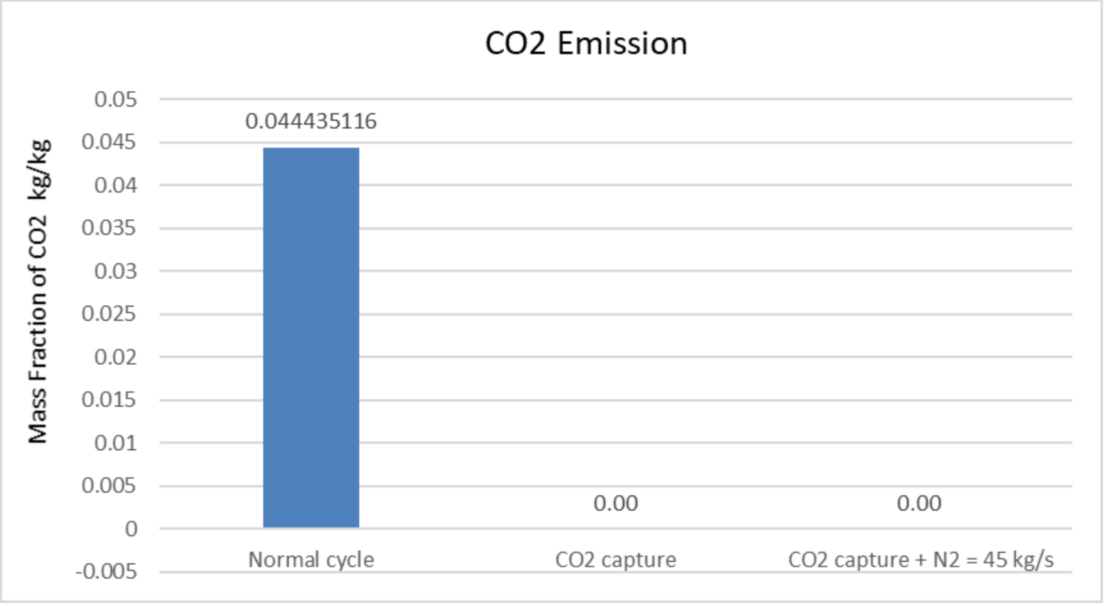

Figure 12: CO_2 Emission in Three Cases

CONCLUSION

In this work the effect of injected N_2 into the compressor on the energy and exergy of the combined cycle was analysed. The simulation program IPSEpro has been applied successfully to the gas and steam turbine combined cycle using conventional thermodynamic analysis applying the first law and second law of thermodynamics. The analysis investigated the effects of different ambient temperatures and different masses of N_2 used in injection on the cycle performance. The air separation cycle is used to separate the Oxygen O_2 from the N_2 so we can use O_2 for CO_2 capture and the N_2 for injection into the compressor of the gas turbine. The system performance heavily depends on the type of fuel, with H_2 being the best, the present study introduces a comparative energy and exergy analysis for the CO_2 capture combined cycle with N_2 injection, this causes an increase in the power output of a gas turbine and an increase in cycle efficiency, both being higher than that in the common combined cycle, whilst the CO_2 emission is reduced by 100 %. Finally, when this system is employed, exergy destruction is increased, the increase in the non-injection case is small, but the largest increase is when N_2 is injected. Further studies should evaluate investment costs associated with the cycle, in addition to the cost of exergy destruction within each system component.

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