DESIGN AND OPERATION SIMULATION OF A 760MW NATURAL GAS MIXED SERIES POWER PLANT VIA OPTIMAL EXHAUST GAS, HEAT EXCHANGER

Engr. Nnadikwe Johnson[1], Engr. Ewelike Asterius Dozie[2], Ugochukwu Chidi Philips[3], Oha Ezinne Jane[4]

[1] *H.O.D in Department of Petroleum and Gas Engineering, Imo State University, Nigeria*

[2] *H.O.D in Agricultural Engineering, Imo State University, Nigeria*

[3] *Lecturer in department of Chemical Engineering, Federal University of Technology Owerri, Imo State, Nigeria*

[4] *Lecturer in department of Quantity Surveying, Imo State University, Nigeria*

ABSTRACT

It is the primary goal of this study to determine the optimal exhaust gas recirculation ratio in a 760 MW-NGCC power plant with 100% extra air in order to achieve an exhaust gas composition suited for successful amine solution absorption. Recirculated exhaust gas is mixed with secondary air (dilution air) used to cool the turbine in order to achieve this purpose. Using the slope change in the relationship between the molar percentage of oxygen in the exhaust gas and the exhaust gas recirculation ratio, the optimal value of a 0.42 FGR ratio is determined. Recirculation of exhaust gas from the NGCC power plant raises the carbon dioxide concentration in the exhaust gas from 5% to 9.2%, and reduces the oxygen concentration in the exhaust gas from 10.9 to 3.5 percent. The influence of exhaust Gas recirculation on various energy inputs and outputs, as well as the overall efficiency of the power plant, is also explored, since energy efficiency is a critical characteristic of energy conversion systems. Exhaust gas recirculation (EGR) has a greater impact on the generation of electricity from the steam turbine generator (STG) than on the cooling of the combustion turbine generator (CTG) (CTG). It has no impact on the water pump of the steam cycle, and the increase in energy used by the exhaust Gas compressor is compensated for by the reduction in energy consumed by the fresh air compressor. The recirculation of exhaust gas boosts the power plant's total efficiency by 1.1%, from 57.5% to 58.2%, based on the natural gas's low heating value (LHV).

Keywords: *Natural Gas Mixed Cycle (NGCC), Exhaust Gas Recirculation, Absorption by Amine, CCS*

---

1. INTRODUCTION

In the future decades and centuries, global climate change is likely to be the most difficult environmental crisis the world has ever faced. The primary driver of global warming is the burning of fossil fuels, particularly coal and natural gas, for power generation, which accounts for 67% of worldwide energy production [1]. Climate change mitigation options advocated by the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) include carbon capture and storage (CCS) (IEA). Because it can be applied on a broad scale, CCS is an excellent and practical alternative for lowering CO2 emissions. However, prospective CCS developers and investors often mention the high initial cost as a major hurdle. A CCS plant's operational costs may be as high as 80% because to the significant quantity of energy required for CO2 collection from power producing units, according to some published statistics [2].

In order to minimize carbon dioxide emissions from the electricity generating industry, gas-fired power stations with Carbon Capture and Storage (CCS) are projected to play an important role CHP facilities powered by Natural Gas Mixed Cycle (NGCC) technology emit less CO2 than coal or oil-fired CHP units [3]. It is also preferable to heavier fuels like coal and oil because to environmental concerns, as well as a reduction in the overall cost of a Carbon Capture and Storage (CCS) system due to avoiding corrosion and other technical issues caused by impurities in the collected CO2, such as H2S, NOx, and HCl. The combustor, on the other hand, has a normal overall excess air ratio (EAR) of 3 to 3.5 in order to maintain the gas turbine's temperature within acceptable limits. Because of this, exhaust Gas contains a molar proportion of CO2 in exhaust Gas of roughly 3% to 3.5 % [4]. A molar CO2 concentration of between 10 and 15 is advised for successful CO2 collection by amine solutions [5]. Solvent loading must be reduced to provide a suitable "driving force" between the solvent and the exhaust Gas stream in order to accomplish high levels of CO2 collection at low CO2 concentrations in the exhaust Gas. A greater CO2 removal from the solvent is required to reduce the amount of energy used in the stripper as well as the cost of the CO2 collection plant for leaner solvent loadings.

Oxygen in exhaust gas causes amine solutions to corrode and degrade, which results in operational, financial, and environmental issues. In the presence of oxygen, these solvents experience both oxidative and thermal deterioration, according to a study of laboratory and pilot plant size tests [6]. Exhaust Gases that include a molar concentration of oxygen of around 5% might cause oxidative deterioration of amine solutions. Since natural gas-fired turbine exhaust gas contains a greater proportion of oxygen, it raises operating costs of the CO2 collection unit.

It is preferable to have high Exhaust Gas Recirculation (FGR) ratios since they raise CO2 concentrations and reduce O2 concentrations. Combustion, on the other hand, has a limit because of the resulting drop in O2 concentration. It is necessary to conduct combustion experiments in order to determine the optimal possible recirculation rate for the CO2 removal process. There are several factors that influence the optimal FGR ratio, such as how much extra air is utilised and how mechanically constrained the turbine.

Aspen HysysV9.0 and the Soave-Redlich-Kwong (SRK) equation of state are used to simulate a Natural Gas Mixed Cycle (NGCC) capable of producing around 760 MW of electricity. It is also hoped that this research will help to reduce the cost of capturing CO2 and minimize the technical difficulties associated with amine degradation. To this end, an investigation of the effects of the exhaust Gas recirculation ratio on CO2 and oxygen composition in exhaust Gas will be carried out. Final purpose is to research how exhaust gas recirculation affects power plant efficiency and various energy inputs and outputs using the Optimal FGR ratio as a guide. The second phase of this study will replicate an enhanced oil recovery (EOR) project's carbon dioxide absorption plant using amine solution and carbon dioxide compression unit based on the findings of this inquiry.

2. METHODOLOGY

2.1. Typical natural gas mixed cycle power generation facility

There are seven separate control volumes in the basic NGCC (Natural Gas Mixed Cycle) power plant, as seen in Figure 1. These include: Compressor, Combustor, Combustion Turbine, Steam Turbine, Heat Recovery Steam, Condenser, and Pump (P).

In accordance with the process flowchart: The compressor is filled with fresh air. After then, it is compressed to a greater degree of intensity. Incoming air from the compressor

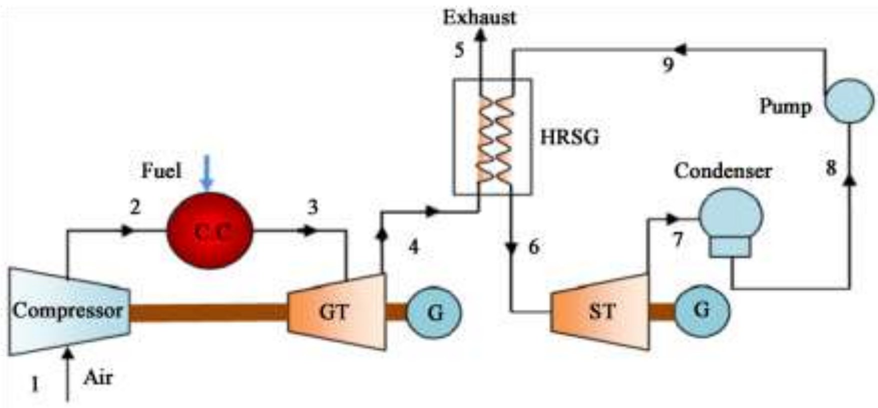

Figure 1. Model of a mixed-cycle natural gas power plant [8].

where natural gas (NG) is introduced and combustion takes place. During combustion, the pressure remains relatively steady throughout the whole process. Combustion Turbine Generator exhaust gas exits the combustor and enters the CTG (CTG). Exhaust gas is used to generate power in the turbine portion. 4) The CTG's exhaust gas is quite hot as it exits. To begin with, the power plant's Open Cycle Gas Turbine (OCGT) (OCGT). A Heat Recovery Steam Generator uses the gas turbine's hot stream to create steam for the NGCC's second stage (HRSG). In order to generate electricity, the steam cycle consists of an HRSG, a STG, a condenser, and a pump. High-pressure water enters the HRSG, and the generated steam powers the steam turbine generator to generate energy (STG). Before returning to the HRSG, the saturated steam exiting the steam turbine is first condensed, and then its pressure is raised. This inquiry does not cover the steam cycle de-aerator..

2.2. Preliminary Calculations

Preliminary calculations are aimed at estimating the quantity of natural gas, the amount of extra air, and the potential amount of exhaust. NGCC power plant's gas recirculation ratio for generating roughly 600 MW of energy.

2.2.1. Mass Flowrate of the Natural Gas

In the gas turbine's combustor, ambient air is compressed to 3 MPa before being combined with natural gas (NG). It is believed that all of the carbons in NG have been converted to CO2 by the time of combustion. Table 1 shows the average composition of the readily accessible natural gas supply.

The average Low Heat Value (LHV) of the natural gas is 46.7 MJ/kg for the specified mass composition (Aspen Hysys). NGCC's total efficiency is estimated at 58 percent based on LHV data [9]. The flow rate of hydrocarbons in natural gas is 22.74 kg/s for a 600 MW power plant with an overall efficiency of 58 percent. The natural gas stream's mass flow rate is thus 23.81 kg/s.

Table 1. Natural gas composition.

Fuel Composition	Mole (%)	Mass (%)	MW
CO_2	1.0	2.6	44
CH4	93.0	87.6	16
C2H6	3.0	5.3	30
C3H8	1.0	2.6	44
O_2	2.0	1.9	16
Total	100	100	16.98

2.2.2. Stoichiometric Air

The stoichiometric combustion is a theoretical point at which the optimum quantity of oxygen and fuel mix creates the most heat feasible and achieves optimal combustion efficiency. All of the carbons in natural gas are thought to be converted to CO2 when they are mixed with compressed air in a combustor. When estimating how much theoretical air is required for burning, only the following processes were used:

$$CH_4 + (2O_2 + 7.52N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2 \quad (1)$$

$$C_2H_6 + (3.5O_2 + 13.17N_2) \rightarrow 2CO_2 + 3H_2O + 13.17N_2 \quad (2)$$

$$C_3H_8 + (5O_2 + 18.81N_2) \rightarrow 3CO_2 + 4H_2O + 18.81N_2 \quad (3)$$

The mass balance of the atoms of Carbon, Oxygen, Hydrogen, and Nitrogen in Equations (1) to (3) was used to compute the AFR (Air Fuel Ratio) (3). An AFR (Air Fuel Ratio) of 9.90 and a mass AFR of 16.91 have been determined after solving the atomic material balances of the four atoms. Therefore, a stoichiometric air flow of 384.53 kilograms per second must be supplied to a natural gas stream flowing at a rate of 23.81 kilograms per second in order to complete combustion. However, in a natural gas turbine, 10 percent of the stoichiometric air is generally injected for combustion [10]. As a percentage increase above the stoichiometric requirement, EA is defined as excess air;

$$EA = \frac{\text{Actual AFR} - \text{Stoichiometric AFR}}{\text{Stoichiometric AFR}} \times 100\% \quad (4)$$

It is sometimes convenient to use the Excess Air Ratio (EAR) defined as:

$$EAR = \frac{\text{Actual AFR}}{\text{Stoichiometric AFR}} \quad (5)$$

Equation (4) shows that the optimum molar and mass AFRs are 10.89 and 18.60 for a 10% extra air volume. When just primary air is used, the optimum mass flowrate is 422.98 kg/s.

2.2.3. Optimal Values of Exhaust Gas Recirculation (FGR) Ratio

As shown in Figure 2, primary air of the gas The primary combustion air comes from the turbine. The fuel is subsequently ignited with the help of this incoming air. Combustion air is referred to as intermediate air. The reaction is completed by the addition of this air, which serves as a catalyst that

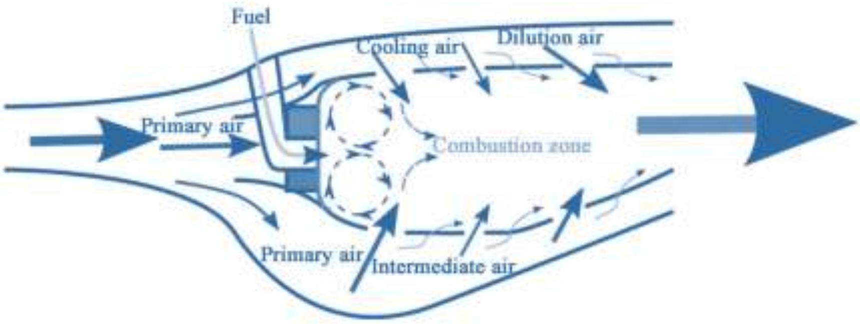

Figure 2. Gas turbine air flow pathways [11].

the combustion gases cool down. Adding dilution air helps cool exhaust air before it enters the turbine stages by circulating in and out of the combustion chamber as it moves through it. For the sake of this investigation, it is assumed that the primary air contains both primary and intermediate air, with the diluting air acting as a secondary source of air. To keep the turbine cool, recirculated exhaust gas is mixed with secondary air.

A maximum flue recirculation ratio is required for the exhaust gas to be treated in the absorption unit to maximize CO2 concentration and decrease O2 concentration. However, the flame's stability and combustion efficiency are also important criteria to take into account when determining the minimal quantity of oxygen required for a given reaction. The flame should function within the stability limitations while using the least amount of fuel feasible for an energy-efficient combustion process. Partially premixed flames are often achieved by the use of air entrainment. Fuel and air mixtures can't maintain themselves at an oxygen concentration of less than 13 to 14 vol percent [12], according to experiments done in a 65 kW combustor in pre-mixed flame mode. According to ElKady and colleagues, excellent combustion efficiency with tolerable low levels of CO requires an oxygen concentration of 16 - 17 vol percent or higher [13]. Methane is a much more powerful greenhouse gas than carbon dioxide is, and therefore any methane that is released before it reaches its final destination has a major influence on climate change. Aspen HysysV9.0 and the Soave-Redlich Kwong (SRK) equation of state are initially used to determine the maximum FGR ratio for an excess air ranging from 100 percent to 600 percent in this research.. For EA (Excess Air), early estimates reveal that the optimal FGR may range from 100% to 600% (see Table 2).

The mass AFR of 33.82 corresponds to an excess air of 100 percent in the specified case study. As a result, 768.9 kg/s of air is required for combustion and cooling. (422.98 kg/s of primary air for burning and 346.09 kg/s of secondary air for cooling) An ideal FGR ratio of 0.44 may be achieved with this figure in mind. Figure 3 depicts the link between the Optimal FGR ratio and the EA values..

Table 2. Optimal Exhaust Gas Recirculation Ratio for Various EA.

EA (%)	Mass AFR	Total air (kg/s)	(Air + NG) (kg/s)	Optimal Flue gas recycled (kg/s)	Optimal FGR ratio
100	33.82	768.9	792.89	346.09	0.44
200	50.72	1153.37	1177.18	730.39	0.62
300	67.63	1537.96	1561.77	1114.98	0.71
400	84.54	1922.45	1946.26	1499.47	0.77
500	101.45	2306.94	2330.75	1883.96	0.81
600	118.36	2691.43	2675.67	2225.44	0.83

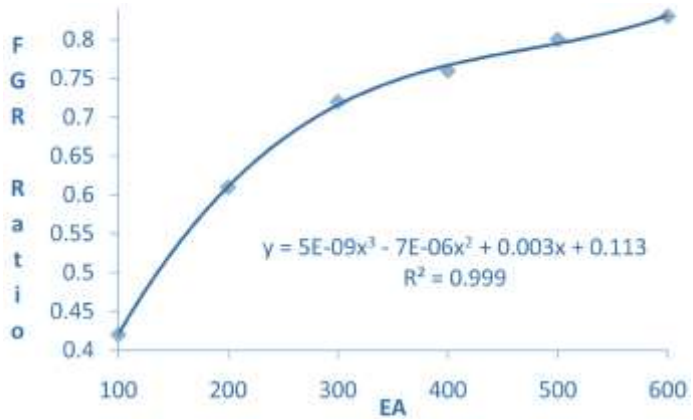

Figure 3. Excess air (EA) effects on optimal FGR ratio.

2.3. Simulation of FGR Ratio Effects on Exhaust Gas Composition

The molar proportion of CO_2 in the exhaust gas must be more than 10% in order for amine solutions to effectively absorb the gas. The proportion of O_2 in the exhaust gas should also be lower than 5% in order to prevent technical issues related to amine oxidative degradation in the CO_2 collection plant. Research on the favorable impacts of FGR on exhaust gas composition is being conducted as well. [2] (Page 5 of 14) (Page 12 of 14) Research conducted by Akram et al. [5] examined the effects of recirculating exhaust gas in a TurbecT100 CHP gas turbine producing 100 KW (plus 150 KW hot water). Using a recirculation ratio of 0.45, the molar CO_2 concentration grew from 1.5% to 3.0% while the molar O_2 concentration declined from 18.2% to 16.0 percent, according to the study's preliminary findings Reusing some of the exhaust gas reduces NOx emissions by reducing the flame temperature, according to their findings. Natural gas-fired power plants of 700 MW produce CO_2 emissions of 3.3 percent and O_2 emissions of 13.8 percent when the recirculation ratio is set at 0.4, according to figures reported by Bolland and Saether [2]. Exhaust Gas was cooled before reinjection into the combustor to maintain high cycle efficiency. An IGCC power plant with a low-pressure gasifier was simulated by Abu Zahra [14] using Aspen plus and the Peng-Robinson equation of state. CO_2 concentration rose from 7.3 (percent mol.) to 14.0 (percent mol.) when the exhaust gas recirculation ratio was raised from 0 percent to 45 percent, according to the findings. With the same increase in exhaust Gas recirculation, O_2 content dropped from 14.2 (per cent mol.) to 8.0 (per cent mol). Exhaust gas recirculation ratio (EGR) affects the composition of the exhaust gas in a gas turbine with 100% excess air (EA). Figure 4 shows the molar proportion of CO_2 in the exhaust gas as a consequence of the simulation findings.

In Figure 4, the molar percentage of carbon dioxide in the exhaust gas entering the absorption unit rises from 5.8 (FGR = 0.1) to 11.0 (FGR = 0.53). When the FGR ratio is 0.5 or higher, the molar carbon dioxide concentration remains constant.

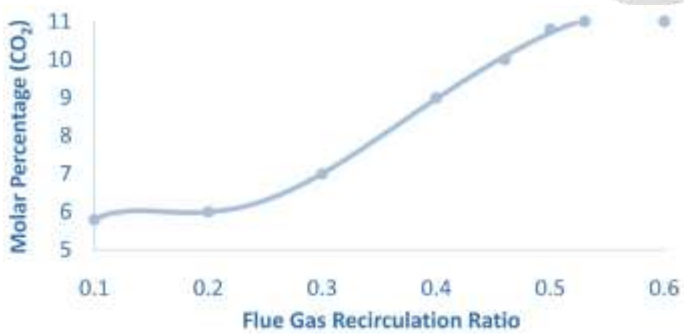

Figure 4. A FGR ratio effect on CO_2 concentration in exhaust gas.

Due to a lack of oxygen, carbon monoxide is produced instead of CO2. The predicted mass flow rate of fresh air (361.1 kg/s) is below the required stoichiometric value of 384.53 kg/s. The optimum exhaust gas recirculation ratio should be less than 0.50. Figure 5 shows the impact of the exhaust Gas recirculation ratio on the concentration of O2 entering the absorption unit.

In the absorption unit, the molar proportion of oxygen falls from 9.4 (FGR = 0.1) to 0.0 (FGR = 0.53). However, the slope of the curve for FGR ratios over 0.42 is greater than the slope of the curve for FGR ratios below 0.42. This is the study's optimal FGR ratio. The extra air in primary air is 17%, while the oxygen molar content in natural gas-primary air is 0.19. This molar oxygen concentration in the gas–air combination is greater than the 0.17 concentration recommended in the literature for flame stability [13]. In reality, adjusting the exhaust gas oxygen and carbon monoxide concentration improves combustion efficiency. For example, the observed CO concentration may be utilized to regulate combustion in two ways: regulating O2 when it exceeds a preset value and switching to CO when it falls below it, or giving the O2 concentration a CO concentration bias (compensation) (Figure 6).

2.4. A Brief Description of the NGCC Power Plant Simulation Process

A 600 MW-NGCC with an exhaust Gas recirculation ratio of 0.42 is depicted in Figure 7 in this research. There should be a battery limit of 23.81 kg/s of natural gas (CH4 = 93% mol) and 449.2 kg/s of fresh air at design conditions compressed to 3.1 MPa in a three-stage compressor with intercooling at 25 °C, respectively. It is assumed that all of the carbons in NG have been converted to CO2 in the combustor and that the combustion process is complete. There is a temperature of 2100 degrees Celsius in the combustion gasses. Cooling the combustion process is done by mixing secondary air with recirculated exhaust gas.

Figure 5. FGR ratio effects on O_2 concentration in exhaust gas.

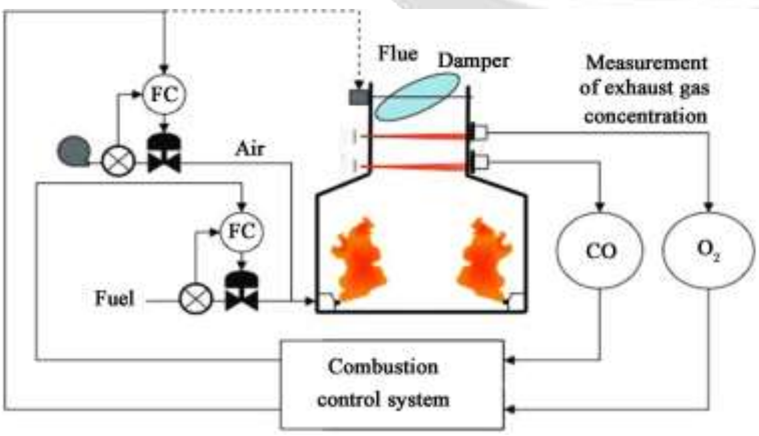

Figure 6. CO and O_2 control system for combustion [15].

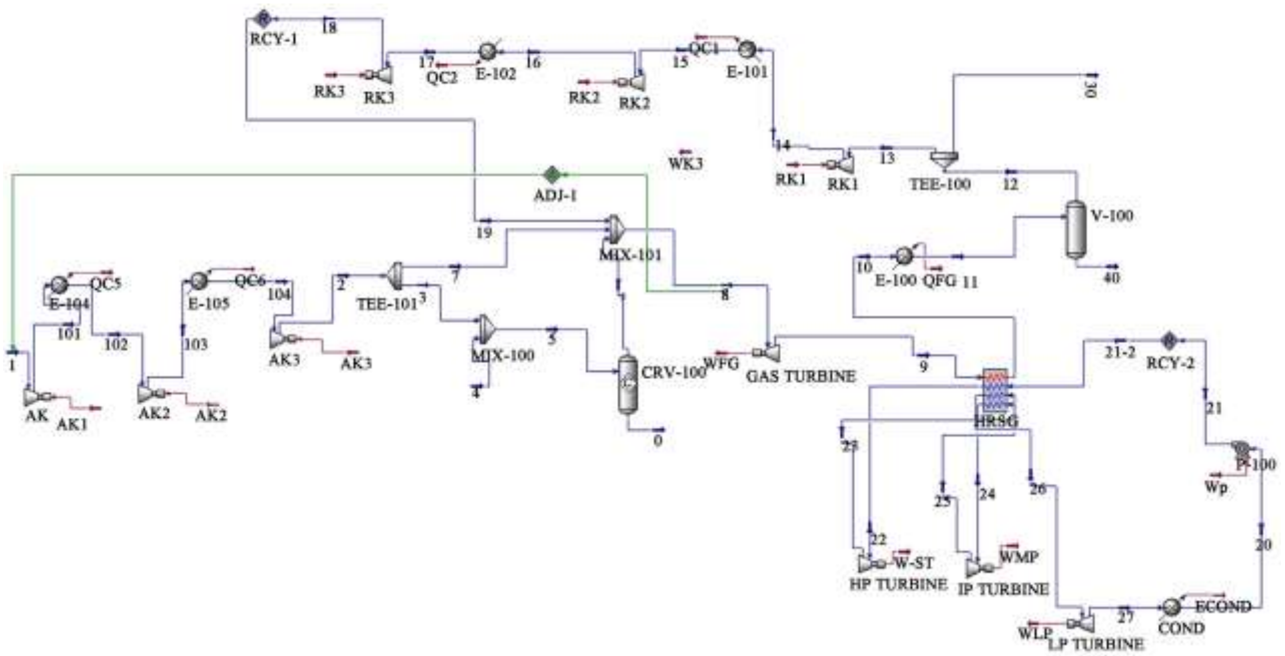

Figure 7. Process flow diagram for an NGCC power plant.

before entering the turbine. The exhaust gases from the gas turbine are 618°C. In order to create 55 kg/s of steam, the exhaust gas enters HRSG at three pressure levels: high pressure (173 bars, 600°C), intermediate pressure (65 bars, 565°C), and low pressure (2 bars, 350°C) with double reheat. Steam is heated to 438-565C for medium pressure steam and 206-350C for low pressure steam. After exiting the HRSG, the exhaust gas is cooled to 40°C to remove water in the separator V-100, and 42% of the exhaust gas is recycled. The recycled gas pressure will be increased from 110 kPa to 3.1 MPa using a three-stage compressor with intercooling at 40°C.

2.5 FGR Ratio Effect on Power Plant Energy Streams Simulation

The effect of exhaust gas recirculation on the power input or output of various power plant equipment is being studied. The goal is to compare the output of each piece of plant equipment with and without an exhaust gas recirculation ratio of 0.42.

2.5.1 Compressors

Air at 15 °C (Design conditions) is compressed to 3.1 MPa in three steps, each with 40 °C intercooling, in this research. When performing three phases of intercooling, the pressure of the recovered gas rises from 110 kilopascals to 3.1 MPa. We chose an adiabatic efficiency of 85 percent for both of our compressors [16]. Exhaust Gas recirculation ratio impacts on compressor energy consumption for ambient air and exhaust Gas are shown in Figure 8.

Energy consumption of ambient air compressor is reduced as a result of increased exhaust gas recirculation ratio. Considering that nitrogen is a major component of exhaust gas and ambient air, the slopes of both compressors are quite comparable.

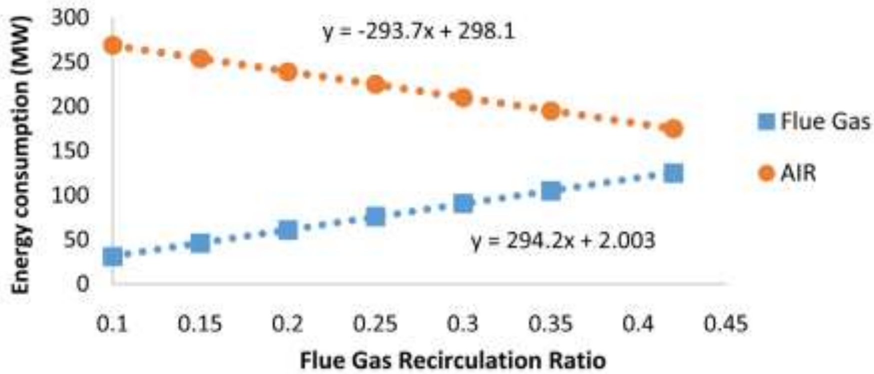

Figure 8. Effects of FGR ratio on compressor energy consumption.

2.5.2 Thermal Steam Generator 2.5.2. (HRSG)

Steam turbines in mixed cycle plants are often used in high pressure (HP) circuits right now. Two extra evaporators are employed to increase the heat absorption. IP (intermediate pressure) circuit The second circuit, which operates at lower pressure (LP). The addition of economizers and superheaters at these pressures allows for more heat absorption. Heat recovery steam generator (HRSG) outputs show that exhaust gas temperatures entering and exiting the heat recovery steam generator (HRSG) are 618°C and 67°C, respectively. There is an HP steam (173 bars, 600 °C), an IP steam (65 bars, 565 °C), and an LP steam (two bars, 350 degrees Celsius, with double reheat) in the steam cycle. Heat ranges from 438 to 565 degrees Celsius for medium-pressure steam (IP) and 206 to 350 degrees Celsius for low-pressure steam (LP). As illustrated in Figure 9, exhaust Gas recirculation has an impact on the amount of heat available to make steam in a computer simulation of an HRSG (heat recovery steam generator).

Exhaust Gas recirculation, as shown by the simulations, increases the HRSG's heat capacity. It's possible to get 3.1% more heating capacity with an optimal value of 0.42 than with no exhaust gas recirculation. Exhaust Gas has a larger specific mass heat capacity (1.124 kJ/kg C) than air (1.01 kJ/kg C) for the same temperature differential and mass flow rate, which might explain the good impacts of exhaust Gas recirculation.

2.5.3 Pump and Steam Turbine

With two reheats, the steam cycle goes through three pressure stages: high pressure, mid-pressure, and low pressure. It is decided that the adiabatic efficiency of the turbine, generator, and condensate pump will each be 75% [17]. Figure 10 illustrates the impact of exhaust gas recirculation on the steam turbine's output of power and the pump's energy consumption.

Figure 10 confirms that exhaust is shown in Figure 9. When gas is recirculated, the steam turbine generates more power. However, it has no impact on the steam cycle's water pump's energy usage. Based on modeling data, the steam cycle produces 4.2 percent more power than a steam power plant with no exhaust when the FGR is set to 0.42. Recirculation of gas.

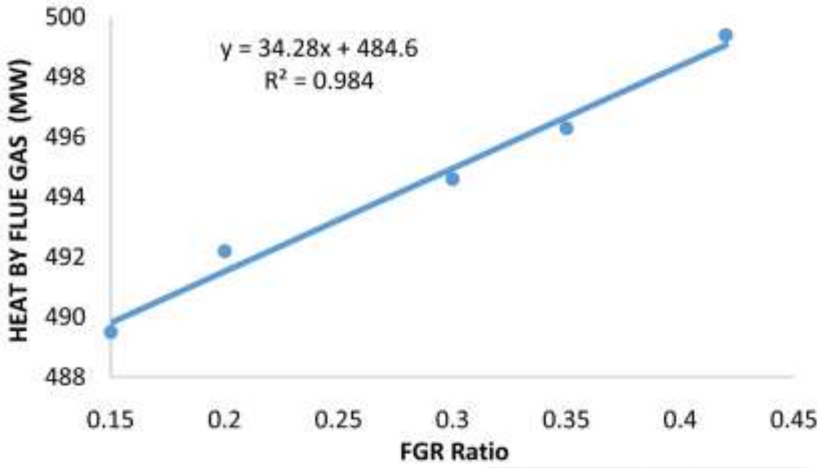

Figure 9. FGR ratio effects on HRSG heat availability.

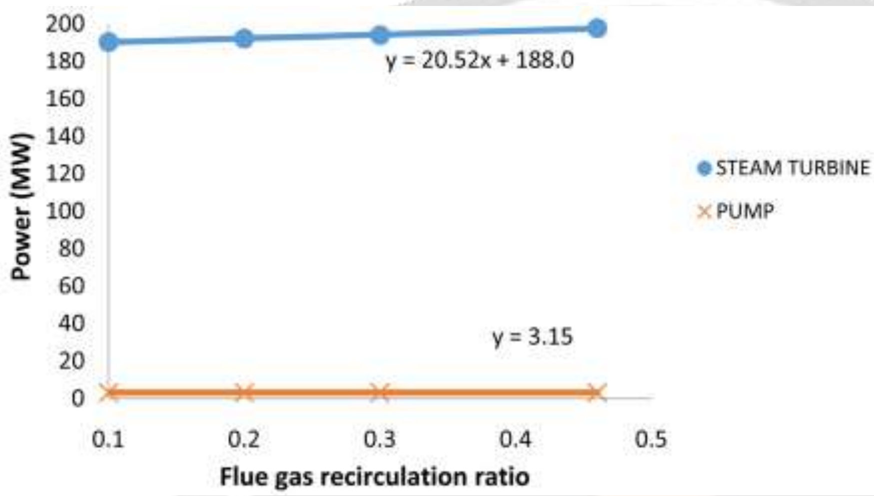

Figure 10. Effects of FGR ratio on steam cycle energy.

2.5.4. Gas Turbine

As exhaust gas temperature rises, so does net production, although this is restricted by the gas turbine's metallurgical limitations. Exhaust Gas Recirculation (FGR) ratio is consequently explored, and the simulation results are given in Figure 11 (as indicated in the figure).

Exhaust Gas recirculation reduces the temperature of exhaust Gas entering the gas turbine linearly, as seen in Figure 11. Even yet, the temperature of recirculated exhaust gas (215°C) exceeds that of fresh air (190°C). One explanation for the cooling effect is that exhaust gas absorbs more heat due to its larger specific mass heat capacity (1.124 kJ/kg C) than fresh air's (1.01 kj/kg C). According to the metallurgical limitations of gas turbine blades, they may reach temperatures of up to 1700 °C, depending on their materials and whether or not they have cooling systems. [10]. Exhaust Gas temperature of roughly 1300 °C places the NGCC type between the D and F kinds.

It is because of this that the temperature of 1300 C is utilized as the metallurgical restriction of the turbine in the research. As can be seen in Figure 13, recirculation of exhaust gas has an impact on gas turbine power generation.

Power output from the gas turbine reduced as a result of the FGR ratio (Figure 11). However, the connection has two distinct slopes. When the FGR ratio is less than 0.25, recirculation of exhaust gas has no influence on gas turbine power production. The detrimental consequences of recirculation of exhaust gas are more apparent when the FGR ratio is greater than 0.25.

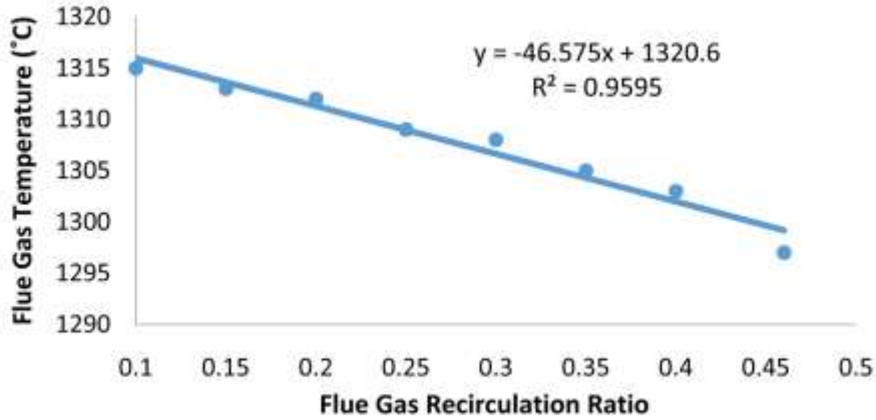

Figure 11. Temp. of exhaust gas influenced by FGR ratio.

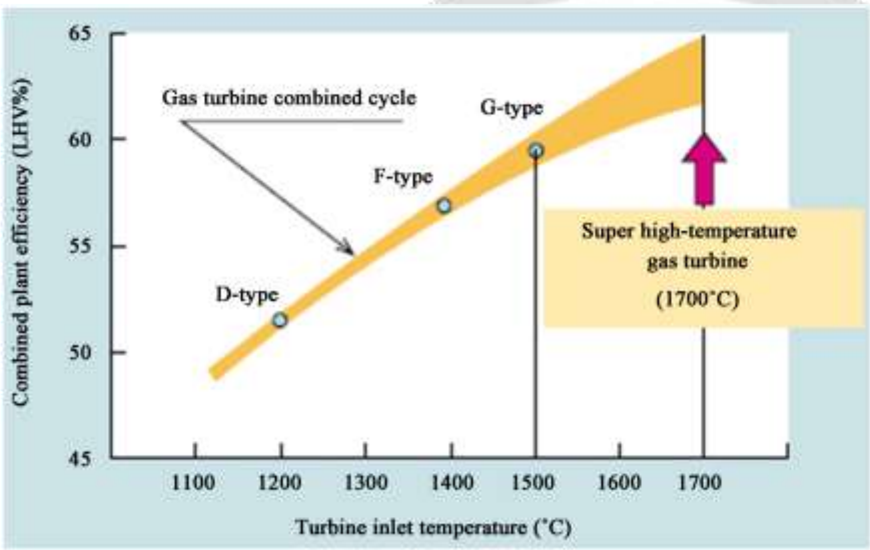

Figure 12. Mixing plant efficiency with turbine inlet temperature [16].

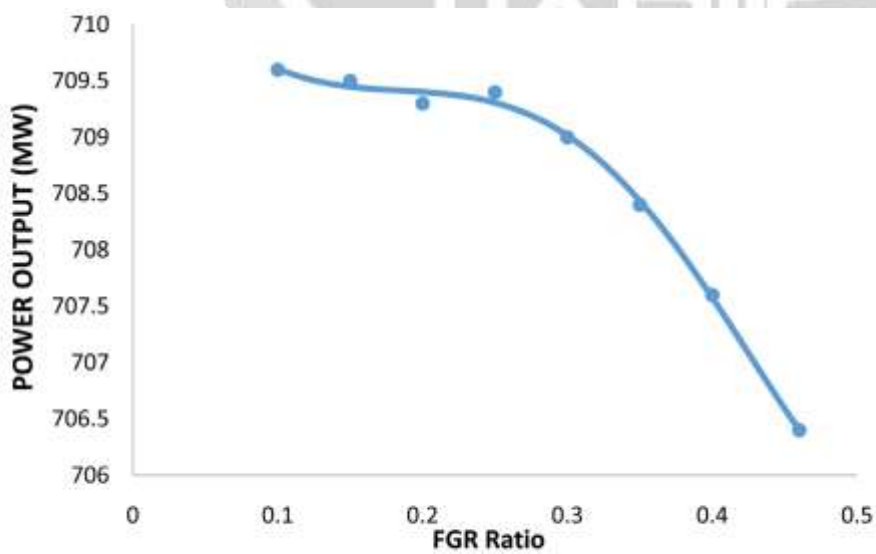

Figure 13. The impact of the FGR ratio on the gas turbine's output power.

2.6. Effects on Power Plant Efficiency of Changing the FGR Ratio

A system of producing electric power that combines gas turbine power generation (CTG) with steam turbine power generation (NGCC) is called NGCC power generation (STG). Among thermodynamic power cycles, gas and steam cycles are two of the most common types. The Brayton cycle governs the operation of gas turbines. To express the Brayton cycle's isentropic efficiency (iso) in terms of the temperatures and pressures (P1 and T1) entering and exiting the compressor:

$$\eta_{iso} = 1 - \frac{T_1}{T_2} = 1 - \left(\frac{P_1}{P_2}\right)^{\frac{k-1}{k}} \tag{6}$$

Where here, k is the temperature-to-volume ratio. According to Equation (6), the gas turbine's efficiency may be improved by raising the temperature or increasing the pressure ratio of the stream exiting the compressor. Exhaust gas temperatures are restricted to 1300 °C in this experiment, which uses fresh air at 15 °C as the design temperature. The gas turbine's isentropic efficiency is 0.82 under these operating circumstances. In order to simulate the natural gas Mixed Cycle, this adiabatic efficiency was chosen for the gas turbine. The gas turbine's corresponding output is 708.5 MW. The compressors for fresh air and exhaust gas recirculation consume a total of 174.21 MW and 125.89 MW, respectively. The gas turbine's total output is 408.4 MW.

The following equation may be used to evaluate the gas turbine's total efficiency:

$$\eta = \frac{W_{\text{net output}}}{m_{NG} \times \text{LHV}} \tag{7}$$

There, W_{net} output is the difference between the output of the combustion turbine generator (CTG) and that consumed by the various equipment, $^{m}{}_{NG}$ is the mass flow rate and LHV is the low heating value. The gas turbine's efficiency is calculated at 36.1% using the Low Heating Value (LHV) and the mass flow rate of natural gas (46.7 MJ/kg and 23.81 kg/s, respectively). The Open Cycle Gas Turbine's efficiency is represented by this number (OCGT). Heat Recovery Steam Generators (HRSGs) will utilise the 617 °C exhaust gas stream to generate steam, which will be used to generate additional power (HRSG). The Rankine cycle is used to power a steam turbine in a mixed-cycle power plant. The ideal Rankine cycle has four internal reversible mechanisms like the Brayton cycle. The Carnot efficiency stated in Equation is the theoretical maximum efficiency of a Rankine cycle (8).

$$\eta_{\text{Carnot}} = 1 - \frac{T_{\text{Cold}}}{T_{\text{Hot}}} \tag{8}$$

Steam entering the HP turbine at 585 C is the hottest temperature, while water exiting the condenser at 30 C is the coldest in this experiment. According to these figures, the steam cycle's maximum efficiency is 64.7 percent. In the same temperature range, the Rankine cycle's thermal efficiency is lower than that of the Carnot cycle. This is mainly due to the fact that in the Rankine cycle, the energy transfer as heat in the boiler is not continuous. When steam is heated to a higher temperature, it removes any moisture that may be present in the steam, so allowing for a greater amount of heat to be transferred into the cycle.

The thermal efficiency of the reheated Rankine cycle is provided by Equation 14 based on Figure 14. (9):

$$\eta = \frac{(h_1 - h_2) + (h_3 - h_4) + (h_6 - h_5)}{(h_1 - h_6) + (h_3 - h_2)} = \frac{W_{\text{net-out}}}{Q_{\text{in}}} \quad (9)$$

There are three turbines that generate 32.74 MW (HP), 114.3 MW (IP), and 66.8 MW of electricity, respectively (LP). The pump uses 3.15 MW of power. Steam turbines have an efficiency of 18.9 percent due to the poor heating value of natural gas.

Because the Rankine steam cycle and the Brayton GT cycle both have temperature ranges between 1300°C and 618°C, the natural gas mixed cycle (NGCC) has the potential to provide much higher thermodynamic cycle efficiency than either cycle alone (Figure 15).

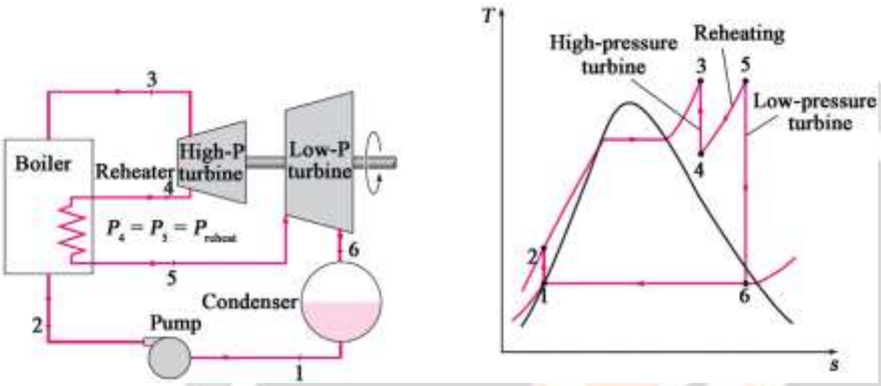

Figure 14. Ideal reheat rankine cycle [18].

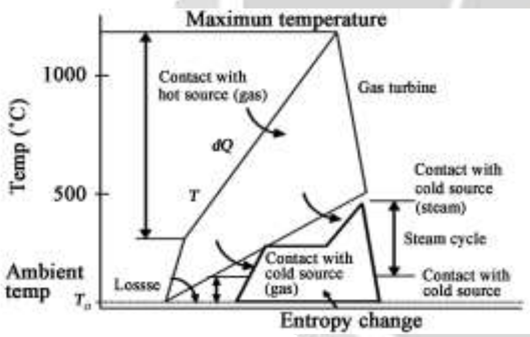

Figure 15. T-S diagram of NGCC cycle [19].

According to the calculations, the NGCC power plant's net production without FGR is 610.89 megawatts (MW). The power plant's total efficiency rose by 1.1%, from 57.5 percent to 58.2 percent, based on the natural gas's low heating value (LHV)..

3. THE SIMULATED RESULTS IN BRIEF

There is a comparison in Table 3 between the molar compositions of exhaust gas without recirculation and 0.42 recirculation ratio. Exhaust Gas with a FGR ratio of 0.42 has a molar composition of carbon dioxide and oxygen near to the criteria for CO2 absorption, which are CO2 10% and O 2 5.2% in exhaust Gas.

Second, Table 4 summarizes the modeling findings for the impacts of exhaust Gas recirculation on the power input/output of the various power plant equipment.

4. DISCUSSION AND CONCLUSIONS

A natural gas Mixed Cycle (NGCC) power plant with a capacity of 760 MW was the initial objective of this research. Preliminary calculations assumed full combustion of natural gas and calculated the required mass flow rates of natural gas and ambient air with 100 percent extra air. The effects of exhaust gas recirculation on the concentrations of CO2 and O2 in the exhaust gas leaving the simulated power plant were investigated because natural gas-fired power plants with Carbon Capture and Storage (CCS) are expected to play an important role in reducing carbon dioxide emissions from the power generation sector.

Table 3. Exhaust gas molarity Gas with a FGR ratio of 0.42 and no recirculation.

Component	FGR = 0	FGR = 0.42
CO2	0.050	0.092
O2	0.109	0.035
H_2O	0.067	0.067
N2	0.774	0.806
Total	1	1

Table 4. Results of the simulation summarized.

Equipment	Power Input (MW)		Power Output (MW)		Net Output (MW)	
	FGR = 0	FGR = 0.4	FGR = 0	FGR = 0.4	FGR = 0	FGR = (
Air Compressor	299.73	174.8				
FG compressor	0	125.96				
Gas turbine			709.1	708.6		
HP steam turbine			22.85	32.74		
IP steam turbine			114.3	114.3		
LP steam turbine			67.47	66.79		
Water pump	3.1	3.1				
Total	302.83	303.86	913.72	922.43	610.89	618.57

The goal was to achieve a CO2 molar percentage of 10%. O2 molar proportion in exhaust gas should also be reduced to 5 percent in order to avoid technical difficulties caused by amine oxidative degradation. The recirculated exhaust gas is mixed with the secondary air and used to cool the turbine. It was determined in this study that the optimum value of 0.42 was derived from a change in slope between the molar concentration of oxygen in exhaust gas and the FGR (Figure 5). Exhaust Gas from the NGCC power plant with exhaust gas recycling rose from 5% to 9.2% carbon dioxide and from 10.9 to 3.5% oxygen, respectively, as compared to the power plant without exhaust gas recycling.

Power plant energy inputs and outputs were examined as a result of exhaust gas recirculation. Because of this, it was found that the exhaust gas recirculation ratio increased compression energy requirements while decreasing compressor energy consumption. As shown in Figure 8, there is no difference in the amount of energy used by the compressors in the plant when exhaust Gas is recirculated.

Energy from the exhaust gas was used to improve steam output by 3.1% in a Heat Recovery Steam Generator (HRSG) (Figure 9). The fact that exhaust gas has a specific mass heat capacity that is 1.124 kJ/kg C greater than air's (1.01 kJ/kg

C) might explain these favorable effects. The simulation findings revealed that the steam cycle generated 4.2 percent more power than the steam power plant with no exhaust gas recirculation in accordance with the increase in heat available in the HRSG. In contrast, exhaust gas recirculation had no influence on the energy consumption of the steam cycle's water pump.

In this study, the gas turbine's metallurgical limit was set at 1300 °C. Recirculation of exhaust gas cools the turbine because of the difference in mass specific heat capacity between ambient air and exhaust gas. There is relatively little loss of net power production since the recirculated exhaust gas is hotter (222 degrees Celsius) than the compressed secondary air (190 degrees Celsius). The power plant's net production rose by 1.3 percent from 610.89 to 618.57 MW when the exhaust gas recirculation had a FGR ratio of 0.42.

Amine solutions can effectively absorb carbon dioxide from the exhaust gas with a FGR ratio of 0.42, and the total power plant efficiency rose by 1.1 percent from 57.5 percent to 58.2 percent because of the low heating value (LHV) of the natural gas. Exhaust's beneficial effects Heat recovery steam generator (HRSG) and steam turbine generator (STG) outputs are more essential than the cooling effects on combustion engine power of the recirculated exhaust gas (CTG).

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Centre for Energy Resources and Refining at Imo State University, Owerri, Nigeria for their technical support, especially providing access to their own software application.

REFERENCES

[1] https://www.eia.gov/energyexplained/index.cfm?page=electricity_in_the_united_sta tes

[2] Bolland, O. and Sæther, S. (1992) New Concepts for Natural Gas Fired Power Plants Which Simplify the Recovery of Carbon Dioxide. Energy Conversion and Management, 33, 467-475. https://doi.org/10.1016/0196-8904(92)90045-X

[3] Asa, M., Simon, H. and Thore, B. (2006) Technical, Environmental and Economic Analysis of Co-Firing of Gasified Biofuel in a Natural Gas Mixed Cycle (NGCC) Mixed Heat and Power (CHP) Plant. Energy, 31, 1614-1631. https://doi.org/10.1016/j.energy.2005.05.029

[4] Al Wahedi, F.S. and Dadach, Z. (2013) Cost Effective Strategies to Reduce CO_2 Emissions in the UAE: A Literature Review. Industrial Engineering & Management Journal, 2, 1-9. https://doi.org/10.4172/2169-0316.1000116

[5] Akram, M., Khandelwal, B., Blakey, S. and Wilson, C.W. (2013) Preliminary Calculations on Post Combustion Carbon Capture from Gas Turbines with Exhaust Gas Recycle. Proceedings of ASME Turbo Expo 2013: Turbine Technical Conference and Exposition (GT 2013), San Antonio, Texas, USA, 3-7 June 2013.

[6] Thong, D., Dave, N., Feron, P. and Merched, A. (2012) Environmental Impacts of Amine-Based CO_2 Post Combustion Capture (PCC) Process. CSIRO-Advanced Coal Technology Portfolio.

[7] Chakravarti, S., Gupta, A. and Hunek, B. (2001) Advanced Technology for the Capture of Carbon Dioxide from Exhaust Gases. 1st National Conference on Carbon Sequestration, Washington DC, 15-17 May 2001, 1-10.

[8] Ibrahim, T.K. and Rahman, M.M. (2012) Effect of Compression Ratio on Performance of Mixed Cycle Gas Turbine. International Journal of Energy Engineering, 2, 9-14.

[9] Mathieu, P. and Bolland, O. (2013) Comparison of Costs for Natural Gas Power Generation with CO_2 Capture. Energy Procedia, 37, 2406-2419. https://doi.org/10.1016/j.egypro.2013.06.122

[10] Piper, J.E. (1999) Operations and Maintenance Manual for Energy Management, Library of Congress Catalogues, 93.

[11] Combustor in Wikipedia.

[12] Røkke, P.E. and Hustad, J.E. (2005) Exhaust Gas Recirculation in Gas Turbines for Reduction of CO_2 Emissions; Combustion Testing with Focus on Stability and Emissions. International Journal of Thermodynamics, 8, 167-173.

[13] ElKady, A.M., et al. (2009) Application of Exhaust Gas Recirculation in a DLN F-Class.

[14] Abu Zahra, M.R.M. (2009) Carbon Dioxide Capture from Exhaust Gas. PhD Dissertation, Delft University of Technology, Netherlands.

[15] Hiraoka, T. (2000) Reduction of Fuel Costs and CO_2 Emissions by O_2 Control for Packaged Boilers. Yokogawa Technical Report, 44, 85-86. (In Japanese)

[16] Ishikawa, M., Terauchi, M., Komori, T. and Yasuraoka, J. (2008) Development of High Efficiency Gas Turbine Mixed Cycle Power Plant, Mitsubishi Heavy Industries, Ltd. Technical Review, 45.

[17] Allahyari, N. (2013) Economic Evaluation of Capturing CO_2 from Natural Gas Power Plant and Injecting CO_2 for Enhanced Oil Recovery as an Integrated System. Ms. Thesis, University of Regina, Canada.

[18] Rankine Cycle, Wikipedia.

[19] Beér, J.M. (2007) High Efficiency Electric Power Generation: The Environmental Role. Progress in Energy and Combustion Science, 33, 107-134.