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Effect of Steam Injection and Combined Cycle Technologies on Fuel Consumption and CO₂ Emissions in Gas Turbine Power Plants

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ABSTRACT

This study investigates and compares the performance of a simple gas turbine plant with two advanced techniques: steam injection and combined cycle, focusing on fuel consumption and carbon dioxide (CO₂) emissions. The results indicate that at an air compressor inlet temperature of 15 °C the specific fuel consumption (SFC) for the simple gas turbine is 230.44 kg/MWh. The steam injection technique significantly reduces SFC to 153.36 kg/MWh, achieving a 33.5% improvement, whereas the combined cycle reduces it to only 162.86 kg/MWh, with a 29.3% improvement. In terms of CO₂ emissions, the simple cycle emits 632.16 kg/MWh, which is decreased to 420.71 kg/MWh with steam injection (33.4% reduction) and to 446.78 kg/MWh with the combined cycle (29.3% reduction). The results demonstrated that steam injection outperforms the combined cycle in fuel efficiency and emission reduction under moderate inlet temperatures, highlighting its potential for cleaner and more efficient power generation.

KEYWORDS: Steam Injection, Gas Turbine, Fuel Consumption.

1. INTRODUCTION

In recent decades, environmental degradation has become increasingly evident as a result of technological advancements. Among the most pressing environmental challenges faced by the industrial sector are greenhouse gas emissions, despite the presence of other significant local environmental impacts [1,2]. These concerns have driven international efforts, particularly the 21st Conference of the Parties (COP21) on Climate Change held in Paris, to adopt a target of limiting the global average temperature rise to below 1.5°C, an objective reinforced by the United Nations and other international bodies [3,4]. Power generation facilities and industrial energy consumers are among the primary contributors to carbon dioxide (CO₂) emissions, which are considered the most critical greenhouse gas in terms of climate impact [5–7]. Statistical data indicate that fossil fuel combustion accounts for approximately 73% of atmospheric CO₂ emissions [8]. As global energy demand continues to rely on coal, natural gas, and petroleum products, CO₂ emissions are expected to rise further, thereby exacerbating global warming [9, 10]. In response, both governments and private entities



have intensified their efforts to develop and adopt energy technologies that reduce the environmental footprint of the oil and gas industry [11]. Nevertheless, the widespread infrastructure supporting fossil fuel usage continues to pose a challenge to transitioning away from these sources in the near term [12]. Studies have shown that the combustion of natural gas emits CO₂, nitrogen oxides (NO_x), and, in cases of incomplete combustion, methane [13–15]. However, natural gas is recognized for releasing lower quantities of CO₂ compared to coal [6,16]. Among anthropogenic greenhouse gases, CO₂ remains the most significant contributor to climate change due to its abundance and long atmospheric lifespan [17–19]. The average CO₂ emissions from gas-fired power plants are estimated at approximately 644.893 kg/MWh, with an annual total reaching around 634,066,348.44 kg, which remains within the guaranteed upper limit of 726,000,000 kg/year [20]. Consequently, researchers have focused on developing effective mitigation strategies, particularly in the power generation sector [21]. Among the most prominent and proven technologies in this domain are the combined cycle and steam injection techniques. The combined cycle technology recovers exhaust heat from the gas turbine to produce steam, which drives an additional steam turbine, thereby enhancing overall system efficiency, increasing energy output, and reducing emissions [22–24]. A thermodynamic simulation of a combined cycle power plant (CCPP) demonstrated that variations in economic parameters and design factors influence the optimal trade-off between costs and returns while simultaneously reducing carbon emissions [25]. Additional analyses of various power system configurations have affirmed that heat recovery from exhaust gases improves plant efficiency and reduces emissions [26].

Furthermore, a mathematical model developed using MATLAB software for simulating thermal processes and evaluating thermal efficiency in combined cycle systems indicated that optimizing heat recovery could raise efficiency to approximately 60%. This approach proves effective in enhancing energy output and reducing specific fuel consumption. The study also showed that improving heat exchanger performance minimizes thermal losses, thus enhancing operational efficiency and lowering both costs and emissions [27]. Outputs from the HOMER software confirmed that integrating renewable energy sources with combined cycle plants significantly improves efficiency and lowers carbon emissions [28].

On the other hand, steam injection technology involves introducing a controlled amount of steam into the combustion chamber of the gas turbine. This process improves thermal efficiency and reduces emissions of CO₂ and NO_x [24, 29, 30]. Moreover, steam injection helps cool the exhaust gases, thereby protecting turbine blades from high-temperature damage and reducing NO_x formation [30–32]. Lowering flame temperatures also minimizes the production of undesirable byproducts. A notable advantage of this technique over the combined cycle is its ability to enable rapid start-up operations with lower emissions [33].

This study presents a practical evaluation of both combined cycle and steam injection techniques by applying them to SGT5-2000E gas turbines operating at the West Tripoli Power Plant in Libya. This turbine type is characterized by high operational flexibility, efficient fuel consumption, low-emissions combustion systems, and integrated water injection for increased output [34].



The analysis in this paper focuses on the performance of both systems under identical operating conditions, with an emphasis on improving environmental performance by reducing CO₂ and NO_x emissions. This aligns with sustainable development goals, promotes more efficient energy use, and minimizes environmental impact through the implementation of advanced technological solutions.

2. METHODOLOGY

Thermodynamic Simulation of the Gas Power Plant. The Siemens SGT5-2000E gas turbine is a single-shaft machine equipped with a dual silo-type combustion chamber that ensures high combustion efficiency and contributes to the reduction of nitrogen oxides (NO_x) and carbon dioxide (CO₂) emissions. The turbine also includes a compressor and a four-stage turbine section. This model is considered unique among gas turbines, as the generator is directly coupled to the shaft located adjacent to the compressor. Furthermore, it is characterized by its high operational reliability and its ability to operate with both gaseous and liquid fuels. The Siemens SGT5-2000E gas power plant operates based on the Brayton cycle. The manufacturer's operational data under International Organization for Standardization (ISO) conditions are presented in Table (1).

Table 1. Operating Data for Siemens SGT5-2000E Gas Power Plant under ISO Conditions [35]

Siemens Performance SGT5-2000E Series	ISO Conditions
Grid Frequency (Hz)	50
Power (MW)	166
Thermal Efficiency (%)	34.7
Heat Rate(kJ/kWh)	10,375
Heat Rate(Btu/kwh)	9,834
Turbine Exhaust Temperature (°C/°F)	541/1,005
Exhaust mass flow rate (kg/s)	525
Pressure ratio	12

2.1. Aspen Plus software

Aspen Plus is a comprehensive simulation tool widely used in engineering applications for modeling and analyzing thermodynamic processes, especially in the energy and industrial sectors. The software enables users to simulate a wide range of systems, including power plants. It excels in modeling complex processes, evaluating performance, and optimizing designs, making it a powerful tool for analyzing energy systems and their environmental impacts [36].

Aspen Plus provides a detailed and systematic approach to modeling various components and processes in power generation systems. It includes a wide array of thermodynamic models and physical property databases, allowing for accurate mass and energy balances and emissions analysis. These capabilities are essential for the design and optimization of power plants, particularly those involving advanced technologies such as steam injection and combined cycle systems [37], ensuring the simulations



reflect real-world conditions as closely as possible. The software employs accurate mathematical models to simulate fluid dynamics, heat transfer, chemical reactions, and mechanical processes, providing reliable predictions of system performance [38].

In power plant simulations, Aspen Plus is frequently used to model both simple gas turbine cycles and combined cycles, as well as steam injection in gas turbine systems and other advanced techniques that enhance efficiency and reduce emissions. Its robust libraries allow for the simulation of various system configurations, enabling engineers to evaluate different operational strategies for optimal economic and environmental performance. Aspen Plus utilizes advanced numerical methods to solve the governing equations that describe system behavior, ensuring convergence to accurate solutions even in complex systems with multiple interacting components. The program’s thermodynamic property capabilities allow for precise calculations, ensuring realistic modeling and accurate performance forecasts [36, 37].

2.2. Thermodynamic model equations

The compressor discharge temperature T_2 is calculated using equation (1), while the turbine exhaust gas temperature T_4 is determined by equation (2), as described in Sengel and Boles. The pressure ratio for the compressor r_{pc} and for the turbine r_{pt} are evaluated using equation (3) [38, 39].

$$T_2 = T_1 \left[\left(\frac{r_{pc}^{y_a-1}}{\eta_c} \right) + 1 \right] \dots\dots\dots (1)$$

$$T_4 = T_3 \left[1 - \eta_T \left(1 - \frac{1}{r_{pt}^{y_g-1}} \right) + 1 \right] \dots\dots\dots (2)$$

$$r_{pc} = \frac{P_2}{P_1} \quad , \quad r_{pt} = \frac{P_3}{P_4} \dots\dots\dots (3)$$

The equations from (4) to (6) were used to determine the various performances of the gas turbine model, and were obtained from Sengel and Boles. [38, 39] The work done by the compressor W_C and the turbine W_T can be evaluated using equations (4) and (5).

$$W_C = \dot{m}_a \cdot cp_a \cdot (T_2 - T_1) \dots\dots\dots (4)$$

$$W_{GT} = \dot{m}_g \cdot cp_g \cdot (T_3 - T_4) \dots\dots\dots (5)$$

The net work of the turbine $P_{thermal}$ for the gas power plant is calculated using equation (6).

$$P_{thermal(GT)} = W_{GT} - W_C \dots\dots\dots (6)$$

When steam is injected, the nominal power of the turbine $W_{T(SIGT)}$ is calculated using equation (7) [40, 41].

$$W_{T(SIGT)} = (\dot{m}_g + \dot{m}_s) \cdot cp_g \cdot (T_3 - T_4) \dots\dots\dots (7)$$



The thermal power $P_{thermal(SITG)}$ of the gas plant with steam injection is determined by applying equation (8).

$$P_{thermal(SITG)} = W_{T(SITG)} - W_C \dots\dots\dots (8)$$

The steam turbine receives high-pressure, high-temperature steam; therefore, the work done in the turbine can be calculated using the relation shown in equation (9) [27].

$$W_{ST} = \dot{m}_S(h_{in} - h_{out}) \dots\dots\dots (9)$$

The work done by the pump is calculated using equation (10).

$$W_p = \frac{\dot{m}_w(h_{out}-h_{in})}{\eta_p} \dots\dots\dots (10)$$

The steam turbine power $P_{thermalST}$ is expressed by equation (11).

$$P_{thermalST} = W_{ST} - W_p \dots\dots\dots (11)$$

The net generated electrical power P_{net} is expressed by equation (12).

$$P_{netGT,SITG,CCPP} = P_{thermalGT,SITG,CCPP} - P_{LOSSGT,SITG,CCPP} \dots\dots\dots (12)$$

The specific fuel consumption rate SFC is calculated using equation (13) [25, 38, 39].

$$SFC = \frac{3600 \cdot \dot{m}_f}{P_{netGT,SITG,CCPP}} \dots\dots\dots (13)$$

The amount of carbon dioxide gas emissions $\dot{CO2}_{EMISSION}$ can be calculated using equation (14).

$$\dot{CO2}_{EMISSION(GT,SITGCCPP)} = \frac{\dot{m}_{EMISSION}}{P_{netGT,SITGCCPP}} \dots\dots\dots (14)$$

2.3. Simulation of the SGT5-2000E Gas Power Plant Using Aspen Plus

The simulation process began by identifying the main components of the system, where the compressor, combustion chamber, and turbine were designed based on operational data obtained from reference studies and actual operational data from Siemens. [35, 38, 39] In this simulation, the compressor input data was used according to ISO operating conditions, including an inlet air temperature of 15°C and 1.013 bar of pressure. According to the composition of dry atmospheric air, the oxygen and nitrogen ratios are O2= 20.95%, N2=79.02%, and CO2= 0.03%. [29] As for the combustion chamber, methane gas was used as fuel, which aligns with the natural gas composition as it contains 98% methane.

[29] The combustion chamber was designed using the RStoic unit to accurately simulate the chemical reactions and fuel combustion. For the turbine simulation, Siemens operational data was used [35], as well as research papers [38, 39] to ensure model accuracy. When the gas turbine is operated under design conditions, it is referred to as the ISO condition. If the plant operates in a condition different from the ISO specifications, it is defined as off-design performance. To verify the model, a model was developed to produce power and thermal efficiency using Aspen Plus with ambient air temperature. Pressure data, pressure ratio, exhaust mass flow rate, and temperature from Table (1) were used to simulate the Siemens GT5-2000E gas power plant, as shown in Figure (1). The turbine pressure ratio was also adjusted, considering isentropic efficiencies of 85% and 90% for the compressor and turbine, respectively, and

mechanical efficiency of 98.5% for the turbine and compressor shaft and 99% for the generator, as specified by the manufacturer.

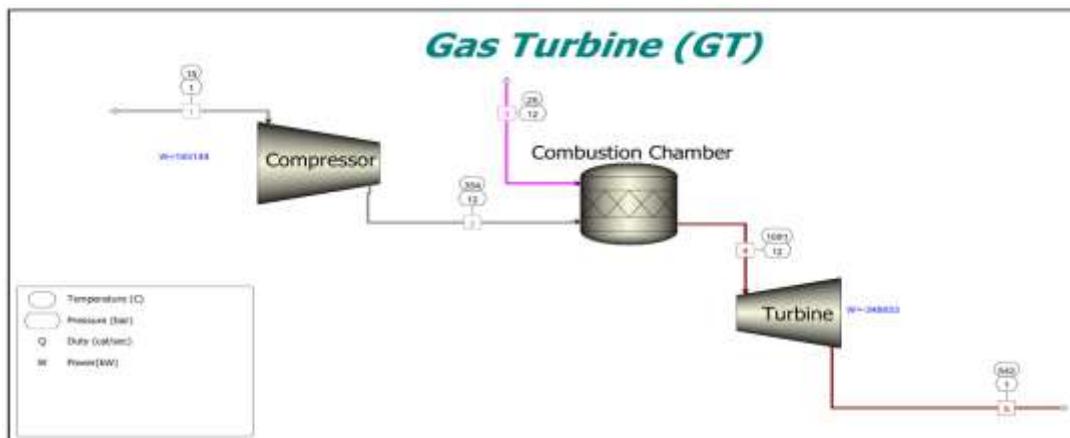


Fig. 1. Simulation model of the Siemens GT5-2000E gas power plant

All results were extracted using the built-in analysis tools in Aspen Plus for the gas power plant components, and their validity was verified using Microsoft Excel to compare calculated values such as efficiency, generated electrical power, exhaust temperature, and heat rate. As shown in Table (2), equation (15) can be used to calculate the model error percentage. [39]

$$Model_{Error} = \frac{(Actual\ data - Model\ data) * 100}{Actual\ data} \dots\dots\dots (15)$$

Table (2): Validation results of the gas power plant model according to the manufacturer’s operational data[35]

NO	Parameters	ISO Conditions	Aspen Plus	Diff	%Error
1	Power (MW)	166	165.68	0.31	0.18
2	Thermal Efficiency (%)	34.7	34.7	0	0
3	Turbine Exhaust Temperature (C)	541	542	1	0.18
4	Exhaust mass flow rate (kg/s)	525	525	0	0
5	Heat Rate(kJ/kWh)	10375	10372.4	2.58	0.02

The results showed agreement with the manufacturer’s operational data. The generated electrical power in the simulation was 165.689 MW, while the operational value was exactly 166 MW, with an error percentage of 0.19%. As for thermal efficiency, it matched exactly with the operational value of 34.7%. Furthermore, the exhaust temperature and gas flow rate showed agreement with the operational data, with error rates below 0.2%, reflecting high model accuracy. It is evident that the simulation results match the operational data from Siemens. This agreement proves that the model is capable of accurately simulating the gas plant performance, making it a reliable tool for evaluating advanced technologies such as steam injection and combined cycle. Based on these results, the model can be used to study the impact of applying different technologies on plant efficiency and overall performance, efficiency, enhancing

production capacity, and studying the effect of the two technologies on reducing harmful emissions.

2.4. Simulation of the Target Gas Plant Using Steam Injection Technology (STIG) and Combined Cycle (CCPP)

This paper investigated the use of two SGT5-2000E gas units located west of Tripoli to evaporate water through Heat Recovery Steam Generator (HRSG) units, in order to benefit from the exhaust gases of the two units. To apply steam injection technology as shown in Figure (2) and the combined cycle shown in Figure (3), with the aim of increasing efficiency, enhancing production capacity, and studying the effect of the two technologies on reducing harmful emissions.

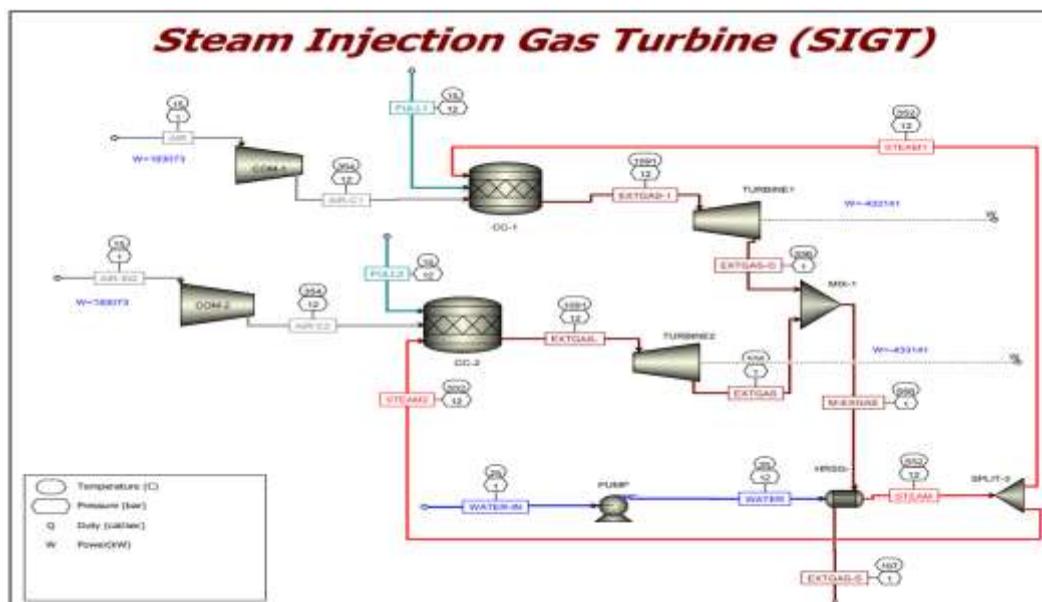


Fig. 2. simulation of two gas unit with steam injection technology

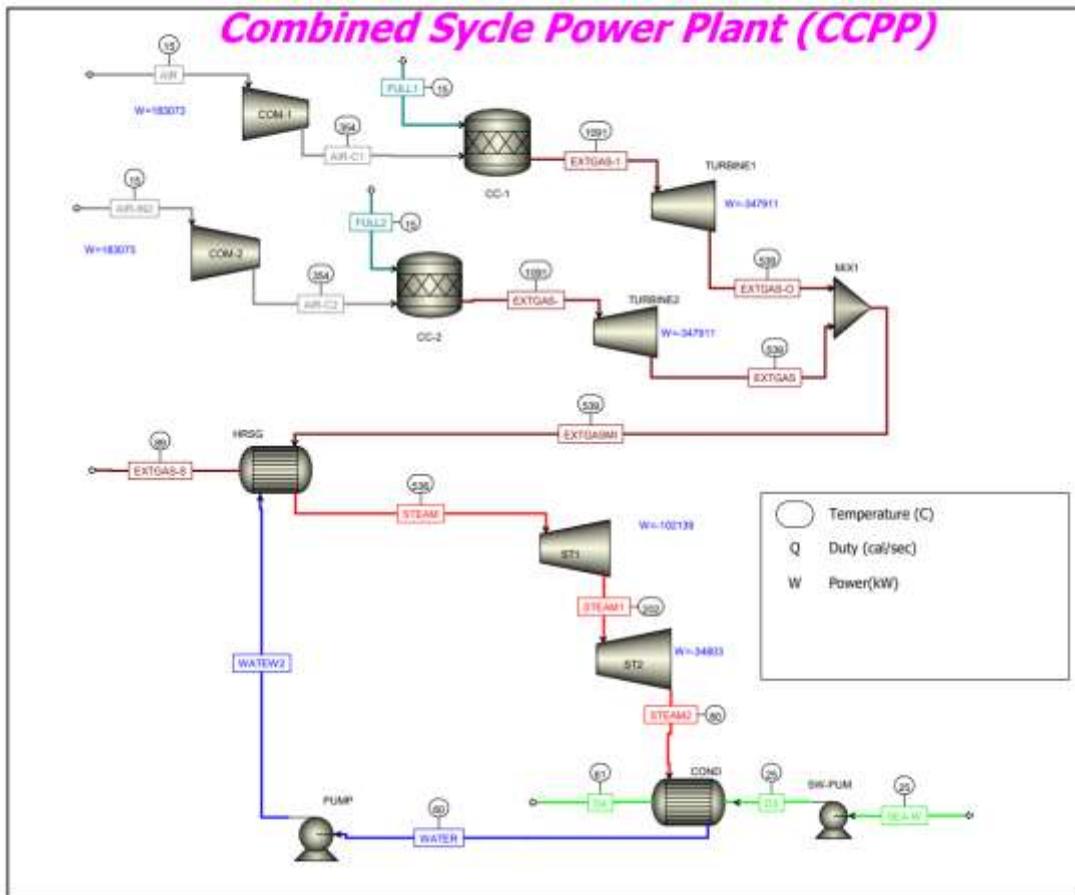


Fig. 3. Simulation model of two gas units using the combined cycle

3. RESULTS AND DISCUSSION

3.1. Specific Fuel Consumption Rate

Figure (4) shows that the steam injection technology achieves greater improvement in specific fuel consumption compared to the combined cycle. At an inlet air temperature to the compressor of 15°C, the specific fuel consumption in the two gas units was 230.44 kg/MWh, while it dropped to 153.36 kg/MWh using steam injection technology, achieving an improvement of 33.5%. In comparison, the consumption in the combined cycle decreased to 162.86 kg/MWh, reflecting an improvement of 29.3%. This difference between the two technologies is 4.2% in favor of steam injection, making it the more effective technology in improving specific consumption. At higher inlet air temperatures to the compressor, steam injection technology remains lower in fuel consumption compared to the combined cycle. When the air temperature entering the compressor increased from 15°C to 45°C, the specific consumption in steam injection technology increased from 153.36 kg/MWh to 165.82 kg/MWh, with a total increase of 8.1%. In the combined cycle, the specific consumption increased from 162.86 kg/MWh to 176.99 kg/MWh, with a total increase of 8.1%. In the combined

cycle, the specific consumption increased from 162.86 kg/MWh to 176.99 kg/MWh, with a total increase of 8.6%. The results indicate that steam injection technology achieves lower specific fuel consumption compared to the combined cycle at all temperatures, making it the most efficient technology in terms of fuel consumption. This is due to the steam injection into the combustion chamber, which improves combustion efficiency.

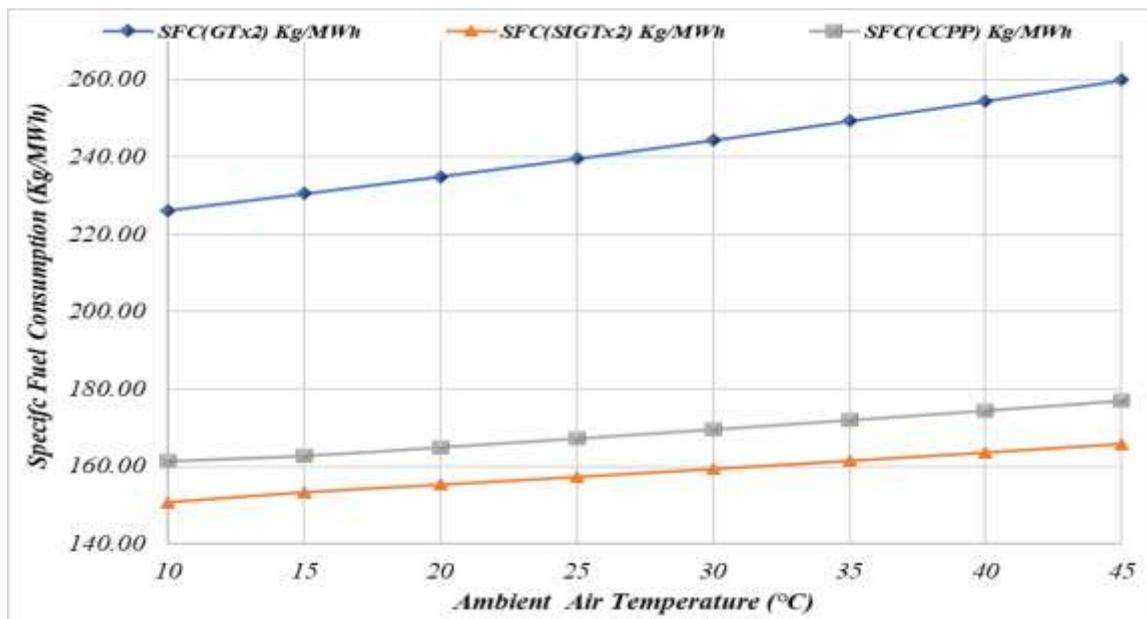


Fig. 4. Effect of Compressor Inlet Air Temperature on Fuel Consumption Rate

4. Carbon Dioxide Emissions (CO₂)

Steam injection significantly contributes to the reduction of carbon dioxide emissions, mainly due to its role in improving the efficiency of the combustion process. In the two gas units in the simple case, the CO₂ emissions reached 632.16 kg/MWh at 15°C as shown in figure 5. After applying steam injection technology to the same two gas units, emissions dropped to 420.71 kg/MWh, reflecting a reduction of 33.4%. This is due to the contribution of water vapor in enhancing combustion and reducing unburned fuel, in addition to lowering the combustion chamber temperature, which limits the formation of harmful gases. After applying the combined cycle to the two gas units, which relies on recovering heat from exhaust gases to power an additional steam turbine, emissions were recorded at 446.78 kg/MWh at the same temperature (15°C), lower than the emissions from the gas units in the simple case by 29.3%. This result is due to the utilization of wasted thermal energy and its conversion into additional electrical power, resulting in more electricity produced using the same amount of fuel. The results shown in Figure 5 demonstrate the effect of rising compressor inlet air temperature on emissions. In the two gas units in the simple case, emissions increased from 632.16 to 712.64 kg/MWh when the temperature rose from 15 °C to 45 °C, with a total increase of 12.7%, or about 2.5% for every 5°C. In the gas units with steam injection, emissions increased from 420.71 to 454.90 kg/MWh for the same temperature

increase, with a total increase of 8.1%, equivalent to 1.6% per 5°C. These results illustrate that steam injection helps reduce the negative impact of rising temperatures on emissions compared to the simple case. In the case of the combined cycle, CO₂ emissions increased from 446.78 to 485.53 kg/MWh with the same temperature rise (from 15°C to 45°C), with a total increase of 8.7%, or about 1.7% per 5°C. Although this technology is also affected by temperature, the rate of increase remains lower than that recorded in the simple gas units, indicating relatively stable environmental performance.

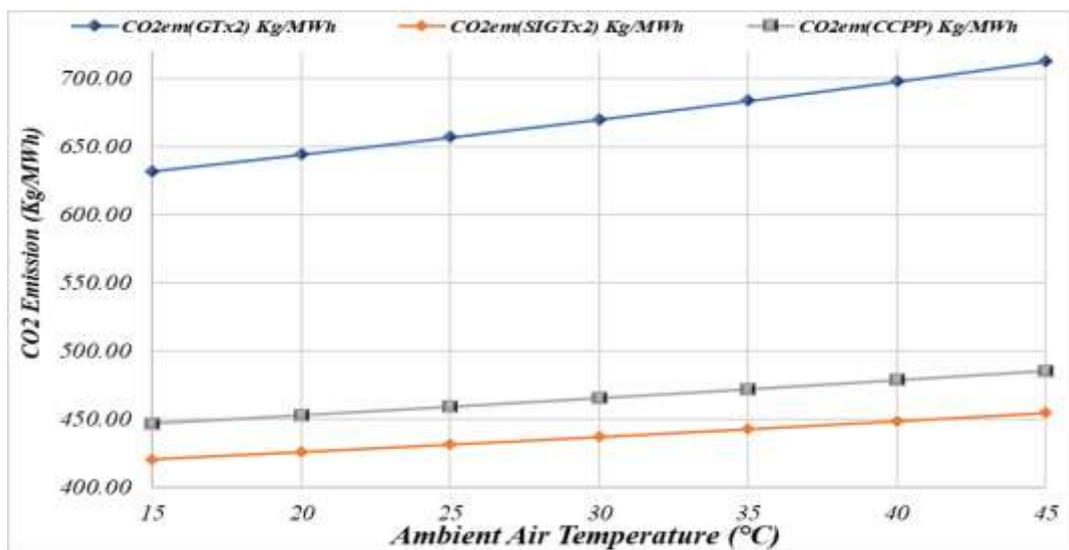


Fig. 5. Effect of Compressor Inlet Air Temperature on CO₂ Emissions

In conclusion, it can be said that both the combined cycle and steam injection technologies effectively reduce CO₂ emissions. However, steam injection shows better environmental performance at moderate temperatures, while the combined cycle is more stable in high-temperature environments. This is because ambient air temperature has no effect on the steam part of the combined cycle, ensuring stable operation of the steam section even at high temperatures, while steam injection is more affected due to changes in temperature, as it is applied directly to the same gas turbine which is influenced by the compressor's response to the inlet air temperature. Therefore, choosing the optimal technology must take operating conditions into account to achieve the best balance between performance efficiency and emissions reduction.

5. CONCLUSION

The gas turbine power plant performance is affected by inlet air temperature, this is reflected in CO₂ emission and fuel consumption, the result obtained from this study can be summarised as follows:

- Steam injection technology shows higher efficiency in reducing fuel consumption compared to the combined cycle, making it a preferred option for improving thermal performance.



- Steam injection technology maintains good efficiency even with rising inlet air temperatures, compared to the combined cycle.
- Steam injection contributes to reducing carbon dioxide emissions more than the combined cycle, enhancing its environmental effectiveness in moderate conditions.
- The combined cycle shows more stable environmental performance in high-temperature environments due to the steam part being unaffected by ambient air temperature.
- The optimal choice between the two technologies depends on the nature and conditions of operation, with the aim of balancing efficiency and emission reduction.

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