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Gas Turbine Performance Enhancement and Evaluation for Power Generation in the City of Karbala, Iraq

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***Abstract:** The performance of gas turbines is highly susceptible to environmental factors, particularly in arid and hot climates. The present study examines the direct impact of ambient temperature on the gas turbine's performance under the climatic conditions of Karbala city. An Excel proprietary software modeled using the law of energy and mass conservation was used to simulate real data collected from the Karbala power plant (gas turbine). The simulation result was found for the gas turbine power plant with steadily increasing compressor entry temperature (T_1). The result show that for a 40K temperature rise from 300K-340K at the compressor inlet stage, net power gained a 13.34% increment; thermal efficiency gained a 13.33% increment and a reduction in the specific consumption of fuel (SFC) by 12% was noticed. The effect was acknowledged to be a resonating one rather than direct. Recommendations suggest that a pre-compressor cooling technology be developed and incorporated with a high efficiency pre-combustor heating technology for compressor reduction and SFC reduction. Best practice.*

***Keywords:** Compressor Cooling, Gas Turbine, Net Power, Performance Enhancement, Thermal Efficiency*

I. INTRODUCTION

The working fluid, air, is converted by gas turbines into high-temperature, high-pressure gas, which powers the turbine engine (Li et al., 2018) [1]. In order to produce electrical power, thermodynamic energy is transformed into mechanical energy. The system's three primary components—the turbine/engine, the combustion chamber (combustor), and the gas compressor—all work together to produce power (Yazdani et al., 2020) [2]. An essential component of the Gas Powerplant (GPP) is the combustor, which is utilized to compensate for the energy lost in the working gas after it leaves the compressor (Liang et al., 2020; Bao et al., 2019) [3][4].

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Several factors pertaining to the functioning processes of each component in the GPP are taken into account when determining the gas turbine's power quality. Many studies and investigations have focused on improving the power output of gas turbines, and it has been determined that improving the pre-turbine process (at the compressor and combustor sections) can have a positive impact on the overall efficiency and power output (Matjanov, 2020) [5]. Cooling the air entering the compressor is believed to be one of the best ways to improve gas turbine performance, particularly in hot climates (Al-Ibrahim & Varnham, 2010; Baakeem et al., 2018) [6][7]; consequently, a lot of researchers have worked on this subject. After comparing various approaches to increase gas turbine efficiency, researchers (Omidvar, 2001; Espanani et al., 2013) [8][9][48][49][50] came to the conclusion that cooling the compressor's incoming air is the most effective strategy. According to the researchers (Ukwuaba et al., 2020) [10], the plant's efficiency can be increased by adding a wetted substance evaporative cooler. Thermal efficiency and net power output decrease by approximately 3% and 10%, respectively, if the surrounding temperature reaches 50°C (Kadhim et al., 2020; Alhwayzee et al., 2021) [11][12]. Alhazmy et al. (2006) [13] investigated how the temperature and moisture content of the study area affected the gas turbine's performance and found that direct mechanical cooling raised the gas turbine's daily capacity by 6.77%. Sanjay and Mohapatra (2014) [14] found that adding a vapor-compression chiller to a combined cycle increases the gas turbine's output and efficiency by 14.77% and 4.88%, respectively. According to Orhorhoro et al. (2016) [15], the average increase in station capacity was 3.631 MW, and when cold air was brought into the compressor entrance, there was a discernible rise in efficiency from 33.279% to 36.855%. Additionally, the researchers found that the most affordable strategy to increase the gas turbine's performance is to cool the air that enters the machine (Kim et al., 2012). Even though it is extremely unlikely, the potential for erosion and corrosion when water is sprayed with air at the gas turbine's inlet is a limiting issue (Sanaye & Tahani, 2010) [16] [17]. Since the compressor is an essential component of the gas turbine, it directly affects the production of the plant, therefore the technology of cooling air entering the compressor can be used (Shukla et al., 2018; Ibrahim et al., 2017; Rashid et al., 2017; Al-Jibory et al., 2018; Rashid et al., 2018; Al-Jibory et al., 2020; Hussein et al., 2020) [18][19][20][21][22][23][24][25][40][41][42]. Barakat et al., (2019) [26][27], tested a hybrid cooling system that included an underground heat exchanger.

Their results indicated that this system reduces the water consumed for gas turbine cooling.

II. LITERATURE REVIEW

One of Saudi Arabia's most significant and expanding industries is power generation, which is essential to the country's economic growth and driven industrialization plans. The Kingdom of Saudi Arabia is situated in the southwest of Asia, bordered by Jordan, Iraq, Kuwait, Bahrain, Qatar, Emirates, Oman, and Yemen. Its land and coastal boundaries are 4431 and 2640 km, respectively, and it occupies an area of more than 2 million square kilometers; virtually all of this land is used for desertification and agriculture, and its climate is generally harsh and dry with extremes of temperature (Di et al., 2019) [28]. The main power generation facilities in the Kingdom are diesel, steam, and modern gas turbine facilities used in single or combined cycle modes (Gang et al., 2017; Abazar & Majid, 2011; Peyman & Sadegh, 2020) [29][31][32]. In 2012, 571 gas turbine units produced 50% of the total capacity, while 104 steam turbine units, 68 combined cycle units, and 83 diesel engine units produced 39%, 10%, and 1% of the total capacity, respectively (Abazar & Majid, 2011) [30]. The International Standards Organization (ISO) rates the production capacity of gas turbines, specifying the following reference air inlet conditions: air 15°C (59°F), relative humidity 60%, and absolute pressure (sea-level) 101.325 kPa (14.7 psia). Gas turbines are considered constant volumetric flow rate machines that use ambient air as the working fluid (Peyman et al., 2018; Sadeghzadeh et al., 2015) [33]. As a result, ambient conditions (temperature, humidity, and pressure) are considered important factors affecting the performance of such power plants. (Sadeghzadeh et al., 2015; Kousuke et al., 2005; Campbell & Rohsenow 1992; Stasiek 1998 Oiu-wang et al., 2014; Ting et al., 2016) [34][35][36][37][38]. According to Kousuke et al. (2005), there are more than 170 gas turbine units in Iran with a total combined capacity of 9500 MW; 20% of this capacity is lost during the summer. The study focused on the performance of gas turbines at varying ambient temperature for specific turbines SGT 94.2 and SGT 94.3 installed at the Dewa Power Station located at Al Aweer, H Phase II and III in Dubai, UAE. The researchers found that for every 1°C rise in ambient temperature above ISO conditions, the units lose 0.1% in terms of thermal efficiency and 1.47 MW of gross (useful) power output. From the performance curves of the gas turbines, they concluded that for each 1 °C increase in ambient air temperature, the power output will decrease by 0.74%, and the air mass flow rate decrease by 0.36%. Oiu-wang et al., (2014) tested the production of a simple gas cycle in the central Qaseem region of Saudi Arabia. They reported that a high mid-day ambient temperature during the summer can cause a 24% decrease in system capacity (Di et al., 2019). Xusheng et al., (2019) [43][44][45] studied theoretically the effect of the average hourly temperature and relative humidity on the performance of a typical gas turbine unit used in three Saudi regions: Dammam, Riyadh, and Jeddah. The obtained results showed that both ambient temperature and humidity have significant effects on the gas turbine performance. They reported that due to weather variation, the maximum electricity production losses were 20%, 18% and 17.5% of ISO production in Riyadh, Dammam, and Jeddah, respectively. More recently, the energy and exergy analysis of 42 MW typical gas turbine was presented by Hui et al., (2022) [39] using average hourly temperature and relative humidity for selected Gulf cities located in Saudi Arabia, Kuwait, United Arab Emirates, Oman, Bahrain, and Qatar. The ISO conditions are taken as dead state conditions. The authors Himanshu & Ralph, (1987) [46] concluded that adding inlet cooling systems to the existing gas turbine units should be considered seriously and could be justified in hot periods.

The following techniques for turbine inlet air cooling (TIAC) are widely used (Di et al., 2019; Kousuke et al., 2005):

- Evaporative cooling systems
  Media evaporative cooling (MEC).
  High pressure fogging (HPF).
- Refrigerated inlet cooling systems
  Mechanical vapor compression, Refrigeration cooling, (MVC).
  Absorption cooling, Absorption chillers cooling, (ACS).
- Thermal energy storage (TES) systems.

Al-Ibrahim and Varnham (2010) reviewed the inlet air-cooling technologies that can be used to improve the performance of gas turbines power plants in Saudi Arabia. The evaporative coolers are divided into evaporative media and fogging systems. These cooling technologies are suitable for hot and dry climates rather than the hot and humid ones (Peyman et al., 2018; Rui et al., 2017) [47]. Two main subcategories of refrigeration cooling systems are mechanical refrigeration and absorption cooling. The refrigerated inlet cooling systems have high power consumption and so many auxiliary equipment, but they have a greater performance than media evaporative and fogging. In thermal energy storage (TES) system, chillers are used to cool water or one of the aqueous fluids or to make ice, and store it in a tank for later use to meet the cooling needs. TES is used during the peak loads when power is highly valued (5–7 h per day). Chillers are sized to run during non-peak demand times (perhaps 17–19 h per day) (Matianov 2020). The amount of stored cooling energy depends on the temperature difference between the chilled water stored in the tank and the warm water returned from the heat exchanger (Shukla et al., 2018). Many studies conducted comparison research between those technologies. Using Engineering Equation Solver (EES), the thermodynamic models of single-effect water-lithium bromide (H_2O-LiBr) absorption chillers and evaporative coolers were created (Sanjay & Mohapatra 2014). Alhazmy et al., (2006) examined the influence of inlet air-cooling on gas turbine power output and efficiency utilizing two alternative cooling approaches, direct mechanical refrigeration and evaporative water spray cooling using the EES software. The authors used the daily air temperature and humidity of Jeddah on the 16th of August, in which the temperature fluctuated between 33 and 41 °C and the relative humidity reached 100%.

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They reported that under the hot humid conditions of Jeddah, the daily power output of the ABB-11D5 gas turbine was increased by 6.77 and 2.57% by using the direct mechanical refrigeration and the spray air-cooling, respectively. Omidvar (2001) studied the effect of using evaporative cooling and absorption chillers on the power and efficiency of a gas turbine compared with the ISO performance. The results indicate that absorption chillers were the best cooling option for ambient air that was both hot and had a low relative humidity. Using typical meteorological year (TMY) data, the power needs of various inlet air cooling strategies for GE Frame 6B gas-turbine power plants in two locations—Marmul and Fahud, Oman—were assessed (Hussein et al., 2020). A 48.8 °C summertime ambient temperature and a nominal power output of 40 MW at base load were taken into consideration. Evaporative and fogging cooling systems yielded power gains of 9.83% and 11.36%, respectively. According to Orhorhoro & Orhorhoro (2016), in both sites, fogging cooling uses 11.4% less electrical energy than evaporative cooling. For Marmul location, the annual water requirements were 12 655 and 14 085 tons for evaporative and fogging, respectively. The design compressor inlet air temperature for H2O-LiBr chilling systems was 14 °C, and for both aqua-ammonia absorption and vapor-compression refrigeration systems was 8 °C. For H2O-LiBr chilling systems, a maximum power boosting of 15.32% (from 34.6 to 39.9 MW) could be gained. Besides, for both aqua-ammonia absorption and vapor-compression refrigerating systems, a maximum average temperature dropped of 26.7 °C and a maximum power boosting of 19.7% (from 34.6 to 41.4 MW) were expected in August. The H2O-LiBr cooling offered 40% and 55% more energy than fogging cooling at Fahud and Marmul, respectively. The aqua-ammonia water and vapor-compression cooling offered 39% and 46% respectively of annual power production at Ukwaba et al., (2020) studied the effects absorption cooling, evaporative cooling, and steam injection on the inter-cooled reheat recuperated gas turbine cycle. A comparison between water spraying system and cooling coil was achieved by Alhazmy and Najjar (2006). The performance characteristics were examined for a set of design and operational parameters including ambient temperature, relative humidity, turbine inlet temperature, and pressure ratio. The found results showed that the less expensive option was the spray coolers but they deeply influenced by ambient temperature and relative humidity. While cooling coils gave full control over inlet conditions but had large parasitic power requirements. The spray coolers reduced the temperature of incoming air by 3–15 °C, enhancing the power output by 1–7% and improving efficiency by about 3%. The cooling coils enhanced the turbine output power by 10% during cold humid conditions and 18% during hot humid conditions. The lack of energy storage caused net power to go down by 6.1% and 37.6% for cold and hot humid conditions, respectively. On the other hand, other authors have proposed and developed new techniques to enhance the performance of gas turbines (Sanjay & Mohapatra, 2014; Shukla et al., 2018; Matianov 2020). Alhazmy and Najjar (2006) used the waste heat from the exhaust of the gas turbine to enhance the power output and efficiency combined with reducing inlet air temperature. The system consists of an upper propane Organic Rankine Cycle (ORC) cascaded by a gas refrigeration lower propane cycle. The effect of the ambient temperature, gas turbine exhaust temperature, compression ratios of the upper and lower cycles and the saturation pressure of the condenser were investigated. They compared their method with the absorption, the mechanical compression, the evaporation cooling and the fogging system. For economic analysis, four cities, Abu-Dhabi, Riyadh, British Colombia and Amman, were used to find the recovery period and overall performance of the system using the peak hours weather data of the day. Yazdani et al., (2020) used the air Brayton refrigerator (reverse Joule Brayton) cycle to cool the intake air at the compressor of gas turbine cycle. The typical weather data for Jeddah, Saudi Arabia were used. Barakat et al., (2019) used the earth to air heat exchanger (EAHE) as a new application to the inlet air cooling of gas turbines. They developed a model solving the discrete numerical equations applied to the New Gas Damietta power plant as a case study. Using the earth to air heat exchanger increased the output power and thermal efficiency of the gas turbine by 9% and 4.8% respectively. In the economic analysis, the annual revenue increased by 1.655 MUSD with a payback period of 1.2 years.

III. RESEARCH METHODOLOGY

A. Description of The Powerplant

Data obtained from the Karbala powerplant will be used in this research work. The power plant is a 2× (125MW) frame 9001EA gas turbine with 250MW capacity, connected to the Iraqi National Grid. It is owned by the Iraqi Ministry of Electricity and supplied by the General Electric (GE) Company. The station started commercial operation in October 2012. Karbala power Station is location by coordinates of lat.32.435899˚N and long.44.126398˚E.

B. Data Collections

The working data of Karbala powerplant were collected from the daily operation reports. These collected data for the cold months and hot months were studied. Summary of an operating parameter of a unit 1GT (Frame 9001EA) gas turbine used for this study at an ambient temperature of 25℃ shows in Table 1. The thermodynamic analysis was done for all gas turbine components where the energy conservation and mass conservation laws were applied as governing equations of each component and the performance of the plant was evaluated having a fogging cooling system.

Table 1: Operating Parameters for Kabala Powerplant (Kadhim *et al.*, 2023)

Operating Parameters	Value	Unit
Fuel Flow Rate	6	kg/s
Ambient Temperature	300	K
Pressure Ratio across all states	10	--
Compressor Isentropic Efficiency	87	%
Turbine Isentropic Efficiency	88	%
Lower Heating Value	48439	kJ/kg

C. Thermodynamic Analysis and Simulation of the Gas Turbine

Thermodynamic analysis is carried out using the first law of thermodynamics with respect to energy and mass conservation. The analysis was performed across all thermodynamic stages and processes inherent in the operation of the gas turbine system. The thermodynamic model performed in this analysis is shown below:

i. For Compression and Expansion Phases

Isentropic compressor power (kW) $P_{ic} = \dot{m}_{air} Cp_{air}(T_2 - T_1)$ (1)

Mechanical compressor power (kW) $P_{mc} = P_{ic}/\zeta_{mc}$ (2)

Isentropic turbine power (kW) $P_{iT} = \dot{m}_{gas} Cp_{gas}(T_3 - T_4)$ (3)

Mechanical turbine power (kW) $P_{mT} = P_{iT}/\zeta_{mT}$ (4)

Mechanical Net Power (kW) $P_m = P_{mT} - P_{mc}$ (5)

Mechanical Net Power (Maximum)(kW) $P_m = \dot{m}\, Cp[(T_{max}\, \zeta_{iT}\zeta_{mT})\left(1 - \frac{1}{\tau}\right) - (\frac{T_{min}}{\zeta_{ic}\zeta_{mc}})(\tau - 1)]$ (6)

Eqn. 6 is however only used with the assumption that mass flow rates, specific heat capacities and ratios are the same for air and exhaust gases.

ii. For Combustion Phase

Mass balance (kg/s) $\dot{m}_{air} + \dot{m}_{fuel} = \dot{m}_{exh\ gases}$ (7)

Energy balance (kW) $\dot{m}_{air} Cp_{air} T_2 + HCV \dot{m}_{fuel} \zeta_{cc} = \dot{m}_{exh\ gases} Cp_{exh\ gases} T_3$ (8)

Overall efficiency (%) $\zeta_o = \frac{P_m}{\dot{m}_{fuel} LHV}$ (9)

Specific fuel consumption $SFC = \frac{\dot{m}_{fuel}}{P_m} 3600$ (10)

The above model was used to create an Efficiency, Output power, and SFC calculator using Microsoft Excel

IV. RESULTS

The results derived from running the data in table 1 using the model (1-10) presented above are presented in the table and charts below.

Table 2: Research Results

Inlet Temp (K)	Net Output (Mw)	SFC (kg/kWh)	Total Flow (Kg/S)	Overall Eff. (%)
300	87.81	0.25	304	0.30
305	89.27	0.24	304	0.31
310	90.74	0.24	304	0.31
315	92.20	0.23	304	0.32
320	93.66	0.23	304	0.32
325	95.13	0.23	304	0.33
330	96.59	0.22	304	0.33
335	98.06	0.22	304	0.34
340	99.52	0.22	304	0.34

Expressed in the figures below are the charts of compressor inlet temperatures against corresponding quantities of Net Output, SFC and Overall Efficiency;

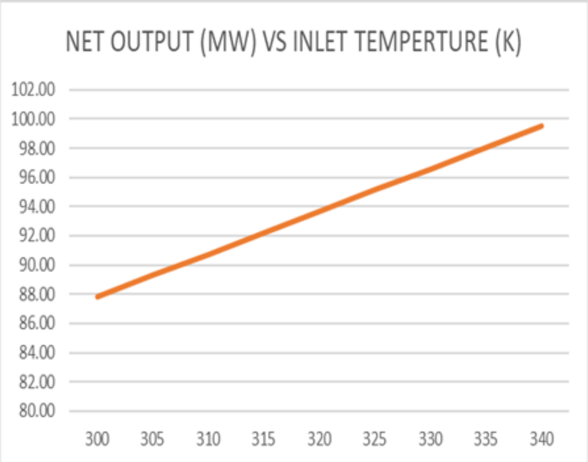

Fig. 1: Net Output Against Compressor Inlet Temperature Chart

Fig.1 above shows the graphical relationship of the result between net output and compressor inlet temperature of the GPP. From this chart, we notice an upward pattern from left to right, showing a direct proportional relationship for both quantities under review. The figure expresses a net 13.34% increase in power output for a 40K rise in ambient temperature between 300 and 340K. Fig. 2 below further gives insight on the effect of increasing ambient temperature on GPP performance as derived from this analytical research

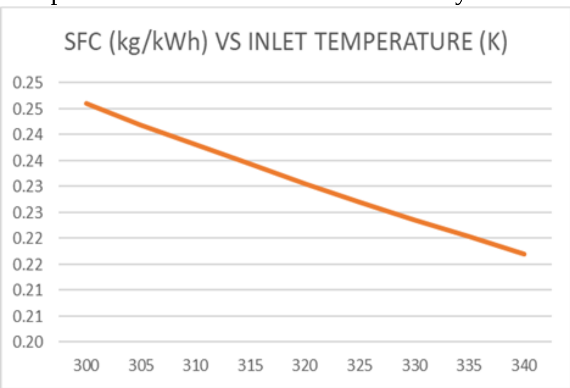

Fig. 2: SFC Against Compressor Inlet Temperature

Fig. 2 goes ahead to show the graphical relationship of the result between specific fuel consumption (SFC) and compressor inlet temperature (CIT) of the GPP. From this chart, we notice a downward pattern from left to right, showing an inverse proportional relationship for both quantities under review. The figure expresses a net 12% reduction in SFC for a 40K rise in ambient temperature between 300 and 340K.

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Fig. 3 below attempts to illustrates the direct impact of ambient temperature on thermal efficiency within the confines of this analytical research. Finally, Fig. 3 above shows the graphical relationship of the result between overall efficiency and CIT of the GPP. From this chart, we notice an upward pattern from left to right, showing a direct proportional relationship for both quantities under review. The figure expresses a net 13.34% increase in power output for a 40K rise in ambient temperature between 300 and 340K.

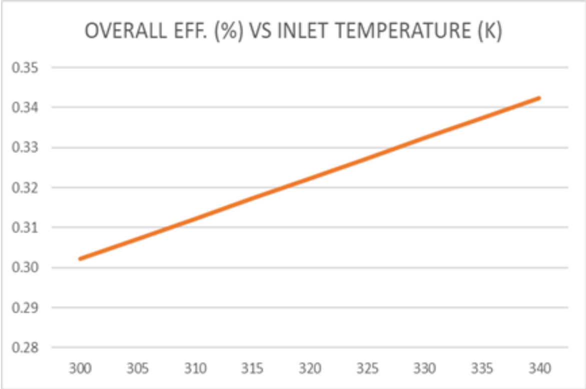

Fig. 3: Overall Rfficiency Against Inlet Temperature

A. Research Assumptions

The above are results derived from analysis while respecting the following assumptions;

- Pressure ratio across all thermodynamic processes remained constant
- Mass flow rate was not constant for air and exhaust gases
- Specific heat ratios for air and exhaust gases were not identical
- Specific heat capacities for air and exhaust gases were unidentical

V. CONCLUSION

Converse to the usual phenomenon that suggests that a rise in the compressor inlet temperature of a GPP results in a consequential rise in its SFC, and a drop in its production capacity and overall efficiency, this research has shown otherwise. With data collected from the Karbala powerplant and analyzed using a proprietary spreadsheet embedded with eqn. (1-10) thermodynamic model that obeys the first law of energy and mass conservation, the research goes ahead to suggest that for every rise in temperature, there was a drop in SFC; and a consequential increase in net production capacity and overall efficiency. This is possible because a rise in the compressor inlet temperature (T_1), directly caused an increase to the combustor entry temperature (T_3), thereby reducing the amount of fuel needed for ignition. This directly affects the SFC which according to thermodynamic model, is inversely proportional to net mechanical power output (P_m). Hence for a mathematical expression as such, a dip in the SFC value will yield an equal but opposite increase for the P_m. Furthermore, the P_m relates mathematically to the overall efficiency (ζ_o) by a direct proportionality. Suggesting that an increase in the value of P_m will give an equal amount of increase in the value of ζ_o. Hence the results presented and discussed in this research.

VI. RECOMMENDATION

Giving the findings from this research and acknowledging that in practice, cooling the compressor inlet air increases air density and reduces compressor work which is good for production capacity, the following will be suggested;

- Pre-compressor cooling technologies be researched on and developed to aid compressor work reduction
- High efficiency heat exchanging technologies that are cost effective be further developed for pre-combustor heating from waste exhaust gases heat. This will reduce the amount of fuel needed for continuous combustion, impacting positively in the GPP SFC that ultimately results in power output and overall efficiency increase.

The proposed system can be seen in the schematic fig. 4 below;

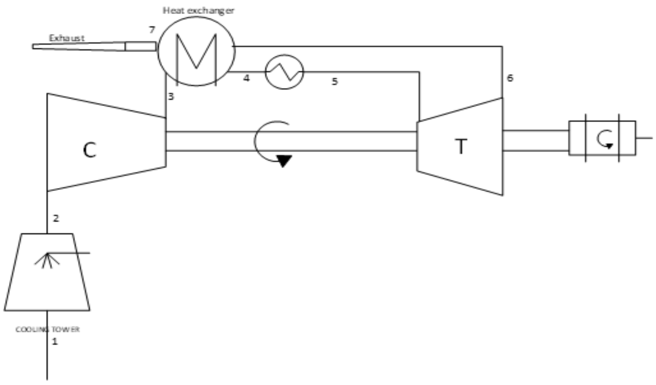

Fig. 4: Schematic of Recommended GPP

Fig. 4 above provides a schematic of the recommended simple GPP with pre-compressor cooling and pre-combustor heating modifications. Process (1-2), ambient air enters the cooling tower to be cooled before compression. After cooling, the cooled air of higher density enters the compressor (C) (2-3) for compression at constant entropy. The compressed air leaves the compressor at high pressure and reduced volume, and is preheated using a counter-flow heat exchanger (3-4) by waste heat from exhaust gases. (4-5) the preheated air at high temperature and enthalpy enters the combustor for isobaric heat addition. (5-6) high enthalpy gas enters the turbine (engine) for energy extraction by turbine blades and expansion. (6-7) high temperature exhaust gases enters the heat exchanger from the turbine for heat extraction to aid pre-combustion heating. (7-1) heat is rejected under isobaric condition to the environment by exhaust gases. This system looks to ensure reduction in compressor work and SFC of the GPP, giving rise to increased power output and thermal efficiency.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Funding Support:** This article has not been funded by any organizations or agencies. This independence ensures that the research is conducted with objectivity and without any external influence.
- **Ethical Approval and Consent to Participate:** The content of this article does not necessitate ethical approval or consent to participate with supporting documentation.

- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Authors Contributions:** The authorship of this article is attributed equally to all participating authors.

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Stanley James-Diwa Enyia, is an exceptional scholar and force to reckon with in STEM. He has several awards in STEM including Mathematics, Physics, Chemistry, Further Mathematics, etc. he is an undergraduate scholar who has already familiarised himself with thermodynamics and is making meaningful contributions to gas turbine technology and maintenance. He is a young and ambitious individual with a passion for academic excellence and innovation. Stanley has consistently demonstrated exceptional academic prowess and a keen interest in the field of Mechanical Engineering. He is Currently pursuing a degree in Mechanical Engineering and completed high school education with outstanding grades and awards. His Interests include Mechanical Engineering design and development, Renewable energy and sustainable technologies, Robotics and Automation, Research and innovation. He aspires to become a leading expert in Mechanical Engineering and contribute to innovative solutions for real-world problems, pursue a career in research and development, focusing on sustainable energy and technologies, and inspire and mentor young minds in STEM education. He is a Curious and innovative thinker with strong problem-solving skills and an analytical mind, with excellent communication and teamwork skills, passionate about learning and self-development.

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