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A Comparative Study of Sustainable Energy Brayton Cycles in the Oil and Gas Industry. Part 1: Performance

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Abstract: ***Brayton cycles are open gas turbine cycles extensively used in civil aviation and the petrochemical industry because of their advantageous volume and weight characteristics. With the bulk of engine emissions associated, it is necessary to promote their environmentally-friendliness, including sound technical performance regularly. This research considers high bypass-low specific power plants in aviation and aero-derivative gas turbines combined-heat-and-power generation in the petrochemical industry. The investigation encompasses the comparative assessment of simple and advanced gas turbine cycle options including the component behaviour of the systems. This comprises the performance module. The research has contributed to understanding the technical performances of simple and advanced cycle helicopter engines, and aero-derivative industrial gas turbine cycles at design and off-design conditions. The simple cycles were modified for better fuel burn and thermal efficiency by using some additional components to form the advanced cycles. The helicopter engine investigated was converted to a small-scale aero-derivative industrial engine. Modeling the combined-heat-and-power performance of the small, medium, and large-scale aero-derivative industrial gas turbines was also implemented. The contribution also includes understanding the technical performances of both simple and advanced aero-derivative gas turbines combined heat-and-power at design and off-design A case study underlies the development and deployment of this model. The novelty is the conception of a tool for predicting the most preferred simple and advanced cycle aero-derivative engines combined heat-and-power generation in the petrochemical industry and the derivation of simple and advanced cycle small-scale aero-derivative industrial gas turbines from helicopter engines.***

Keywords: ***Aero-derivative Engine, Brayton Cycles, Gas Turbine, Helicopter Engines, Techno-Economics***

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I. INTRODUCTION

This research considers high bypass-low specific power plants in civil aviation and aero-derivative gas turbines combined heat-and-power generation in the petrochemical industry. The investigation encompasses a comparative assessment of simple and advanced gas turbine cycle options including the component behaviours and the environmental and economic analysis of the systems. Fundamentally, the Brayton cycle is the thermodynamic cycle based on which principles gas turbine power plants operate. It is commonly referred to as the standard open gas turbine cycle [1][33][34]. Brayton cycles are extensively used in the civil aviation and petrochemical industry because of their advantageous volume and weight characteristics. These cycles are used as prime movers in the mechanical drive of rotating equipment, pumping of fluids, electric power generation, and industrial process heat generation in combined-heat-and-power concepts Gas turbine is a unique heat engine (also a fluid machine) that has over the years brought thrust and power generation to fore, and unarguably one of the most important developments of the 20th century that has changed human lives in many ways [2]. Inevitably, emissions from gas turbine engines in both aviation and industrial applications have contributed immensely to the degradation of local air quality, and to the greenhouse effect and global warming worldwide. It is, therefore, needful to regularly promote environmentally friendly operation of the cycle engines. Based on this fact, for instance, the Advisory Council for Aeronautics Research in Europe (ACARE) has defined some targets for 2020 and 2050 among which is reducing CO_2, emissions by 50% [3]. Also, the Clean Sky Joint Technology Initiative (JTI) European Union collaboration, has set goals aiming at reducing fuel consumption and CO_2 emission by 50%, NO_x by 80%, and sensed external noise by 50% [4]. Besides, gas turbine user requirements have, over the years, necessitated technological advancement in engine performance, and comprehensive research is being conducted to achieve this [5]. Technically, the improvement of thermal efficiency for industrial and aero gas turbines is of paramount importance to the overall performance of the engines. An increase in thermal efficiency depends on certain factors including changes in some engine cycle parameters, cutting-edge technology of engine components, and, the introduction of different overall thermodynamic cycles [6] [7].

More so, the performance and economic viability of gas turbines are inseparable. This is because performance is made up of shaft power or thrust sold by a gas turbine manufacturer and bought by a user. If an engine with bad performance is designed, the sellers will struggle hard to sell and most likely make losses. Likewise, a user who buys a poorly designed engine will lose income [8]. This research aims to adapt the most preferred for aero-derivative gas turbines combined heat- and power generation in the petrochemical industry.

II. LITERATURE REVIEW

The concept of the Brayton cycle was highlighted [9], [10][30][31]. The emergence and application of the TERA-techno-economic and environmental risk analysis framework in areas of multi-disciplinary optimization and management of power plants was explained [11]. Furthermore, research was carried out on technical risk analysis of gas turbines for natural gas liquefaction [12]. On helicopter engine performance, improvements predictions were made in 1968 and 1971 that by the year 1980, there would be increases of about 17% in OPR, 7% in TET, and a decrease of about 17% in SFC [13]. Also, the potential of the growth of the turboshaft engine of a helicopter with time, customer taste, and technological advancement, and improving the preliminary design of the Rolls-Royce/Turbomeca RTM 322 engine model through increasing the TET; flaring the LP compressor, and, zero staging the LP compressor, were reported [14]. About aero-derivative industrial gas turbines, it was reported that a performance platform was developed for Manx Electricity Authority (MEA) for their two existing GE LM2500+ aero-derivative gas turbine engines providing a graphical user interface, which is flexible enough to implement varying operating conditions in performance and diagnostics analysis. More so, a new version of PYTHIA software and an off-design adaptation method were developed that will enable the engine model to match the MEA's service engine performance at part load conditions [15] [16]. Aero-derivative gas turbines give various advantages over their industrial design counterparts, in technology, project implementation, and maintenance. Modern aero-derivatives are also a feasible option for combined-cycle gas turbine and CHP applications where power in the 60-120 MW class is anticipated [17][32]. The GE LM6000 offers a 25% simple cycle power increase compared to the GE LM2500, owing to advanced technology. The advancement to the GE LM6000 gas turbine produces an 18% increase in exhaust energy and 25% increase in power and about 52% combined-cycle efficiency. With GE's dry low emission (DLE) technology, an efficiency of about 56% can be attained though at slightly less power output [18]. About CHP, mention was made of the work done on an overall techno-economic analysis of the gas turbine and absorption cooling (LiBr/Water) tri-generation plant. The effects of the use of different types of fuel, ambient conditions, part load conditions, degradation, or the extraction of power for district heating or absorption cooling were simulated [19]. The results suggested that the simple cycle tri-generation technology mode was more economically favorable than the conventional technology. The integrated tool was capable of helping potential investors decide if it is profitable to proceed with their investments in such technology [20]. It was also found that the thermal efficiency of aero-derivative engines combined-cycle units is higher than that of individual gas turbine or steam turbine units [21]. Regarding engine performance, how to model and establish the design point (DP) of a gas turbine was explained in detail. Besides, the method of obtaining its general performance over the entire operating range of power output and speed known as Off-Design (OD) performance by the use of computer model simulations such as TURBOMATCH was vividly explored [22] [6] [23] [24]. This research investigates advanced cycle helicopter engines by the use of additional components to modify simple cycles. Also, the conversion of helicopter engines to small-scale aero-derivative industrial engines and its application in CHP in the petrochemical industry is investigated.

A. Aero-Derivative Engines Combined-Heat-and-Power in the Petrochemical Industry

Contemplating environmentally-friendly Brayton cycles in the petrochemical industry identification is made of combined heat-and-power (CHP) as one prominent application that would make gas turbine operation very pleasant to the environment in the sector in terms of fuel efficiency and reducing emissions. CHP simply defined is the simultaneous generation of mechanical power and heat energy in a single system from the same fuel input International Energy Agency (IEA). In light of this, the performance of aero-derivative gas turbines discussed earlier is herein examined in CHP application in the petrochemical industry.

B. Petrochemical Industry Processes

In this research, the petrochemical industry encompasses both refineries and petrochemical processing plants where crude oil and natural gas are transformed into various Hydrocarbon compounds and finished products. It is important to clarify that these industry processes are not treated here in detail but rather focus is only made on the process heat energy and electrical power demand of the plants. Petroleum refining is the mother industry for petrochemical industries [25]. Crude oil is refined and transformed into various products by three major processes: separation, conversion, and purification. The process of distillation in columns by boiling point differences is used to separate the various primary components of the crude by vaporizing it through the action of heat supplied by a furnace. Such fractions as gases, naphtha, jet oil, gas oil, heavy gas oil, and atmospheric residue, are tapped at various sections along the column. The distillation column temperature ranges from about 370°C at the bottom to about 30°C at the top. The conversion process is utilized to transform low-grade fuel oil into high-grade gasoline, and other lighter products. A catalytic cracking unit is employed to convert heavier hydrocarbons into petrol, liquefied petroleum gas, and diesel under the action of heat reforming is another conversion process used to increase petrol blends octane number, and to produce hydrogen that would further be used in the refinery.

Finally, to meet specifications of product quality and environmental standards after separation and conversion, the resulting products are purified mainly to remove Sulphur.

C. Petrochemical Processes

Many processes occur in the petrochemical industry, but from the perspective of energy consumption, the most important technologies are steam cracking of heavier feedstock, polymerisation, and processing of aromatics [26]. In steam cracking feedstock such as naphtha and gas oil are converted at elevated temperatures into a wide array of products such as olefins (ethylene, propylene, and butylene), aromatics (benzene, toluene, and xylene), pyrolysis gasoline, and methane. Polymerisation is the process whereby small compounds called monomers are linked together to yield chains of larger products called polymers. Polymerisation technology is generally based on catalytic conversion at temperatures above 100°C and at elevated pressures. The four most important polymers (plastics) produced by this means are polyethylene, polypropylene, polystyrene, and polyvinyl chloride.

D. Steam Utilization

Many processes in the petrochemical industry occur at relatively moderate temperatures (below 600°C), and steam is generally the source of their heat energy supply. Steam could be generated by conventional boilers or heat recovery steam generators in CHP technology. It is worth stating that combined heat and power (CHP) generation of steam and electricity is presently a key energy saving, as well as environmentally-friendly technology in the petrochemical industry [26].

E. CHP Modeling

CHP systems are either developed as "Topping cycles" or "bottoming cycles" Topping cycles describe systems where there occur primary power generation and subsequent heat utilization, whereas bottoming cycles pertain to systems where heat is primarily utilized with subsequent power generation [27]. In this research, a topping cycle arrangement is adopted where power is primarily generated from a gas turbine, and a heat recovery steam generator (HRSG) is designed to match process steam production. Performance parameters of the aero-derivative gas turbines discussed in the previous research are employed to determine the parameters of the HRSG.

F. HRSG Performance Modeling

A set of heat exchangers that utilises the exhaust heat of a gas turbine to produce steam is referred to as a heat recovery steam generator (HRSG). Three types of HRSGs are identified: unfired, supplementary fired, and exhaust fired. The most common and widely used HRSG is the unfired one because it is simple in design and cheap [28]. HRSG of the unfired type is considered here without recourse to the material dimension of the heat exchangers. It is pertinent to declare that only the thermodynamic performance in terms of the temperature profile of exhaust gas, steam temperature/flows, and heat capacity, of the HRSG are being modeled in this piece of work. Pinch/approach points technology was adopted in modeling the HRSG performance, and with a single steam pressure mode of operation. Whereas the approach point is the difference between the temperature of saturated steam and the temperature of water entering the evaporator, the pinch point is the difference between the gas temperature leaving the evaporator and the temperature of saturated steam [28]. Steam generation is directly affected by the pinch and approach points. Also affected is the exhaust gas/steam temperature profile. For the design case of an unfired HRSG, selection is usually made of the values of pinch and approach points; pinch point ranges from 10°C to 30°C whereas approach point ranges from 5°C to 15°C based on the sizes of evaporators that can be built and shipped economically, and to maximize heat transfer rate between exhaust gas and steam streams. Using the notations in Figure 1 above path 4-y-x-1 indicates the gas turbine exhaust gas temperature profile whereas path a-b-c-d-e indicates the steam temperature profile. Pinch point = T_x- T_c; approach point = Tc-Tb: process a-b occurs in the economiser; c-d in the evaporator; and d-e in the super-heater.

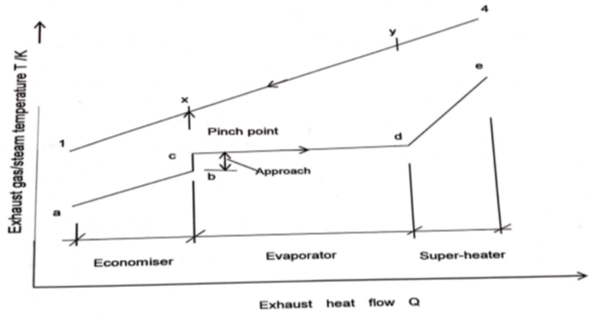

Fig. 1: HRSG Exhaust Gas/Steam Temperature Profiles

III. RESEARCH METHODS

A. CHP Design Point Performance Modeling

To model the design point performance of a CHP plant is necessary to match the parameters of HRSG with the design point of the gas turbine giving particular consideration to desired steam flow or temperature and saturation pressure. In doing so, pinch and approach points are selected by the engineering judgment, and from gas turbine exhaust gas flow, the HRSG temperature profile, duty, and steam flow are established. Using pinch technology and thermodynamic properties of steam, the computation of CHP HRSG gas/steam temperature profile and steam flow is as follows: Gas turbine exhaust gas temperature and mass flow are imported from gas turbine performance simulation while the HRSG pinch and steam saturation pressure (which fixes the steam saturation temperature T_c) are selected. In this design, the steam saturation pressure is 10 bar. With the notations of Figure 1, the temperature of exhaust gas at pinch point (T_x) is given by Equation 1.

$$T_x = T_c + \mathrm{Pinch} = T_c + 15 \ldots\ldots..(1)$$

Where pinch 15

The superheated steam temperature (T_e) is chosen as required by the industrial process heat demand. The steam flow (w_s) is computed from total heat transfer in the super-heater and evaporator using heat balance above pinch as defined by Equation 2

$Q_{4x} = Q_{evap} + Q_{super}; Q_{4x} = w_g c_{pa}(0.99)(T_4 - T_x) = w_s[(h_e - h_c) + 0.02(h_d - h_c]; \therefore w_s = \frac{w_g c_{pa}(0.99)(T_4 - T_x)}{(h_e - h_c) + 0.02(h_d - h_c)}$ ....(2)

Where 0.99 = heat loss factor
0.02 = blow down factor
w_g = exhaust gas flow
c_{pa} = specific heat at constant pressure of air
h_e = specific enthalpy of super-heated steam
h_c = specific enthalpy of saturated water
h_d = specific enthalpy of saturated steam
T_4 = gas turbine exhaust temperature
Q_{evap} = evaporator duty
Q_{super} = super-heater duty

Equation 3 defines the super-heater duty (Q_{Super})

$$Q_{super} = w_s(h_e - h_d) \qquad \ldots\ldots\ldots\ldots(3)$$

Gas temperature drop in the super-heater (▲T4y) is given by Equation 4

$$\Delta T_{4y} = Q_{super} w_g c_{pa}(0.99) \qquad \ldots\ldots\ldots\ldots(4)$$

This implies that exhaust gas temperature to the evaporator (T_y) is calculated using Equn 5

$$T_y = T_4 - \Delta T_{4y} \qquad \ldots\ldots\ldots\ldots(5)$$

Evaporator duty (Q_{evap}) is determined with the aid of Equation 6

$$\text{Evaporator duty } Q_{evap} = w_s(h_d - h_c) \ldots\ldots\ldots\ldots(6)$$

Similarly, Equation 7 defines Economiser duty (Q_{econ})

$$\text{Economiser duty } Q_{econ} = w_s(1.02)(h_c - h_a) \ldots\ldots\ldots\ldots(7)$$

Gas temperature drop in the economiser (▲T_{x1}) is given by Equation 8

$$\Delta T_{x1} = \frac{Q_{econ}}{w_g c_{pa}(0.99)} \qquad \ldots\ldots\ldots\ldots\ldots(8)$$

This implies that exhaust gas exit temperature from the economiser (T_1) is calculated using Equation 9

$$T_1 = T_x - \Delta T_{x1} \qquad \ldots\ldots\ldots\ldots\ldots(9)$$

$$\text{Electrical efficiency} = \frac{P_E}{P_T} = n_e \quad \ldots\ldots\ldots\ldots\ldots(10)$$

The electrical efficiency could be assumed, such that Useful electric power generated PE = n_E X Pτ
Where P_t = gas turbine power
Equation 11 is used to compute CHP efficiency (n_{CHP})

$$\text{CHP efficiency } n_{CHP} = \frac{P_E + Q_{HRSG}}{Q_{comb}} + \frac{P_E + Q_{HRSG}}{\text{FF x LHV}} \quad \ldots\ldots\ldots(11)$$

Where FF = fuel flow in combustor
LHV = Low heating value of fuel
Qcomb = heat input in the combustor
Power to heat ratio of the CHP is given by Equation 12

$$\text{Power to heat ratio} = \frac{P_E}{Q_{HRSG}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(12)$$

[29] (Ganapathy, 1990)

The CHP design point computation was done for the various categories of aero-derivative engines and the HRSG gas/steam temperature profiles as shown in Figure 2 to Figure 4.

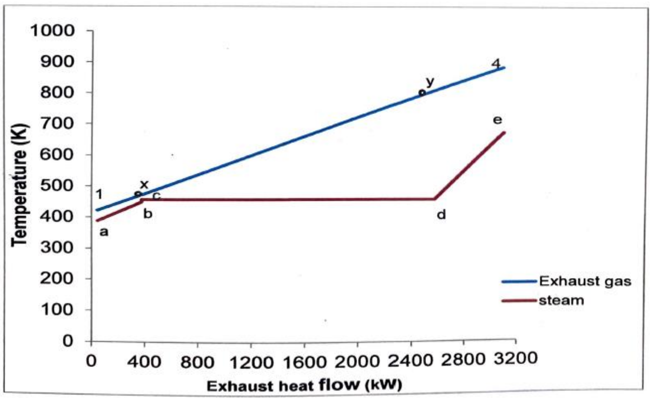

Fig. 2: HRSG Temperature/Heat Profile for the Small-Scale Aero-Derivatives

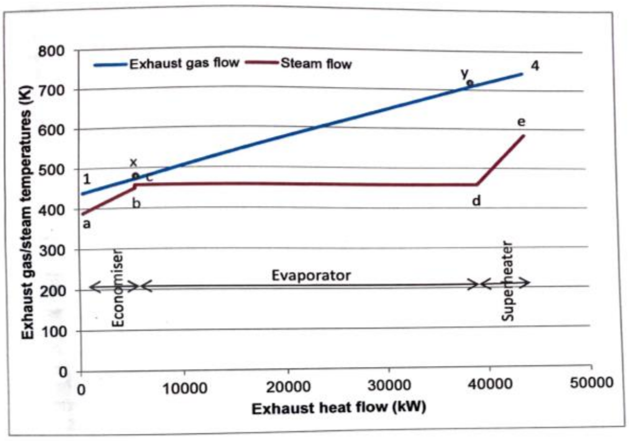

Fig. 3: HRSG Temperature/Heat Profile for the Medium-Scale Aero Derivatives

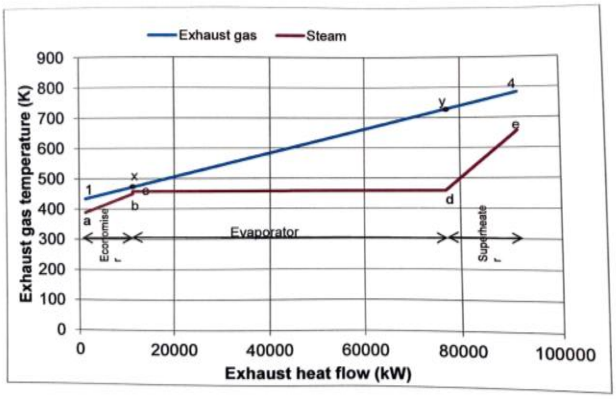

Fig. 4: HRSG Temperature/Steam Profile for the Large-Scale Aero-Derivatives

B. CHP Off-Design Performance

The HRSG would normally not operate at the design point due to variations in the inlet gas conditions and steam parameters. The inlet gas conditions in turn would depend on gas turbine off-design variation in ambient conditions, firing temperature, altitude, etc. This makes the CHP plant exhibit varying outputs. The CHP off-design was modelled with input from the TURBOMATCH engine off-design. The off-design performance results to the CHP of the small, medium, and large-scale aero-derivative engines are shown in Figure 5 to Figure 10 below.

IV. RESULTS DISCUSSION

A. Small-Scale Aero-Derivative CHP

At design and off-design points, the RC and ICR aero-derivative engines exhibit better CHP efficiency than the SC engine in the small-scale category. The CHP efficiencies are observed to increase with increases in both TET and ambient temperature. The percentage increases in RC and ICR CHP efficiencies over SC are 16.5% and 3.8% respectively. This superior performance is due to the lower heat input from burning less fuel in the advanced cycle engines. Nevertheless, the SC engine produces more HRSG duty than the ICR one due to lower exhaust gas temperature and steam rate of the ICR aero-derivative, whereas the highest HRSG duty is produced by the RC engine because of its higher exhaust gas temperature and steam rate.

B. Medium and Large-Scale Aero-Derivative CHP

Both medium and large-scale aero-derivative engines are observed to perform in a similar trend in CHP application. CHP efficiency increases with increasing TET and ambient temperature in all cycle configurations in these categories of aero derivatives. The SC CHP is observed to show higher CHP efficiency than the IC and ICR CHP. The superior performance of SC CHP is a result of its higher HRSG duty due to its higher exhaust gas temperature compared to others. Although less fuel is utilised in the advanced cycles than in the SC, the decrease in combustor heat rate in the advanced cycles is minute compared with the huge increase in exhaust gas temperature and steam rate of the SC CHP as illustrated in figures 5 to 10.

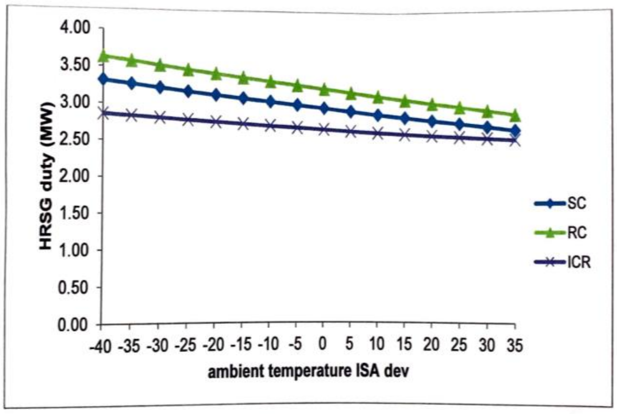

Fig. 5: Effect of Ambient Temperature on HRSG Duty for the Small-Scale Aero-Derivative Engines

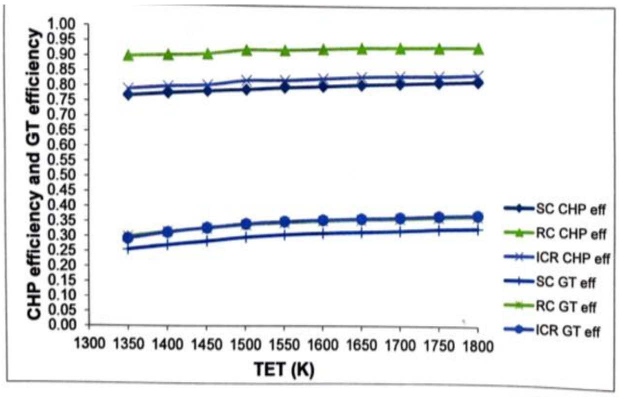

Fig. 6: Variation of CHP and GT Efficiency with TET for the Small-Scale Aero-Derivative Engines

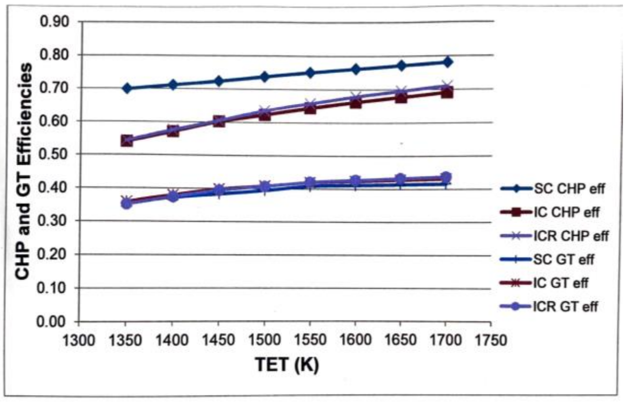

Fig. 7: Effect of TET on CHP and GT Efficiencies for the Medium-Scale Aero Derivative Engines

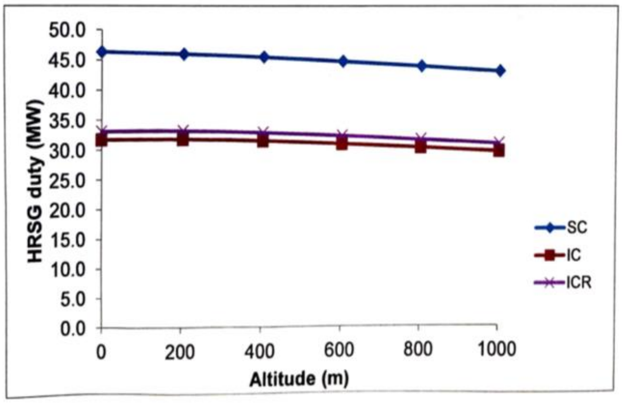

Fig. 8: Variation of HRSG Duty with Altitude for the Medium-Scale Aero-Derivative Engines

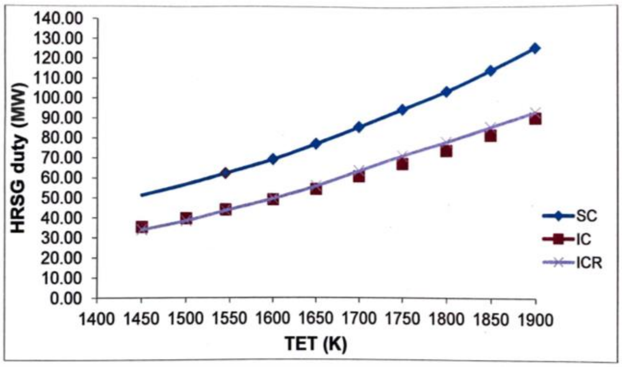

Fig. 9: Variation of HRSG Duty with TET for the Large-Scale Aero-Derivative Engine

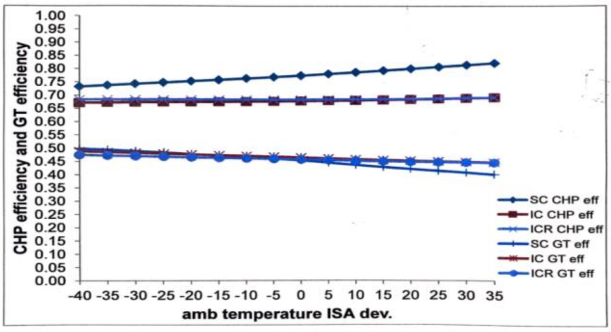

Fig. 10: Effect of Ambient Temperature on HRSG Steam Flow for the Large-Scale Aero-Derivative Engine

V. CONCLUSION

The literature review has aided the understanding of helicopter engines, aero-derivative industrial gas turbines, combined heat-and-power performance analyses, and the need for emphasis on the environmental-friendliness of gas turbine engines generally. More so, the research shows the implementation of the engine performance models of simple and advanced cycle helicopters and aero-derivative gas turbines was established. In doing so, the helicopter engine was converted to a small-scale aero-derivative engine. In continuation, the engine performance module was completed, and aero-derivative engines CHP performance modeling has been achieved. In this wise, small, medium, and large-scale aero-derivative industrial gas turbines were assessed in CHP performance. The contribution to knowledge has been conceptualised as the derivation of simple and advanced cycle small-scale aero-derivative industrial gas turbines from helicopter engines. These stemmed from the objectives of the research. The scenario assessment was undertaken to illustrate the performance of the model and its suitability to satisfy the aim and requirements of this research. The results have shown consistency with trends available in the literature.

DECLARATION STATEMENT

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

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- **Funding Support:** This article has not been sponsored or funded by any organization or agency. The independence of this research is a crucial factor in affirming its impartiality, as it has been conducted without any external sway.
- **Ethical Approval and Consent to Participate:** The data provided in this article is exempt from the requirement for ethical approval or participant consent.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Authors Contributions:** The authorship of this article is contributed equally to all participating individuals.

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Jeffrey Chidiebere Ogochukwu, is a graduate of Mechanical Engineering, with good experience in Power Plant Performance, Thermodynamics, Internal Combustion Engines, data analysis, R programming, MATLAB, Mathematics, and Automobiles—but above all, he possesses an affinity for computer-aided drafting. His interests are centered on structural design, 3D motion rendering, tubes & piping, and the drafting and modeling of 3D mechanical parts using CAD software like Autodesk Inventor, SolidWorks, and CATIA. He's always looking for new challenges and opportunities to grow and develop his skills. Besides his practical experiences, he is committed to advancing his career while helping others unlock their potential in the world of design, engineering, and data analysis.
