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Investigating the Performance of the Pratt & Whitney FT4A Marine Gas Turbine Engine on a Frigate While Voyaging from Onne Port to Apapa Port using Gasturb

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ABSTRACT
This study investigated the performance of Pratt & Whitney (P&W) FT4A marine gas turbine engine installed on a Frigate named Nigerian Navy ship Okpabana while voyaging from Onne port to Apapa port. The voyage route from Onne port to Apapa port consist of 6 voyage stations, namely; Onne Port, Bonny offshore terminal, Brass offshore terminal, Escravos offshore terminal, Lekki deep sea port and Apapa port. The meteorological data of the stations were obtained from National Aeronautics and Space Administration (NASA). The performance analysis was carried out using a Gasturb 11 gas turbine simulation software. The ship sailing at an average speed of 10 knots covers a total distance of 416 nautical miles (nm) between Onne port and Apapa port in about 38 hours and 53 minutes. The gas turbine engine parameters, such as rated power output, specific fuel consumption, thermal efficiency, turbine exhaust temperature, and fuel flow, were determined. The power output of the Pratt & Whitney FT4A gas turbine engine at various voyage stations was between 25.46 and 25.54 MW with the maximum and minimum values obtained at Escravos and Bonny offshore terminals respectively. The specific fuel consumption of the Pratt & Whitney FT4A gas turbine engine at various voyage stations was between 0.2326 and 0.2333 kg/kWh which was relatively high and low at 3 stations each. The thermal efficiency of the Pratt & Whitney FT4A at various voyage stations was between 33.849% and 34.789% with optimum performance at Onne port and Apapa port. The study shows the P &W FT4A engine performance output at the various voyage stations.

Keywords
Frigate, Pratt & Whitney FT4A, Gas Turbine Performance

1. INTRODUCTION

A gas turbine is a device that converts energy from a gas, often air, into rotational motion. [1]. In recent years, gas turbines are progressively being employed in a broad variety of applications such as electric power generation, airplanes, marine vessels, etc. for their ease of start, modular nature, and extensive operating flexibility [2]. Because the gas turbine engine is an air-breathing machine, ambient temperature, humidity, and altitude, which vary by geographical location and season, can have a significant impact on the density of the compressor input air that is inducted into it [3]. Apapa port is located at latitude 60 26' 43" N longitude 30 25' 34" E and has tropical weather, with temperatures ranging from 23.9^{0}C to 32.2^{0}C throughout the year, whereas Onne port is located at latitude 40 44' 39.6024" N longitude 70 2' 7.1376" E and has an average temperature of 21.7^{0}C to 30.6^{0}C.

The Pratt & Whitney (P&W) FT4A Marine Gas Turbine Engine was developed by Pratt and Whitney aircraft is a common option for naval propulsion systems and other industrial applications [4]. The P&W FT4A gas turbine engine consists of a gas generator and a power turbine. This gas turbine consists of the basic machinery of the military and commercial versions of the JT4 jet engine. The power turbine replaces the jet nozzle of the aircraft engine and converts the energy of the hot gases to shaft power rather than to jet thrust. The power turbine is not mechanically connected to the gas generator shaft, but hot gas from the gas generator exits into the power turbine (free turbine) with a separate shaft connected to the loader (propeller) via reduction gear box simple but the aerodynamically coupled to the free power turbine. Accordingly, a frigate is a military warship classified by a nation, and it is typically employed to escort vessels in order to safeguard maritime lines of communication or as an auxiliary element of a strike group.

The importance of this study cannot be overemphasized, as it enables the evaluation of the P&W MGT engine performance on a Frigate while voyaging from Onne port to Apapa port. The ambient weather parameters were used with GasTurb simulation software [5] to obtain the engine output performance result at various stations along the voyage route.

The research objective is to evaluate the performance of the P&W FT4A marine gas turbine engine installed onboard a Frigate warship.

Fig 1: A Picture of a Frigate Warship while Voyaging [6]

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Table 1: Characteristics of the Frigate [6]

Parameters	**Design Values**
Displacement (tons)	3,250
Length (m)	115
Beam (m)	13
Draught (m)	4.6
Design Speed (knots)	29
Range (km)	22,530
Endurance (days)	45

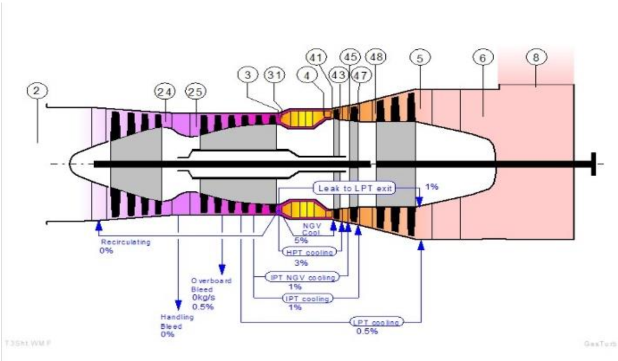

Fig 2: A Gasturb Model of the Pratt & Whitney FT4A engine

2. THERMODYNAMIC CYCLE OF AN IDEAL GAS TURBINE

The Pratt & Whitney FT4A work based upon a modified Brayton cycle. It uses a continuous flow process where different components take air through various processes. The P-V and T-S diagrams are shown at Fig 3 and 4 respectively.

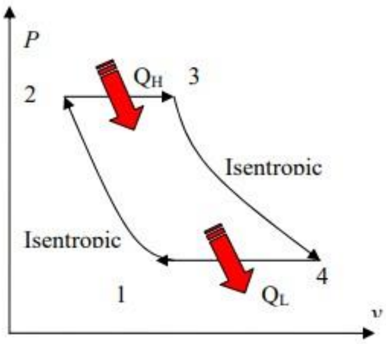

Fig 3: Brayton cycle pressure – volume diagram for a unit mass of working fluid. [7]

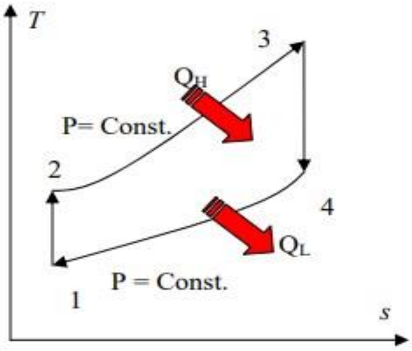

Fig 4: Brayton cycle temperature – entropy diagram for a unit mass of working fluid. [7]

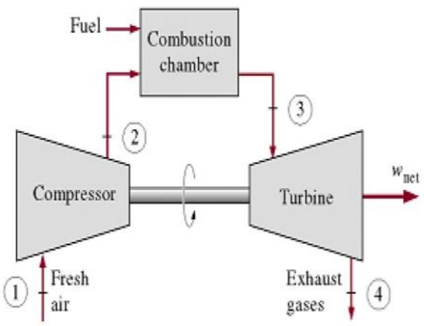

Fig 5: Gas turbine schematic showing relative points from the diagram for the Brayton cycle. [7]

The Ideal Brayton cycle can be analyzed under four internally reversible processes as follows:

Process 1 – 2: In this process, isentropic compression occurs. The air is compressed isentropically from low pressure (P1) to high pressure (P2), and the temperature rises from T1 to T2. In this process, no heat flow occurs. The turbine section drives the compressor section, which uses the turbine's energy to accelerate and compress the air.

Process 2 – 3: In this process, constant (c) pressure heat addition occurs. Heat enters the system, raising the volume from V1 to V3 and the temperature from T2 to T3, while keeping the pressure constant at P2. The heat received is expressed as mcp (T3 – T2). At that stage in the combustor, fuel is injected and burnt to convert chemical energy to kinetic energy.

Process 3 – 4: In this process, isentropic expansion occurs. The air expands isentropically from P2 to P1, and the temperature decreases from T3 to T4. This method produces no heat flow. The expanding gases flow along a shorter exhaust path, resulting in a nozzle effect that increases the exhaust gases. The turbine section uses this energy to power the compressor section, which raises the specific volume while decreasing the overall pressure.

International Journal of Engineering Research & Technology (IJERT)
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Vol. 14 Issue 10, October - 2025

Process 4 – 1: In this process, constant pressure heat rejection occurs. Heat is rejected from the system when the volume and temperature decrease from V4 to V1, but the pressure remains constant at P1. The heat rejected is expressed as mcp (T4 – T1). At the end of the expansion phase, the residual gas in a closed cycle is routed via a cooler and returned to the compressor as air intake, and the cycle continues.
The thermodynamic equations for the gas turbine model is derived using the thermodynamic cycle in Figures 2 – 4 are as follows [8]:

Compressor Power (W_{12}),

$$W_{1,2} = m_a\, CP_a\,(T_2 - T_1) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$= m_a\, CP_a T_1 \left(\frac{T_2}{T_1} - T_1\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1.1)$$

Where m_a is mass of the air (Kg/s), CP_a specific heat capacity of air (KJ/KgK), T2 Compressor discharge temperature OC, T1 Compressor inlet temperature OC

In terms of pressure ratio, equation 1.1 becomes

$$\frac{T_2}{T_1} = PR^{\frac{r_a-1}{r_a}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.12)$$

Where PR is Pressure Ratio and γ is the ratio of specific heats of the gas (Cp/Cv) also known as the isentropic index.

$$W_{1,2} = m_a\, CP_a T_1 \left(PR^{\frac{r_a-1}{r_a}} - 1\right) \quad \ldots\ldots\ldots (1.13)$$

Heat energy added to combustion chamber ($Q_{2,3}$),

$$Q_{2,3} = m_g\, CP_g\,(T_3 - T_2) \quad \ldots\ldots\ldots\ \ldots\ldots (2)$$

Where CP_g is the specific heat capacity of the gas (KJ/KgK), T3 Turbine inlet temperature OC,

T4 Turbine exhaust temperature OC

Noting that,

$$T_3 = T_4\, PR^{\frac{r_g-1}{r_g}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

and

$$T_2 = T_1\, PR^{\frac{r_a-1}{r_a}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Equation 2 becomes

$$Q_{2,3} = m_g\, CP_g \left(T_3 - T_1\, PR^{\frac{r_a-1}{r_a}}\right) \quad \ldots\ldots\ldots\ldots (5)$$

Where m_g is mass of the gas (Kg/s)

Thermal efficiency of the cycle ($\eta_{thermal}$) is expressed as,

$$\eta_{thermal} = \frac{W_{net}}{Q_{23}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

$$\eta_{thermal} = \frac{C_P(T_3 - T_4) - C_P(T_2 - T_1)}{C_P(T_3 - T_2)} \quad \ldots\ldots\ldots (6.1)$$

$$\eta_{thermal} = \frac{(T_3 - T_2) - (T_4 - T_1)}{(T_3 - T_2)} \quad \ldots\ldots\ \ldots\ldots (6.2)$$

$$\eta_{thermal} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (6.3)$$

Substituting (3) and (4) into (6.3);

$$\eta_{thermal} = 1 - \frac{T_1}{T_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (6.4)$$

The specific fuel consumption (SFC) is expressed as;

$$SFC = \frac{3600}{AFR\ x\ W_{net}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Where AFR is Air fuel ratio and Wnet is the net work done

3. MATERIALS AND METHODS

The materials deployed for the study are; Technical specification of the P&W FT4A marine gas turbine engine, Gasturb simulation software, meteological data of the investigated routes obtained from National Aeronautic and Space Administration (NASA), and sea online travel calculator. The Gasturb software was used imputing parameters such as ambient temperature, ambient pressure and relative humidity extracted from the meteorological data obtained from NASA.
The Frigate was assumed to travel at a constant speed of 10 knots and the journey lasted for 1.62 days which is a total of 38 hours 52 minutes and 48 seconds, over a total distance of 416 nautical miles (nm). The locations of the various stations along the voyage routes; Onne Port, Bonny offshore terminal, Escravos offshore terminal, Brass offshore terminal, Lekki deep sea terminal and Apapa Port, are shown on Figure 5.
Gasturb software was further used to assess the performance of marine gas turbine engines by giving a detailed examination of collected data and providing performance prediction.

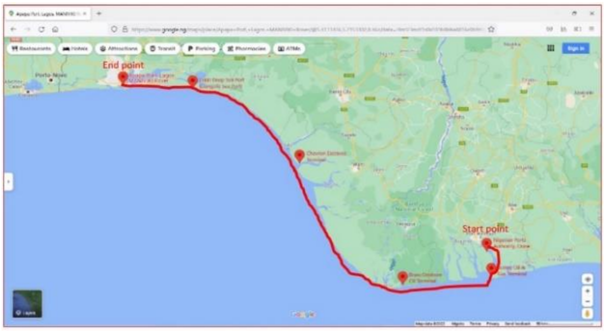

Fig 6: The Travel route of the investigated Frigate [9]

Table 2: Annual Average Metrological data at various stations between Onne Port and Apapa Port for 2020 [10]

	Stations					
	Onne Port	Bonny Terminal	Brass Terminal	Escravos Terminal	Lekki Deep Sea	Apapa Port
Ambient Temperature (ºC)	27.31	27.78	27.4	27.65	27.48	27.32
Ambient Pressure (kPa)	100.8	101.03	101.14	101.05	100.97	100.95
Relative Humidity (%)	86.31	86.33	86.65	86.51	86.11	86.04

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4. RESULTS AND DISCUSSION

The Gssturb software was used to model the P & W FT4A marine gas turbine with a gas generator with a twin spool and axial flow gas turbine engine and the performance of the gas turbine engine was analyzed. The annual average output parameters such as Power output, Thermal Efficiency, Specific Fuel Consumption (S.F.C), Exhaust Temperature and Fuel flow obtained at various voyage stations are shown in Table 3:

Table 3: Average values of output parameters of the Pratt & Whitney FT4A GT Engine

Ser	Voyage Stations	Annual Average Output Parameters				
		Power Output (MW)	S.F.C (kg/kWh)	Thermal Efficiency (%)	Exhaust Temp (°C)	Fuel Flow (kg/s)
1.	Onne Port	21.619	0.2424	34.789	482.23	1.4553
2.	Bonny Terminal	21.574	0.2428	34.717	482.46	1.4548
3.	Brass Terminal	21.635	0.2425	34.746	482.34	1.4574
4.	Escravos Terminal	21.693	0.2427	34.746	482.41	1.4561
5.	Lekki Deep Sea	21.608	0.2426	33.849	482.34	1.4558
6.	Apapa Port	21.617	0.2425	34.772	482.29	1.4563

4.1. Power Output

The Power output at various voyage stations is presented in Fig 7 According to the data, the P&W GT engine generates roughly 21.6 MW of power at the start and finish of the test. The offshore terminals located in Escravos and Bonny generate the maximum power of 21.69 MW and the minimum output of 21.57 MW, respectively.

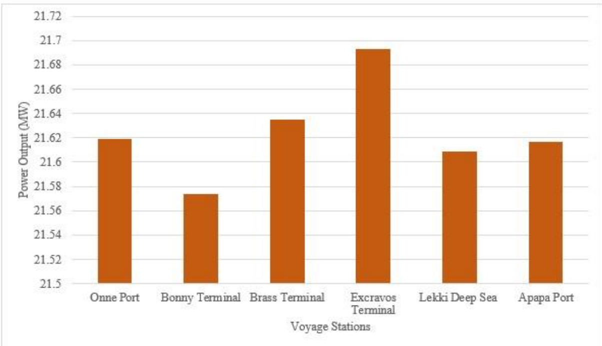

Fig 7: Rated Power Vs Voyage Stations

4.2. Specific Fuel Consumption

An alternative approach to determining the heat input per unit of effort is the specific fuel consumption (SFC). According to the conditions investigated, the results of the SFC for the P & W GT along the voyage route is presented in Fig 8. The SFCs of Lekki Deep Sea Port, Bonny Offshore Terminal, and Escravos Offshore Terminal were all relatively high. In comparison, the SFC of Onne Port, Brass Offshore Terminal, and Apapa Port was low.

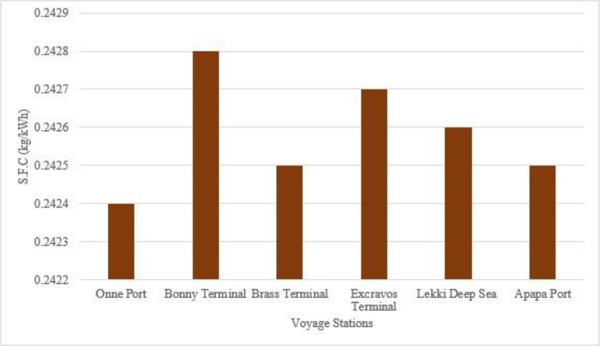

Fig 8: S.F.C Vs Voyage Station

4.3. Thermal Efficiency

Fig. 9 presents the results of the thermal efficiency showing the variation along the Voyage route. It indicates that 33.849% to 34.789% is the range of thermal efficiency. The results revealed that in Onne Port, Bonny offshore terminal, Brass offshore terminal, Escravos, and Apapa port, the P&W GT performed the best in terms of thermal efficiency. The study also indicated that it is the least efficient at Lekki Deep Sea Port.

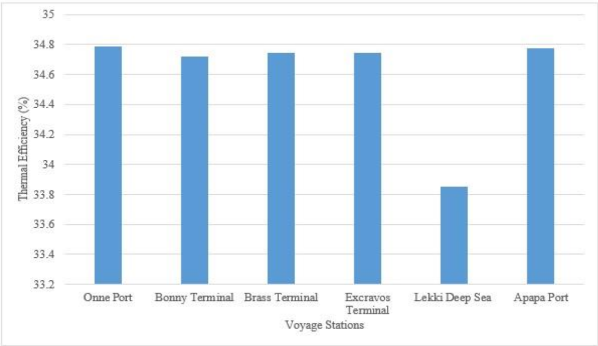

Fig 9: Thermal Efficiency Vs Voyage Stations

4.4. Exhaust Gas Temperature

Fig. 10 shows the result of the turbine exhaust temperature. The rate of exhaust gas temperature determines the thermal efficiency of a gas turbine. Based on the conditions under investigation, the average exhaust temperature for the P & W is 482.35 °C and the lowest was found to be at Onne Port. The exhaust temperature raised to the highest value at Bonny offshore terminal with slight variations at various stations along the voyage route.

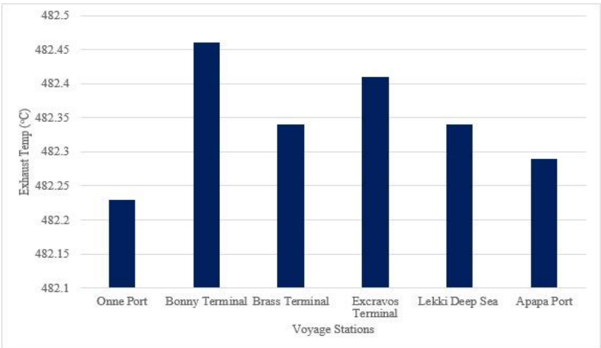

Fig 10: Exhaust Temperature Vs Voyage Stations

International Journal of Engineering Research & Technology (IJERT)
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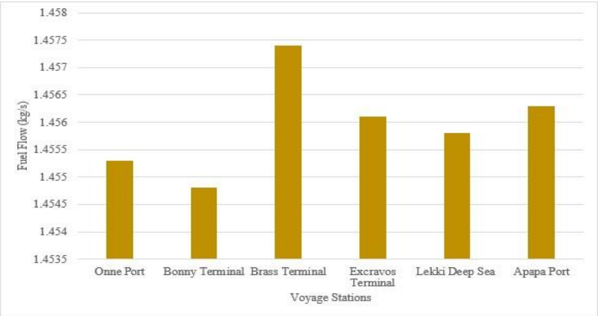
Vol. 14 Issue 10, October - 2025

4.5. Fuel Flow

Fuel flow has a considerable influence on a gas turbine engine's performance and efficiency. Fig. 11 displays the fuel flow on a P&W GT along the voyage stations. Fuel flow was found to be relatively constant in Escravos, Lekki Deep Sea, and Apapa Port. The Brass offshore terminal had the highest fuel flow, while the Bonny offshore terminal had the lowest.



5. CONCLUSION

The study demonstrates how the Gasturb software was used to simulate the operations of a Frigate Warship's P&W FT4A gas turbine engine as it sailed through several stations from Onne Port to Apapa Port. The GT performance parameters at various stations, such as power output, SFC, thermal efficiency, exhaust gas temperature, and fuel flow, were determined using the theories of the thermodynamic model. The varying meteorological conditions at various stations impact the performance of the GT engine.

The engine's power output ranges between 25.46 and 25.54 MW, with the greatest at the Escravos offshore terminal. The gas turbine's ideal thermal efficiency was 34.78%, which was reasonably good for the majority of the stations, with the exception of Lekki deep sea port, which had the lowest at 33.85%. The investigation also reveals that the S.F.C., which determines the heat input per unit, ranges from 0.2424 to 0.2428 kg/kWh. The study examines the performance of the modeled P&W FT4A GT with the Gasturb program. Therefore, further studies could be explored with advanced gas turbine engines.

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