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# Analyzing the Impact of Pressure Ratio Variation on Gas Power Plant Performance at Takoradi Thermal Power Station

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***Authors' contributions***

*This work was carried out in collaboration among all authors. Author EAD designed the study, performed the statistical analysis and wrote the protocol. Author EKSM wrote the first draft of the manuscript. Author EKSM and author JNO managed the analyses of the study. Author JNO managed the literature searches. All authors read and approved the final manuscript. All authors read and approved the final manuscript.*

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## ABSTRACT

This study investigates the influence of pressure ratio variation on the performance of a gas turbine plant located at Aboadze, Ghana. The operational data including daily hourly measurements of pressure ratio, power output, ambient temperature, and gas fuel flow rate were collected during field visits conducted in February and March 2021. The thermal efficiency was computed using a validated equation, and data were analyzed using MAT LAB. The study reveals significant temporal fluctuations in the pressure ratio, power output, and thermal efficiency, highlighting the dynamic nature of the gas turbine plant's performance during daily operation. It was also observed that as

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the pressure ratio increases, the power output and thermal efficiency also increases and vice versa. The average highest and lowest pressure ratio recorded between February and March 2021 were 10.40 and 9.84 respectively, with corresponding average highest and lowest power output of 109 MW and 102 MW respectively. The result also showed an average daily variation in pressure ratio of 0.35 with corresponding power output difference of 5.25 MW. The finding showed that averagely, the lowest thermal efficiency and the highest thermal efficiency were 27.00 % and 28.00 % respectively.
This study is of crucial importance for optimizing power generation efficiency and ensuring sustainable energy production. By studying a specific gas turbine plant located in Aboadze, Ghana, this research contributes valuable insights into the operational characteristics of such plants in the region.

*Keywords: Gas turbine; pressure ratio; thermal efficiency; power output.*

## 1. INTRODUCTION

"A gas turbine, also known as a combustion turbine, is a rotary engine that removes energy from a flow of hot gas produced by the combustion of gas or fuel oil in a stream of compressed air. It has an upstream air compressor with radial or axial flow mechanically coupled to a downstream turbine and a combustion chamber in between. Energy is released when compressed air is mixed with fuel and ignited in the combustion chamber (combustor). Energy is removed from gas turbine in the form of shaft power, and this is used to power electric generators and other machineries"[1-3]. "Gas turbines are becoming increasingly used for power generation for wide variety of applications around the world. It is important to realize that in the gas turbine the processes of compression, combustion and expansion do not occur in a single component as they occurred in a reciprocating engine. It is well known that the performance can be qualified with respect to its thermal efficiency, power output, specific fuel consumption as well as work ratio. There are several parameters that affect its performance including the compressor compression ratio, combustion inlet temperature and turbine inlet temperature (TIT)" [4,5]. "Gas turbine performance is critically limited by temperature variation, especially in hot and rain region like Sub-Sahara Africa. The overall efficiency of the gas turbine cycle depends primarily upon the pressure ratio of the compressor" [3]. "The increases in inlet air temperature become more noticeable especially in the hot weather, and this causes a significant decrease in gas turbine power output. It occurs because the power output is inversely proportional to the ambient temperature and because of the high specific volume of air drawn by the compressor" [6]. "The efficiency and power output of gas turbines changes according to the ambient conditions" [7,8]. "The resulted amount of these disparities greatly affects electricity generation, fuel consumption and plant incomes" [9]. "The effect of temperature is very predominant; for every 56°C increase in turbine temperature, the work output increases approximately 10% and gives about 1.5% increase in efficiency. A plant's energy efficiency has definite economic significance since the heat input at high temperature represents the energy that must be purchased, and the net energy output represents the return for the purchased energy". [10] "The gas turbine output and efficiency are a strong function of the ambient air temperature. For every 1°C rise in ambient temperature above ISO-rated conditions, the gas turbine losses 1% in terms of thermally efficiency and 1.47MW of its gross power output" [11]. At the same time the specific heat consumption increases by a percentage between 1.5% and 4%. Lamfon [12] investigated "the performance of a 23.7 MW gas turbine plant operated at ambient temperature of 30 - 45°C. The net power output is improved by 11% when the gas turbine engine is supplied with cold air at the inlet". "At the ambient temperature of 30°C the net power output increases by 11% at ISO-rated condition, accompanied by a 2% rise in thermal efficiency and a drop in specific fuel consumption of 2%. Mohanty reported that increasing the inlet air temperature from the ISO-rated condition to a temperature of 30°C, would result in a 10% decrease in the net power output. For gas turbine of smaller capacities, this decreased in power output can be even greater. The study also indicated that a rise in the ambient temperature by 1°C resulted in 1% drop of the gas turbine rated capacity" [13]. "The report shows also that when the ambient temperature decreases from 34.2°C to ISO-rated condition, the average power output can be increased by as much as 11.3%. A study carried out on the effects of ambient temperature, ambient pressure as well as the temperature of exhaust gases on performance of gas turbine shows an obvious drop in the power output as the ambient air temperature increases if an increase of intake air ambient temperature from ISO condition 15 to 30°C which is 10% decrease in the net power output". [14] "This is particularly relevant in tropical climates where the temperature varies 25 - 35°C throughout the year" [15].

The expected power output of the GE Frame 9E combustion gas turbine is 110 MW, but in operational conditions the power output falls below the maximum possible power output of the turbine. This study, therefore, analyze the impact of the variation of pressure ratio on the performance of the GE Frame 9E combustion gas turbine at Takoradi thermal plant, Aboadze.

## 2. MODELING OF THERMODYNAMIC GAS TURBINE PLANT

Gas turbine plant is made up of four components including compressor, combustion chamber, turbine, and generator. A schematic diagram for a simple gas turbine is shown in Fig. 1. The air is sucked in by the compressor and delivered to the combustion chamber. Liquid or gaseous fuel is widely used to raise the temperature of compressed air through a combustion process. Hot gases coming out of the combustion chamber expands in the turbine, which produces work and eventually discharges into the atmosphere. "Efficient compression of large volume of air is vital for a successful gas turbine power plant. This has been achieved in two types of compressors, the axial flow compressor and the centrifugal or radial flow compressors. Most power plant compressor design is to obtain the most air through a given diameter compressor with a minimum number of stages while retaining relatively high efficiency and aerodynamic stability over the operating range, and these parameters in terms of temperature are explained in" [17].

### 2.1 Air Compressor Model

Using the first law of thermodynamics and knowing the air inlet temperature to compressor, the pressure ratio ($r_p$) and isentropic efficiency for compressor can be determined. The compression ratio for the compressor ($r_p$) can be defined as in Eq. (1):

$$r_p = \frac{P_2}{P_1} \quad (1)$$

Where $P_1 \ and\ P_2$ are compressor inlet and outlet air pressure respectively.

The isentropic efficiency of the compressor in the range of 80-90% is expressed as Eq. (2) using [16]:

$$\eta_c = \frac{T_{2s}-T_1}{T_2-T_1} \quad (2)$$

Where $T_1$ and $T_2$ are compressor inlet and outlet air temperature respectively, and $T_{2s}$ compressor isentropic outlet temperature. The final temperature of the compressor is calculated from Eq. (3)

$$T_2 = T_1\left(1 + \frac{r_p^{\frac{\gamma_a-1}{\gamma_a}} - 1}{\eta_c}\right) \quad (3)$$

The compressor work($W_c$) when blade cooling is not considered can be calculated as in Eq (2.4)

$$W_c = \frac{C_{pa}T_1\left(r_p^{\frac{\gamma_a-1}{\gamma_a}} - 1\right)}{\eta_m} \quad (4)$$

where $C_{pa}$: The specific heat of air which can be fitted for the range of 200K < T < 800K (R).

$\eta_m$ represent the mechanical efficiency of the compressor.

$$C_{pa} = 1.0189 \times 10^3 - 0.1378T_a + 1.9843 \times 10^{-4}{T_a}^2 + 4.2399 \times 10^{-7}{T_a}^3 - 3.7632 \times 10^{-2}{T_a}^4 \quad (5)$$

where, $T_a$ in Kelvin.

### 2.2 Combustion Chamber Model

From energy balance in the combustion chamber:

$$\dot{m}_a c_{pa} T_2 + \dot{m}_f \times LHV + \dot{m}_f c_{pf} T_f = (\dot{m}_a + \dot{m}_f) c_{pg} \times TIT \quad (6)$$

After manipulating from Eq. (6), the ratio of the mass flow rate ($f$) is expressed as Eq. (7)

$$f = \frac{\dot{m}_f}{\dot{m}_a} = \frac{c_{pg} \times TIT - c_{pa}T_2}{LHV - c_{pg} \times TIT} \quad (7)$$

where, $T_3 = TIT = turbine\ inlet\ temperature$

The specific heat of the flue gas ($C_{pg}$) is given by (Naradasu et al., 2007):

$$C_{pg} = 1.8083 - 2.3127 \times 10^{-3}T + 4.045 \times 10^{-6}T^2 - 1.7363 \times 10^{-9}T^3 \quad (8)$$

### 2.3 Gas Turbine Model

The network of the gas turbine

$$(W_{net}) = W_t - W_c \quad (9)$$

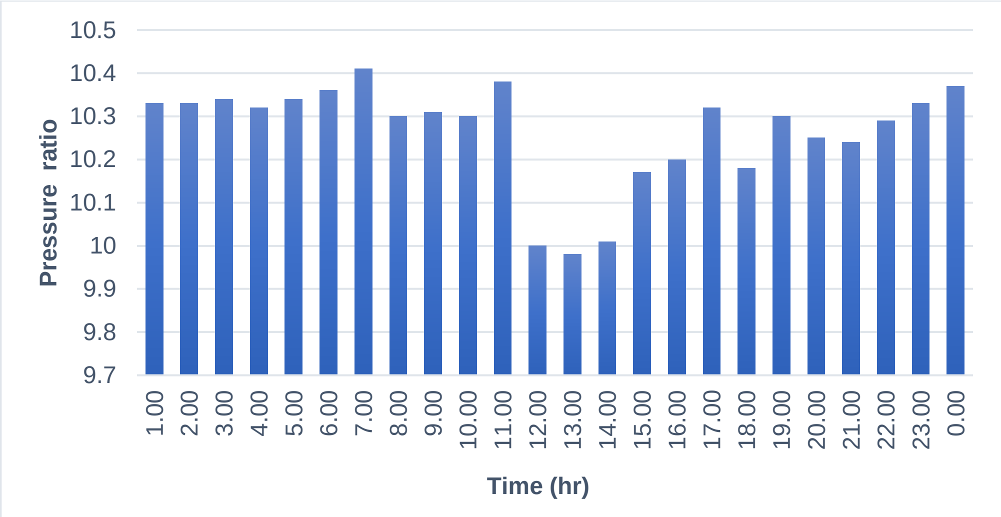


**Fig. 1. Hourly Variation of pressure ratio**

The total output power from the gas turbine plant (P) is given by:

$$P = \dot{m}_a \times W_{net} \tag{10}$$

The heat supplied can be calculated as

$$Q_{add} = c_{pg} \times (T_3 - T_1(1 + R_{pa})) \tag{11}$$

## 2.4 Gas Turbine Efficiency

Thermal efficiency is a long-established indicator of performance for power plants working on a cycle where the working fluid moves through a set of components required to undergo multiple processes and returns regularly to a certain “initial” state. It is predicated on the First Law of thermodynamics. During the process cycles, heat and work may be shared with the environment (Ramalingam and Rajendran, 2019). The thermal efficiency is expressed as the fraction of the net output of the work to the heat input:

The gas turbine efficiency is determined as:

$$\eta_{th} = \frac{W_{net}}{Q_{add}} \tag{12}$$

## 3. RESULTS AND DISCUSSION

The performance analysis of the thermal plant covers February and March 2021 using information on the daily hourly pressure ratios, power outputs and ambient temperatures. This paper examines the impact of variation of pressure ratio on the performance of the gas thermal plant.

### 3.1 Effect of Variation of Pressure Ratio

Fig. 1 establishes that the operational value of the pressure ratio is not constant and varies hourly. The average highest and lowest pressure ratio are 10.40 and 9.84, respectively, with a corresponding average highest and lowest power output of 109 MW and 102 MW, respectively. The study also shows an average daily variation in pressure ratio of 0.35 with corresponding power output difference of 5.25 MW, which is in agreement with [18].

### 3.2 Effect of Variation of Ambient Temperature with Pressure ratio

Fig. 2 shows a strong negative correlation between the pressure ratio and ambient temperature. This indicates that, the pressure ratio decreases as the ambient temperature increase. The study establishes that the ambient temperature varies hourly, and that the highest-pressure ratio of 10.41 corresponds with the lowest ambient temperature of 300 K; Also the lowest pressure ratio of 9.98 relates with the highest ambient temperature of 303 K at the study period. This result is in agreement with a study conducted by [17,19] that the pressure ratio is inversely proportional to the ambient temperature.

### 3.3 Effect of Variation of Pressure Ratio on Thermal Efficiency

Study results in Fig. 3 displays a strong positive correlation between thermal efficiency and the pressure ratio. From the scatter diagram, it is observed that the thermal efficiency increases as the pressure ratio increases. From the study, averagely, the lowest thermal efficiency and the highest thermal efficiency are 27.01 % and 28.87 %, respectively. This high pressure ratio gives an increase in thermal efficiency of the gas turbine which is consistent with study done by [20].

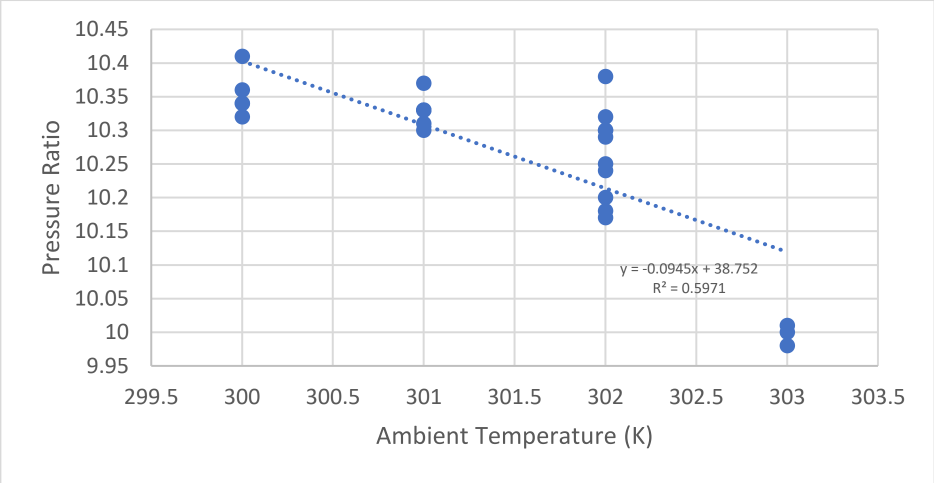


**Fig. 2. Variation of ambient temperature on pressure ratio**

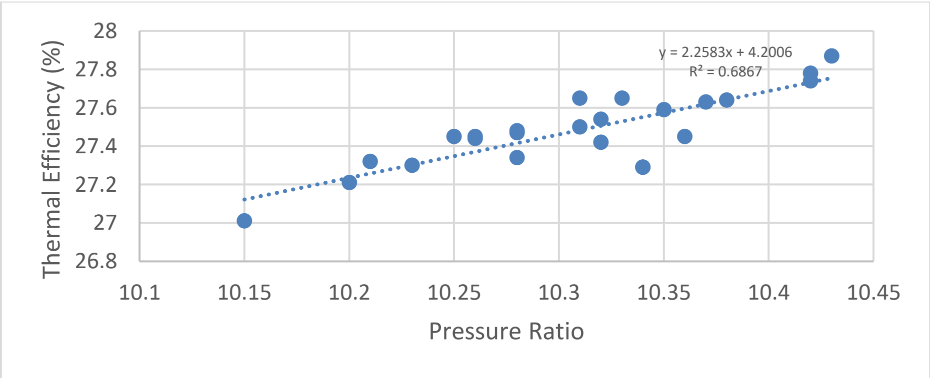


**Fig. 3. Variation of pressure ratio on thermal efficiency**

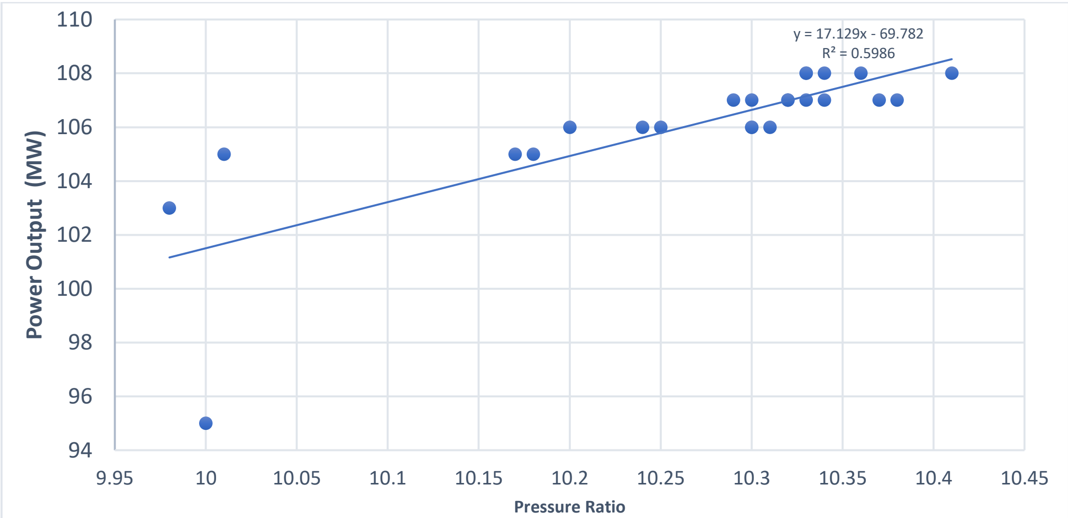


**Fig. 4. Variation of pressure ratio on power output**

### 3.4 Effect of variation of pressure ratio on power output

Study result in Fig. 4 shows that there is a strong positive correlation between the pressure ratio and the power output. This implies that power output increases as the pressure ratio also increases. The highest power output for the study period was 108 MW whiles the lowest power output was 95 MW. The difference between the highest power output and lowest power output is about 13 MW with a corresponding pressure ratio difference of 0.41. The findings are in line with a study conducted by [17]. Which reveals that pressure ratio is directly proportional to the power output.

## 4. CONCLUSION

The study shows that variation of pressure ratio affects the thermal efficiency of the gas turbine, as an increase in pressure ratio results in an increase of the thermal efficiency and vice versa. Study again, indicates that variation of the pressure ratio affects the power output of the gas turbine, since increase in the pressure ratio results in an increase in the power output and a decrease in the pressure ratio results in a decrease in the power output. Also, reports establish the peak thermal efficiency and power output on daily operation of the thermal plant occur at the hours with the higher-pressure ratio.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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