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Integration of High-Pressure Fogging Air Intake Cooling System in a Gas Turbine Powered Plant

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ABSTRACT: It is suggested that one way to increase a gas turbine power plant's power output is to reduce the air intake to the compressor by incorporating a high-pressure fogging system, which is one of the air intake cooling technologies. This study's methodology entails simulating a gas turbine power plant system without cooling, then incorporating cooling systems into the gas turbine system using the plant's actual operating data and comparing their performance. Aspen HYSYS simulation software was used. The findings of simulating a simple system gas turbine at 25.690 °C ambient air temperature revealed that the temperature of the surrounding air raises the specific fuel consumption and heat rate while decreasing net power output and thermal efficiency. Furthermore, data indicated that the addition of high-pressure fogging to the simple system gas turbine resulted in a decrease in the ambient air temperature (17.010 °C), which raised the thermal efficiency of the net power production and decreased the specific fuel consumption and heat rate.

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Nigeria experiences hot, rainy weather together with high relative humidity (Akinsanola and Ogunjobi, 2014; Ebunilo *et al.,* 2016; Madu, 2018a). Gas turbines are rated by the International Standard Organization ISO to operate at 150 degrees Celsius, 60% relative humidity, and 101.32 kPa at sea level (Orhorhoro *et al.*, 2018; Ukwamba *et al.*, 2018). The environment in which gas turbine power plants operate has a considerable impact on the plant's performance (Al-Tobi, 2009; Madu, 2018b; Madu, 2018c; Orhorhoro *et al.,* 2018). One cooling strategy suggested to lessen the impact of ambient temperature on gas turbine power plants is to cool the intake air to the compressor by implementing a high fogging system (Orhorhoro and Orhorhoro, 2016). Evaporative cooling is a viable method of cooling in hot and dry areas because it uses the latent heat of vaporization to raise the ambient air temperature from the dry temperature (Amell and Cadavid, 2012; Ana Paula *et al.*, 2012; Madu, 2018d). In evaporative cooling, heat and mass transfer take place when water and the unsaturated air mixture of the incoming air

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are in contact (Farzaneh-Gord and Deymi-Dashtebayaz, 2011). This transfer is a function of the difference in temperature and vapor pressures between the air and water. Evaporative cooling involves passing air across a spray of water or forcing air through a soaked pad that is kept replenished with water (Bhargava *et al.*, 2012; Madu, 2018e). Water injected evaporates due to the low humidity of entering air. The energy required for evaporation is provided by the air stream, which experiences a temperature reduction (Ibrahim *et al.*, 2011). This preserves the fog nozzle from dust and other airborne contaminants that would otherwise impinge upon it. In evaporative cooling, sensible heat from the air is transformed to water, which becomes latent heat as the water evaporates. The water vapour becomes part of the air and carries the latent heat with it (Hosseini *et al.*, 2007; Madu, 2018f; Igbagbon *et al.*, 2024a; Igbagbon *et al.*, 2024b). The air dry-bulb temperature decreases because it gives up sensible heat, but the air wet-bulb temperature is unaffected by absorption of latent heat in the water vapour because the water vapour enters the air at air wet-bulb temperature (Madu, 2018g; Alok Kumar and Sanjay, 2012).

Gas turbine efficiency and electric power generation are dependent on the surrounding environment (Orhorhoro and Orhorhoro, 2016). The extent of these variations has a significant impact on plant incomes, fuel consumption, and electricity generation (Orhorhoro and Orhorhoro, 2016). However, the predominant ambient temperature severely restricts the performance of gas turbines, particularly in hot and humid locations like Nigeria. The output of gas turbines is significantly reduced by the rise in inlet air temperature, which is particularly noticeable during hot weather. The reason for this is that the power output is inversely proportional to the ambient temperature and the high specific volumes of air drawn by the compressor draw it about (Shi *et al.*, 2010). Injecting water into the gas turbine's inlet duct is a well-established method of air inlet cooling nowadays (Kamal and Zuhairam, 2006). This process is called inlet fogging. A nozzle manifold, typically mounted near the air filters, injects a fine mist of water droplets, commonly referred to as "fog," into the air intake. The nozzle manifold injects less or equal amounts of water to what is necessary for saturating the intake air (at given ambient conditions). All or most of the fog evaporates before it reaches the compressor. This lowers the compressor's inlet temperature, which restores the lost power output, efficiency, and decreases the amount of specific fuel used as well as the net heat rate. This measure's efficiency is dependent on temperature and air humidity; it often works best in dry, hot areas but is still quite beneficial in humid, tropical regions like Nigeria.

MATERIALS AND METHODS

Owned by Niger Delta Power Holding Company (NDPHC), the gas turbine power station in southern Nigeria is a national integrated power project (NIPP). When it was first proposed, the government funded it quickly in an effort to stabilize Nigeria's electrical delivery system. Nonetheless, the plant is designed to allow for a future conversion to a combined-cycle gas turbine (CCGT) configuration and operates as an open-system gas turbine power plant using the Brayton cycle.

Furthermore, the plant is equipped with four GE Frame 9E gas turbine units, each of which has 17-stage axial compressors and can generate 112.5 MW. For a year (2023), daily turbine control log sheet data was used to gather operating data for gas turbines. After statistical analysis of the daily average operational variables, mean values for the months of January through December were calculated, and then the annual average.

Component-wise modeling is used to assess the plant's performance once the analysis is split into various control volumes. Each component is subjected to mass and energy conservation principles, and the plant's performance is assessed for both the basic gas turbine system and the gas turbine power plant with the addition of an air intake cooling system (high fogging).

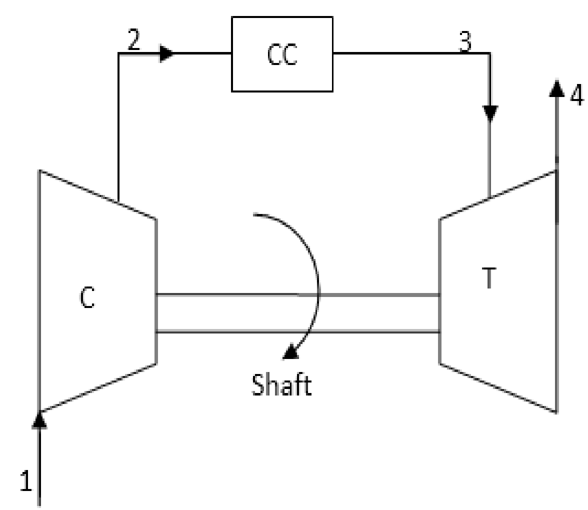

Fig. 1: Schematic diagram of the gas turbine unit

The Brayton cycle, which is represented in Fig. 1, is the most basic type of gas turbine cycle. It is a gas turbine plant that basically consists of a compressor, combustion chamber, and turbine. The compressed and heated air enters the compressor and proceeds to the combustion chamber. Constant pressure burns the fuel, raising the air's temperature to T_3, the firing temperature.

The high-temperature gases that are produced next go into the turbine, where they expand to produce useful work. Thirty to forty percent of the work produced by the gases going through the turbine is used to power the compressor, and the remaining amount is used to produce electricity. An open cycle power plant is one in which the fuel is mixed and burned in the air to provide heat, and the turbine's exhaust gases are released into the atmosphere.

Since the base case ignores the cooling impact and runs the cycle under ISO circumstances (T_1 = 150 °C, P_1 = 101.3 kPa, and 60%), the compressor inlet temperature is equal to the ambient air temperature. Since there isn't any pressure drop at the intake or exhaust ducts, 2% is assumed to represent the pressure drop throughout the combustion chamber. The inlet pressure is given by Equation (1) (Ibrahim *et al.*, 2011).

$$P_o = P_1 \quad (1)$$

The pressure (P_2) of the air leaving the compressor is given by Equation (2).

$$P_2 = P_{1\times}\ \gamma_p \quad (2)$$

The pressure ratio (γ_p) is calculated using Equation (3) (Ibrahim *et al.*, 2011).

$$\gamma_p = \frac{C\rho_d}{P_1} \quad (3)$$

Where CP_d is compressor pressure discharge assuming an ideal gas for states 2 and given isentropic efficiency of compressor to be 87.4 (Al-Tobi, 2009).

The temperature of the fluid leaving the compressor is calculated using ideal gas relations as shown in Equation (4).

$$T_2 = \frac{T_1}{\eta_c}\left[\left[\frac{P_2}{P_1}\right]^{\frac{Y-1}{y}}\right] + T_1 \quad (4)$$

Where η_c is the compressor efficiency; y is the specific heat ratio. The compressor power is calculated from the mass flow rate and enthalpy change across the compressor as depicted in Equation (5).

$$\dot{W}_C = \dot{m}_a CP_a (T_2 - T_1) \quad (5)$$

Where $\dot{m}_a$ is the mass flow rate of air, and C_{pa} is the specific heat capacity of air which is assumed to be 1.005kJ/kgK. The turbine inlet pressure P_3 is calculated as shown in Equation (6).

$$P_3 = P_2 - \Delta P_{cc} \quad (6)$$

Where ΔP_{cc} is the pressure drop in the combustion chamber. The exhaust temperature is given by Equation (7).

$$T_4 = T_3\left[1 - \eta_T\left[1 - \left(\frac{P_3}{P_4}\right)\frac{1 - y_g}{y_g}\right]\right] \quad (7)$$

Where η_T is the turbine entropic efficiency and P_4 equal to ambient pressure (P_1). The turbine power $\dot{w}_t$ is calculated as shown in Equation (8).

$$\dot{W}_t = \dot{m}_g CP_g (T_3 - T_4) \quad (8)$$

Where $\dot{m}_g$ is mass flow rata of the gas, and C_{pg} is the specific heat capacity of combustion product assumed to be 1.15kJ/kgK (Amell and Cadavid, 2002). The mass of flue gas $\dot{m}_g$ is calculated using Equation (9).

$$\dot{m}_g = \dot{m}_a + \dot{m}_f \quad (9)$$

The net power obtained from gas turbine is given by Equation (10).

$$\dot{w}_{net} = \dot{w}_t - \dot{w}_c \quad (10)$$

The thermal efficiency of the gas turbine is calculated using Equation (11).

$$\eta_{th} = \frac{\dot{w}_{net}}{\dot{m}_f \times LHV} \quad (11)$$

The specific fuel consumption (SFC) is determined using Equation (12).

$$SFC = \frac{3600 \times \dot{m}_f}{\dot{w}_{net}} \quad (12)$$

The heat rate of gas turbine cycle is calculated as shown in Equation (13).

$$HR = SFC \times LHV \quad (13)$$

Figure 2 and 3 show the flow chart of simulated simple gas turbine unit, and the schematic diagram of fogging unit incorporate to gas turbine. Aspen HYSYS was used to model the gas turbine and gas turbine with fogging units. The first step in creating the model was the selection of a standard set of components and a thermodynamic basis to model the physical properties of these components. When the component list was created, HYSYS created a new component list called Component List-1. The next step was the selection of a 'Fluid Package' for it. The 'Fluid Package' which is the thermodynamic system linked with the given list of components. The reaction methane was introduced to the process simulation in order to account for the reaction that will occur in the combustion chamber. The process model was built by entering the "Simulation Environment." The data required to incorporate fogging units into gas turbines is displayed in Table 1, and the Pump, Mixer, Separator, Compressor, Conversion Reactor, and Turbine icons from the model palette were clicked and placed on the flow sheet in Figure 3.

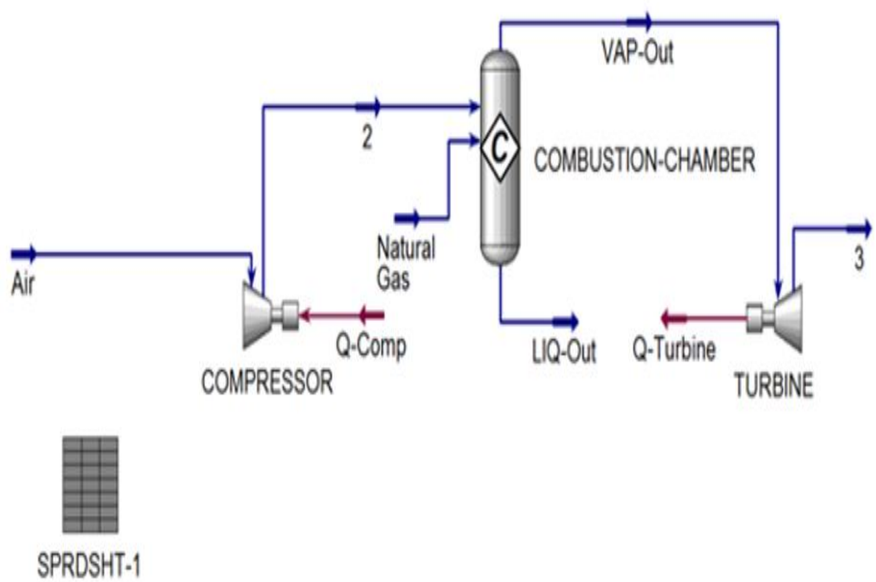

Fig 2: Flow chart of simulated simple gas turbine unit

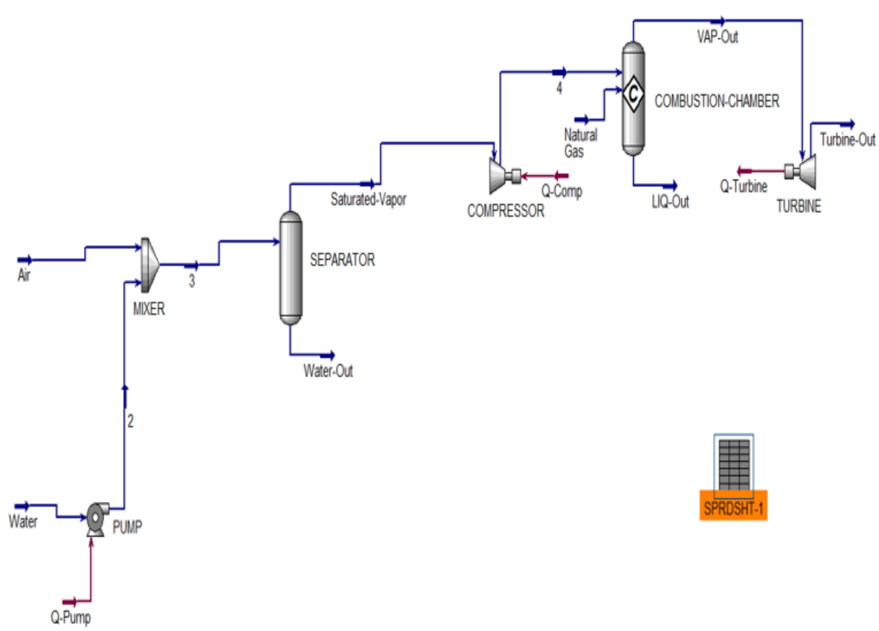

Fig. 3: Process Flow sheet for Gas Turbine with Fogging Unit

Table 1: Data use in incorporating high fogging system into gas turbine

S/N	Operating Parameters	Value	Unit
1	Mass flow rate of air $\dot{m}a$	376.75	kg/s
2	Mass flow rata of fuel $\dot{m}_f$	6.7	kg/s
3	Mass flow rate of exhaust $\dot{m}_{exh}$	386.055	kg/s
4	Pressure of fuel gas p_f	2280	kpa
5	Temperature of fuel gas t_f	328	K
6	Intake temperature to compressor T_3	281.68	K
7	Intake pressure to compressor P_3	101.3	kpa
8	Exit temperature from compressor T_4	565.1	K
9	Exit pressure from compressor P_4	982.804	kpa
10	Turbine pressure P_5	982.784	kpa
11	Turbine temperature T_5	1283	K
12	Exhaust temperature T_6	796.9	K
13	Exhaust pressure P_6	101.3	kpa
14	Pump power $\dot{w}_p$	68.63	kW
15	Volume flow rate of demineralized water V	11.4	m^3/h
17	Pressure of demineralized water	20000	kpa
18	Isentropic efficiency of compressor	87.8	%
19	Isentropic efficiency of turbine	89.4	%
20	Combustion efficiency	99	%
21	Pump efficiency	75	%
22	Lower heat value LHV	46670	kJ/kg
23	Specific heat capacity of air C_{pa}	1.005	kJ/kgK
24	Specific heat capacity of exhaust gas C_{pa}	1.15	kJ/kgK
25	Pressure ratio P_r	9.7	
26	Temperature of dimeralized water T_2	298	K

RESULTS AND DISCUSSION

Equations 10, 11, 12, and 13 were used to calculate the compressor work, turbine work, and other results obtained, such as net power, thermal efficiency, and specific fuel consumption heat rate. The plant's performance was ascertained through simulation using Aspen HYSYS software. The findings are obtained by adding an air intake cooling system (high fogging system), which maintains constants for the mass flow rate of air entering the fogging unit, the ambient air temperature, and the pressure at the inlet and exit. The component was fitted with additional parameters, such as the water's temperature and pressure. The volume flow rate of demineralized water, which was transformed into high-pressure fog nozzles, was varied from case I to 181, in order to find the optimal cooling temperature that would minimize the compressor's power and increase turbine work, resulting in the highest possible thermal efficiency, network output, minimal specific fuel consumption, and heat rate. Aspen HYSYS was used to accomplish all of these results. In this section, these outcomes were visually presented to contrast with the outcomes of the basic gas turbine system. Plotting of the outcomes of the water flow rate variation was also done. Plotting the heat rate of a basic gas turbine system with a fogging system in kJ/kW against the Kelvin (K) ambient air temperature is shown in Figure 4.

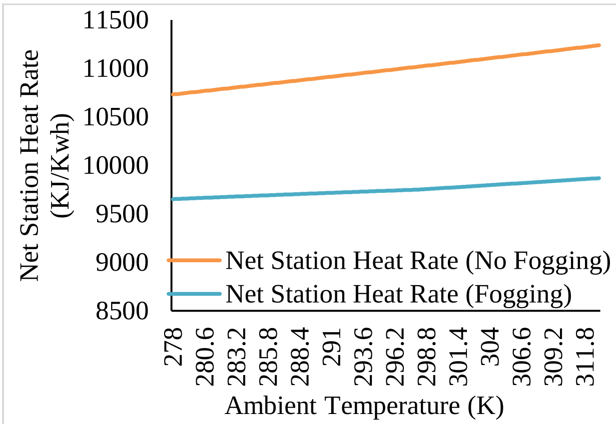

Fig 4: Effect of ambient temperature on heat rate

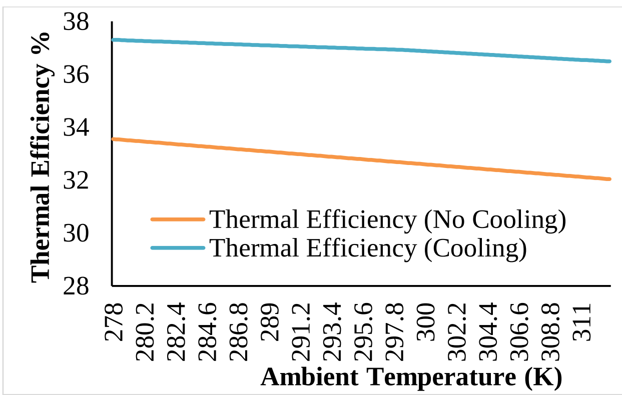

Fig. 5: Evaluation of the effect of ambient temperature on thermal efficiency of gas turbine plant

Because compressor power increases with higher ambient air temperatures together with an increase in specific fuel consumption, the result obtained from a basic gas turbine indicates an increase in heat rate as a result of rising ambient air temperatures. As reported by Ukwamba *et al.,* (2018), the incorporation of an air intake cooling system (high pressure fogging) results in a large reduction in heat rate since less power is needed for compression, which lowers the air intake to the compressor. Figure 5 shows that thermal efficiency of simple gas turbine system decreases with an increasing in ambient air temperature. This is because the net power output of gas turbine cycle decreases due to increase in compressor power (Orhorhoro and Orhorhoro, 2016). Thus, the mass flow rate of gases is also reduced while the fogging system thermal efficiency increases as a result of reduction in ambient air temperature which lower the compressor power, and this agreed with the findings of Al-Tobi, (2009), and Ibrahim *et al.,* (2011).

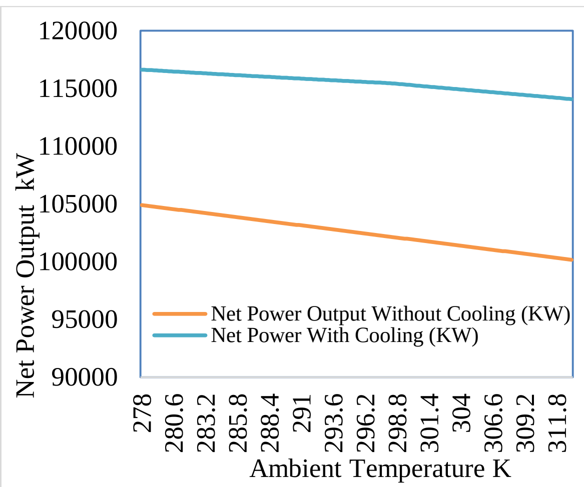

Fig. 6: Effect of ambient temperature on net power output

Figure 6 shows the improvement in net power due to incorporating air intake cooling system (high pressure fogging). As ambient air temperature increase, mass flow rate (the density of air with constant volumetric flow of gas turbine), decreases and compressor discharge temperature increases. Figure 7 is the specific fuel consumption of simple gas turbine system and incorporation of fogging system it is plotted in (kg/kWh) against ambient air temperature in (K). The results revealed that ambient air temperatures have a significant effect on specific fuel consumption on simple gas turbine system. When the ambient air temperature increases the specific fuel consumption increase due to increase in compressor power as a result of higher intake ambient air temperature (Al-Tobi, 2009).

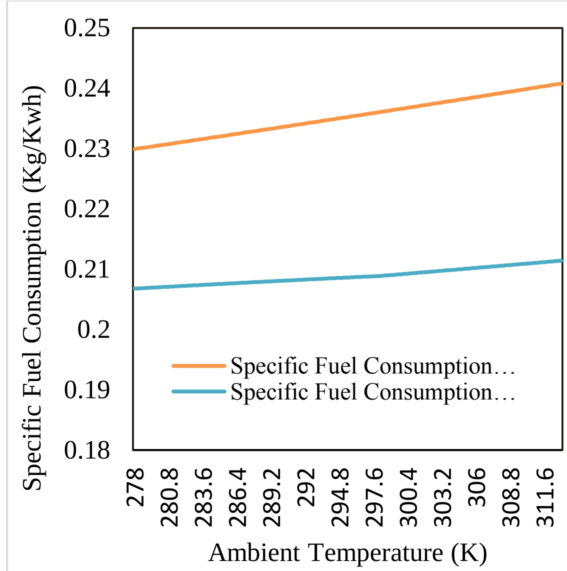

Fig. 7: Effect of ambient temperature on specific fuel consumption

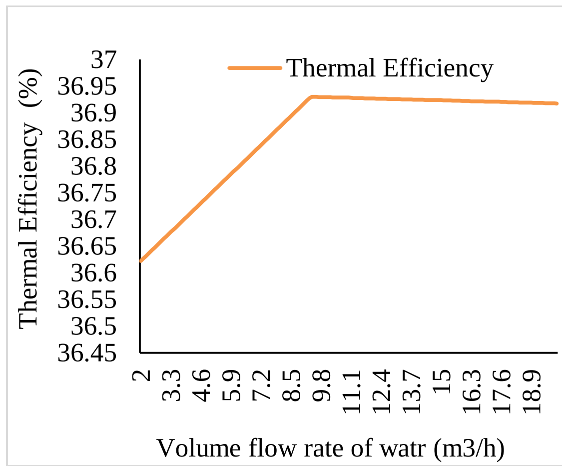

Fig. 8: Effect of variation of volume flow rate of water on thermal efficiency of gas turbine

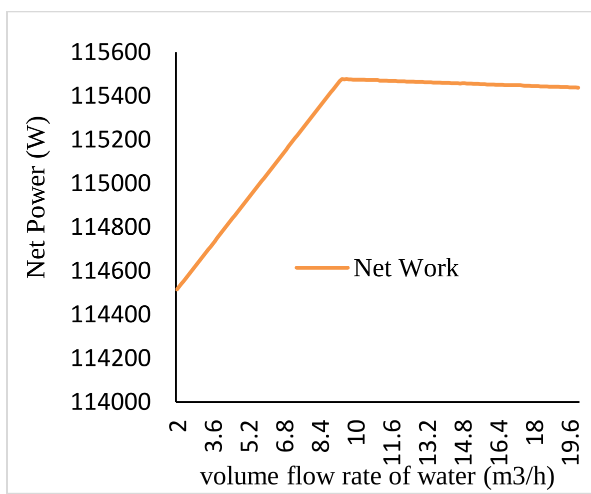

Fig. 9: Effect of variation of volume flow rate of water on net power of gas turbine

The thermal efficiency in (%) and net power in (kW) are displayed against the volume flow rate of water in (m3/h) in Figure 8 and Figure 9, respectively. The graphs demonstrate that, up until a point when the variance becomes constant, the saturated vapor air temperature decreases as the water flow rate increases along with increases in thermal efficiency and net power. Plots of specific fuel consumption in kg/kWh and heat rate in kJ/kWh against the volume flow rate of water in m3/h are shown in Figures 10 and 11, respectively. The figures demonstrate how the saturated vapor air temperature decreases with increasing water flow rate, resulting in a decrease in specific fuel consumption and heat rate as demonstrated in the figures where the fluctuation became constant.

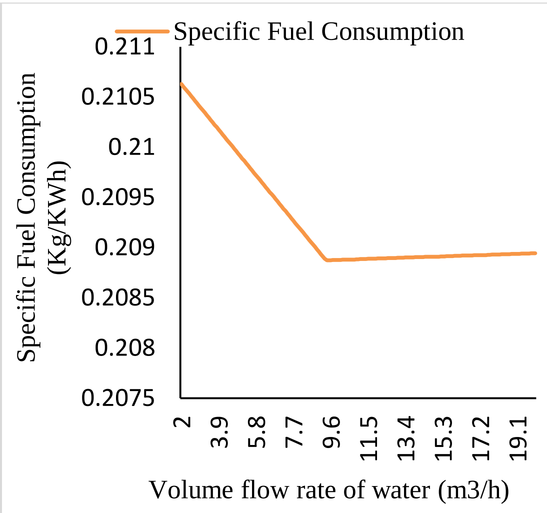

Fig. 10: Effect of variation of volume flow rate of water on specific fuel consumption of gas turbine

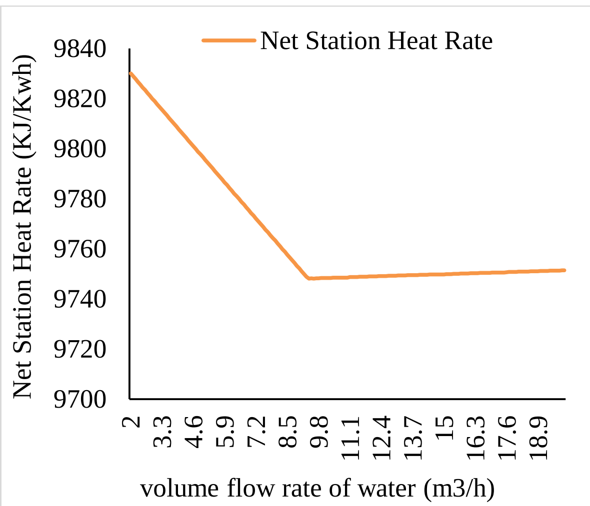

Fig. 11: Effect of variation of volume flow rate of water on heat rate of gas turbine

The thermal efficiency, net power decreases, and specific fuel consumption and heat rate increase with increasing ambient air temperature. Incorporating air intake cooling (high pressure fogging system) improved the performance of gas turbine power plants, as the thermal efficiency and network output were higher than those obtained from simple gas turbine plants. The incorporation of air intake cooling (high pressure fogging system) will reduce environmental pollution as the specific fuel consumption and heat rate are less than those of a simple gas turbine plant.

Conclusion: Particularly in Nigeria, intake air cooling systems are helpful instruments for boosting the net power generating capacity of gas turbine power plants. Lowering the gas turbine's intake air temperature raises the mass flow rate, improves the engine's efficiency, net output, and heat rate associated with specific fuel consumption. In this investigation, a simple-type gas turbine was equipped with a high-pressure fogging system. Each system's performance data was examined in relation to the heat rate, output power, thermal efficiency, ambient air temperature, and particular fuel consumption. Using a high fogging system, a basic gas turbine plant without cooling was replicated for comparison with cooling.

Declaration of Conflict of Interest: The authors declare no conflict of interest.

Data Availability: Data are available upon request from the first author or corresponding author or any of the other authors.

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