RESEARCH ARTICLE OPEN ACCESS

Performa-nce Prediction of a Jatropha-Biodiesel Powered Gas Turbine Plant

WC Solomon[1] MU Bonet[2] SU Mohammed[3] CV Orji[4]
[1234] *Department of Mechanical Engineering, Nigerian Defence Academy, P.M.B 2109, Kaduna, Nigeria.*
*Corresponding Author: * WC Solomon*

ABSTRACT: This paper examines the behaviour of a 75MW gas turbine plant fired with Jatropha biodiesel derived from Nigerian feedstock as a possible alternative fuel. The analysis was carried out by varying the ambient temperature between 288K and 323K while adapting the plant design pressure ratio of 9.9 and turbine entry temperature with the aim of predicting and comparing the results of the performance behaviour of the plant fuelled with both fuels. The specific fuel consumption, fuel air ratio, net power output, and thermal efficiency of the plant were the performance parameters of interest. From the results the highest power output was achieved with the biodiesel. Furthermore the specific fuel consumption, fuel air ratio and thermal efficiency were found to be slightly higher than those obtained with natural gas. These results demonstrate that biodiesel can compete favourably well with natural gas as a gas turbine fuel even though in terms of economy of running the plant natural gas might be the preferred fuel for the plant operators now because of the availability and cost of natural gas compared to the biodiesel. Also should the plant be operated on biodiesel, the fuel lines may need to be adjusted the increased mass flow rate associated with its use.

Keyword: Jatropha biodiesel, natural gas, specific fuel consumption, power output, thermal efficiency, gas turbine.

Date Of Submission: 14-01-2018 Date Of Acceptance: 03-02-2018

I. INTRODUCTION

Gas turbine plants form the bulk of the grid connected electric power plants installed in Nigeria today because of the availability of natural gas in the country. The country's natural gas proven reserve is put at 260 trillion cubic feet which is adjudged to be thrice that of crude oil the country is known for [1]. However this has not been effectively utilised to power the plants available. Consequently there is inadequate supply of power to the national grid and as a result majority of the population are deprived of public power supply. This shortage has impacted on the economy negatively. Most people rely on standby electric generators as alternatives to run their businesses. It is said that grid connected power supply is now the alternative power supply while stand-by generators have replaced the grid power supply. Besides the combustion of natural gas in engines lead to the emission of harmful exhaust pollutants into the environment in contrast to the Kyoto protocol of which Nigeria is a signatory upon which stringent legislations have been put in place to curb the emission of these pollutants into the atmosphere. The depletion of natural reserves due to rising demand as well as the fluid nature of the supply of natural gas to our power stations remains a significant factor as well. This work therefore, is conceived to further assess jatropha biodiesel as a suitable alternative fuel to natural gas for firing power plants in the country.

Biodiesel fuel consists of monoalkyl esters of long-chain fatty acids derived from vegetable oils (soya, rapseed, cotton seeds, jatropha seeds, palm kernels etc) or animal fats (lard, fish oil, tallow, chicken fat etc). The production of biodiesel in Nigeria is in accordance with the American Society of Testing and Materials (ASTM) international standard and its use offers several benefits. Aside from being an oxygenated fuel it is biodegradable, environmentally friendly, renewable, and miscible with conventional diesel. The increased use of this fuel is expected to provide excellent lubricity in engines as well as create public safety and in increased energy security in Nigeria.

Research on the use of biodiesels in gas turbine engines (GTEs) in Nigeria is limited when compared to that carried out on diesel engines despite the fact that most of the thermal power plants are made up of GTEs. The aim of this research therefore is to further investigate the response of GTEs when using biodiesel as fuel. Biodiesel has similar fuel properties to that of conventional diesel and can be burned in gas turbines because of their fuel flexibility though thermal stability may vary with type of biodiesel feedstock.

A study was carried out to investigate the effect of soya biodiesel and palm oil biodiesel both in pure and blended forms in a micro turbine at varying loads. Deductions from the study revealed the specific fuel consumption to be higher when the engine was operated on biodiesel than with conventional diesel and the heat rate was also found to be higher with biodiesels than conventional diesels. For all the fuels, the heat rate dropped when the load on the engine was increased and the biodiesels offered less carbon dioxide emission [2].

Another study was undertaken to explore the possibility of powering gas turbines with biodiesel and its blends with Jet A-1 fuel which further revealed its feasibility as an alternative fuel for powering gas turbines. It found that the fuel flow, fuel-air ratio, and specific fuel consumption increased slightly with biodiesels while the engine thrust and efficiency decreased substantially with increased blend ratio [3]

In a related work, the performance of certain stationary gas turbines running on biofuels including jatropha was investigated and the results obtained showed the performance of jatropha as fuel in different engines was found to be similar to those of conventional fuels because of the similarity in their properties even though the efficiencies were lower when compared to the benchmark fuel natural gas with a trade-off for reduced emissions [4].

Table 1: Physicochemical properties of Jatropha biodiesel [6]

S/No	Properties	Jatropha biodiesel
1	Specific Gravity @ 65^oC	0.893
2	Kinematic viscosity (mm^2/s)	4.86
3	Flash point (^oC)	192
4	Pour point (^oC)	9
5	Calorific value (MJ/kg)	42.22
6	Ash content	0.013
7	Cloud Point (^oC)	12

A probe was also undertaken to examine the characteristics of a micro gas turbine using biodiesel made from waste restaurant oil and its blends and the result compared to that of the baseline fuel of aviation kerosene. The specific fuel consumption for biodiesel was observed to be slightly lower than that of the baseline fuel and when powered with the blends, it produced the same amount of thrust at the same engine speed although with more efficient combustion [5].

This study aims to investigate the behaviour of a 75MW frame type gas turbine power plant located in Afam, Rivers state Nigeria, fuelled with Jatropha biodiesel of Nigerian feedstock as an alternative fuel with the sole purpose of assessing the engine performance in comparison with natural gas.

II. MATERIALS AND METHODS

2.1 MATERIALS

The physicochemical properties of the Jatropha biodiesel and the technical detail of the plant as well as the lower calorific value of the natural gas is as given in

Table 1 and

Table 2.

Table 2: Technical data of the gas turbine power plant [7]

S/No	Technical data	**Values**
1	Compressor inlet pressure (bar)	1.013
2	Compressor isentropic efficiency (%)	85
3	Speed (rpm)	3000
4	Compressor stages	16
5	Compressor exit temperature (^oC)	601.15
6	Pressure ratio	9.9
7	Air flow rate (kg/s)	70
8	Fuel mass flow rate (kg/s)	6.53
9	Maximum temperature (^oC)	1057
10	Turbine isentropic efficiency (%)	87
11	Fuel(natural gas) LHV (kJ/kg)	43591
12	Exhaust gas temperature (^oC)	500

2.2 METHOD

The schematic diagram of the 75MW gas turbine, single shaft operating on open cycle is shown in fig 1 for the purpose of illustrating the work and energy flows from component to component along the plant. It consists of an axial flow compressor, a combustion chamber and a gas turbine plus a turbo generator

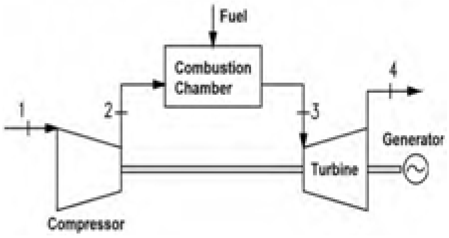

Figure 1: Schematic presentation of a gas turbine cycle

2.2.1 Performance Parameters

The calculation was done in compliance with International Standard Organization (ISO) standards:

Ambient Conditions: P_a =1.013bar, T_a = 15 ºC or 288

Working fluid is air with mass flow: m (kg/s)

For cold section of the engine, (C_{pa}=1.005, r_a=1.4)

For Hot section of the engine,

(C_{pg}= 1.150,r_g = 1.333)

2.2.2 Cycle parameters

Using figure 1,

1-2: COMPRESSOR

$P_2 = P_1 . R_c$ (1)

Where R_c = compression ratio:

$T_2 = \frac{T_1}{\eta_{isc}}\left[(R_c)^{\frac{\Upsilon_a - 1}{\Upsilon_a}} - 1\right] + T_1$ (2)

Where η_{isc} = isentropic efficiency of compressor

The compressor power can be estimated using the first law of thermodynamics:

$W_c = M_a\ C_{Pa.avg}\ (T_2 - T_1)$ (3)

2-3 Combustion Chamber

Where, M_a = mass flow rate of air

Combustion chamber pressure drop and combustion chamber discharge pressure:

$P_3 = P_2 - P1$ (4)

Heat delivered by combustion chamber is determined from energy balance in it as:

$Q_{in} = M_a \cdot C_{Pg \cdot avg}\ (T_3 - T_2)$ (5)

Where, $C_{Pg \cdot avg}$ is flue gases (hot) calculated as the average temperature across the combustion chamber.

Given the lower calorific value of fuel (LCV), mass flow rate of fuel is defined as:

$M_f = \frac{Q_{in}}{\eta_{cc} \cdot LCV}$ (6)

$M_f = \frac{M_a C_{Pa \cdot avg}\ (T_2 - T_1)}{\eta_{cc} \cdot LCV}$ (7)

Where η_{cc} = combustion chamber efficiency

3-4 TURBINE

The discharge temperature of flue gas

$$T_4 = T_3 - \eta_t T_2\left[1 - \left(\frac{1}{P_3/P_4}\right)^{\frac{\Upsilon g - 1}{\Upsilon_g}}\right]$$

(8)

Where η_t = isentropic efficiency of turbine

P_4 "= turbine exhaust gas pressure.

Power produced from the turbine:

$W_t = M_T\ C_{Pgavg}\ (T_3 - T_4)$ (9)

Where $M_T = M_a + M_f$ (10)

Net power (N_N) obtained from the gas turbine:

$W_N = W_T - W_C$ (3.8)

Specific fuel consumption (SFC) is determined by

SFC = $\frac{3600 \times M_f}{W_N}$ (11)

Fuel Air Ratio (FAR):

FAR = $\frac{M_f}{M_a}$ (12)

AFR = $\frac{M_a}{M_f}$ (13)

III. RESULTS AND DISCUSSION

The investigation of the performance of the gas turbine plant was carried out by varying the ambient temperature between 288^0 K and 323^0K while keeping the design pressure ratio 9.9 and turbine entry temperature of 1330^0K was kept constant and the results presented graphically as shown in figures 1 to 7

Figure 2 compares the variation of the plant power and the ambient temperature for the two fuels Jatropha biodiesel and natural gas under investigation. The curve shows an inverse proportionality relationship. As the ambient temperature increases the plant power drops which is expected because with increase in temperature the mass of air inducted into the engine reduces. The result reveals a drop from 91824kW to 73344kW for the biodiesel and 91468kW to 73024kW for natural gas. It is observed that the power obtained from the plant with biodiesel is higher than that with natural gas. However a difference of 356kW and 320kW in power output was obtained at 288 K and 323K respectively which accounts for the closeness of the two curves. This may not be unconnected with the similarity of the lower calorific values of the two fuels: 42055kJ/Kg and 43591kJ/kg for biodiesel and natural gas respectively. Even though the lower calorific value for the Jatropha biodiesel is lower when compared to that of natural gas the plant performed better with the biodiesel.

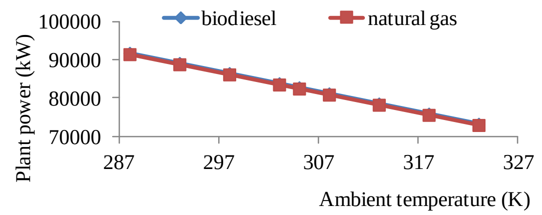

Fig. 2: Graph of plant power versus ambient temperature

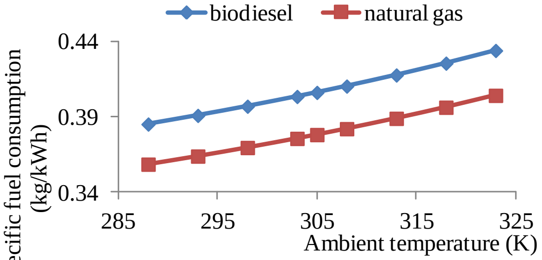

Fig. 3: Graph of specific fuel consumption versus ambient temperature

Figure 3 depicts the variation of the specific fuel consumption of the plant with that of and the ambient temperature. The pattern of the curves shows linearity between the specific fuel consumption and ambient temperature for both fuels. As the ambient temperature rises so does the specific fuel consumption. The specific fuel consumption rose is from 0.3851kg/kWh to 0.4337kg/kWh and 0.3858kg/kWh to 0.4040kg/kWh for biodiesel and natural gas respectively. It is also observed that the difference between the minimum and maximum values for the specific fuel consumption for biodiesel is higher than that of natural gas which implies that more biodiesel is consumed to generate an equivalent power. This could be attributed to the lower calorific value of the biodiesel as well when compared with that of natural gas. Thus, it could be deduced that in terms of specific fuel consumption, it is more economical to run the plant on natural gas than on biodiesel fuel.

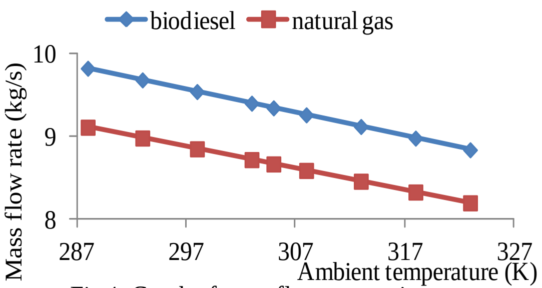

Fig 4: Graph of mass flow rate against ambient temperature

Figure 4 shows the variation of the mass flow rate with ambient temperature. The mass flow rates of both fuels vary inversely with the ambient temperature. As the ambient temperature increases the mass flow rate reduces from 9.822kg/s to 8.837kg/s and 9.110kg/s to 8.196kg/s for the Jatropha-biodiesel and natural gas respectively. Thus the rise in ambient temperature influences the behaviour of the plant in terms of fuel consumption. It could be inferred from this deduction that during hot periods the fuel consumption tends to be higher than in colder periods.

Figure 5 is an illustration of the behaviour of the plant in terms of the plant power and specific fuel consumption. It indicates that as the specific fuel consumption increases the power of the Plant drops for both fuels.

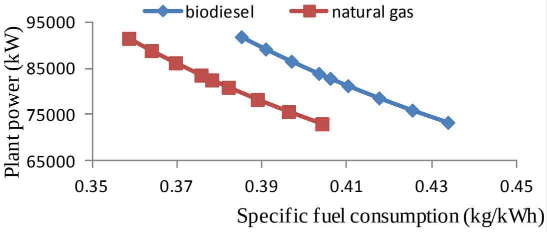

Fig 5: Graph of plant power against specific fuel consumption

Also the specific fuel consumption at 0.434 kg/kWh gives a corresponding drop of 73345kW and 7302kW for the biodiesel and natural gas fuels respectively. Thus the decrease in mass flow rate in fig 3 could have been as a result of this drop in power. Hence the power of the plant drops as air temperature increases.

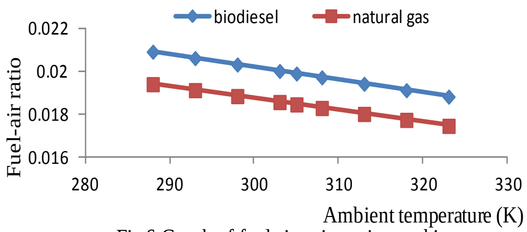

Fig 6:Graph of fuel air ratio against ambient temperature

Fig 6 depicts the variation of fuel-air ratio and ambient temperature. From the graph it can be seen that the fuel air ratio drops with rise in ambient temperature. This could be as a result of change in the density of air as the temperature of the ambient increases. Consequently the amount of air intake into the plant per cycle is less when compared to that at lower ambient temperature.

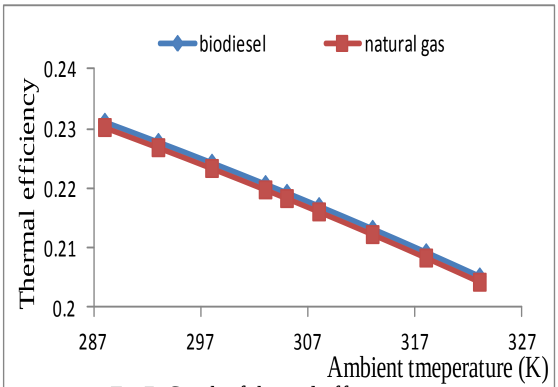

Fig 7: Graph of thermal efficiency against ambient temperature

Figure 7 shows the variation of thermal efficiency of the plant with ambient temperature. As the ambient temperature increases, its thermal efficiency decreases significantly with both fuels. The highest and the lowest thermal efficiencies achieved are 0.2312 and 0.2057 for biodiesel and 0.2300 and 0.2043 for natural gas. From the results obtained, the plant while operating on biodiesel gave the highest thermal which implies that efficiency gave a better thermal efficiency and thus in terms of thermal efficiency the biodiesel is a better fuel to use.

IV. CONCLUSION

A performance investigation of an existing gas turbine plant powered by Jatropha-biodiesel as a suitable alternative in place of natural gas fuel was carried out by varying the ambient temperature whilst keeping the turbine entry temperature and pressure ratio constant and the results of the performance of running the two fuels compared. The performance parameters investigated include plant power, specific fuel consumption, mass flow rate of fuel, fuel/air ratio and thermal efficiency. The result arrived at show that biodiesel competes favourably well with natural gas. It was conspicuously observed that the plant produced more power when run on biodiesel fuel than natural gas even though the LCV of natural gas is slightly higher than that of the biodiesel. Furthermore the plant mass flow rate, specific fuel consumption, fuel-air ratio and thermal efficiency were found to be moderately higher when the engine was run on the biodiesel. However the plant power output was discovered to drop with increase in specific fuel consumption whilst the temperature increased. From the analysis of these performance parameters, the drop in power output and increase in specific fuel consumption and mass flow could be ascribed to the value of the lower calorific value of the biodiesel compared to that of natural gas. The consequence of increased mass flow rate of the biodiesel might require modifying the fuel lines to accommodate such flow for the same plant in order for it to operate well. However despite the availability of several GTs in our country in the power generation industry, not much has been done in studying their operability with alternative fuels such as biodiesel. Therefore there is need for more investigation to be carried out in this area in order to understand the behaviour of these engines while operating on these fuels with the view of their possible use as alternatives to natural gas which is in tandem with best global practices.

REFERENCES:

[1]. Nigeria-Natural Gas, available at www.onlinenigeria.com, accessed on 6/9/14
[2]. E. Cruz dos Santos and M.A. Nascimento (2011), "Biofuels and Gas Turbine Engines" Advances in Gas Turbine Technology, pg 115-138, available at www.researchgate.net, accessed on 9/9/14
[3]. A.R. Abu Thalib, E. Gires and M.T. Ahmad (2014), "Performance Evaluation of a Small-Scale Turbojet Engine Running on Palm Oil Biodiesel Blends", Journal of Fuels, Vol. 2014, Hindawi Publishing Corporation.
[4]. D. Ihiabe (2013), "Assessing Biomass Fired Gas Turbine Power Plants :A Techno-Economic and Environmental Perspective", Doctoral Thesis, Cranfield University.
[5]. E.I. Tan, and W.W. Loui (2011),"Microgas Turbine Engine Characteristic using Biofuel", The Hiltop Review, Vol. 5, No. 1 Art. 6, pg 40-50.
[6]. E.T. Ekhihiero (2013), "Heteregenous Transesterification of Jatropha SeedOil : Effect of Methanol to Oil on the Methyl Ester Yield",International Journal of Innovative Scientific and Engineering

Technology Research, Vol. 2, No. 1, pg 29-33.

[7]. F.I. Abam, I.U. Ugot and D.I. Igbong (2011), “Thermodynamic Assessment of Grid-Based Gas Turbine Power Plants in Nigeria”, Journal of Emerging Trends in Engineering and Applied Sciences (JETEAS), Vol 2, No 6.

*WC Solomon. “Performa-nce Prediction of a Jatropha-Biodiesel Powered Gas Turbine Plant.” International Journal Of Engineering Research And Applications (IJERA), vol. 08, no. 01, 2018, pp. 31–36.