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PARAMETRIC APPRAISAL OF THE PERFORMANCE OF A GAS TURBINE UTILIZING COMPARATIVE BREAKDOWN OF THE PERFORMANCE CRITERIA

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ABSTRACT

This paper presents the parametric appraisal of the performance of a gas turbine utilizing comparative breakdown of the performance criteria. The investigation took thirteen months during which logsheets used for the operations studied and direct measurements performed as well. The results gave the average of each of the performance criteria as follows: thermal efficiency - 24.19%, work ratio - 0.855, TDI - 3.13, NPHR - 14.90MJ/KW and net work ratio - 0.25. There is, thus, significant correspondence with the respective design values: 26.6% ,0.4-0.8,3.42, 10-20MJ/KW and 0.25. It further shows that a 1°C rise in the ambient temperature would cause 0 – 0.054 decrease in the work ratio, 0 – 0.42 increase in the thermal discharge index, 0 – 1.51MJ/kW increase in the net plant heat rate , 0 – 0.04 decrease in the net work ratio and 0 – 2.45% decrease in the actual thermal efficiency. The variation of thermal discharge index with ambient temperature shows that maintaining a maximum ambient temperature of 29°C would reduce thermal energy thereby contributing to the reduction of the depletion of the ozone layer.

Keywords: Thermal Efficiency, Work Ratio, Thermal Discharge Index, Net Plant Heat Rate, Performance.

I. INTRODUCTION

The gas turbine engines are extensively utilized for generating electrical energy in the form of electricity, for the operation of airplanes and for sundry applied industries like refineries and petrochemicals. As the elemental of gas turbine engine cycle which has a low thermal efficiency, it is pertinent to device an ameliorated gas turbine engine base cycle [1]. The overall efficiency of the gas turbine engine cycle is principally dependable on the pressure ratio of the compressor which processes of combustion, expansion and compression happen in a separate component as they do in a reciprocating engine. Also, studying the parameters which affects the operational condition requires proper management of the functioning of the different components [2].

The study of how the intercooler affects the parameters of the performance of the gas turbine engine was done by [3]. In that work, the inter-cooling raise the potency of the power generation efficiency of the proposed gas turbine engine in comparison with the plant without an inter-cooling system. The effect of different parameters like compressor ratios, air - fuel – ratios, turbine – inlet –temperatures, cycle peak temperature ratios together with different ambient temperatures were studied.

The Sapele Thermal Power Station performance was analyzed by [4]. The measurement of the performative index as done against the percentage shortage of the power produced, load factor together with the usage factor from 1997 – 2006. The power station which consists of six units of steam turbine engines and four units of gas turbine engines, and 1020MW capacity. It was found from the analysis that the percentage shortage of the power produced and the load factor were 27.4% - 49.10% and 39.9% - 64% respectively. The percentage shortage indicates incongruous operational maintenance and the load factor is in opposite side with international best practice standard of 80%. Also, ways for ameliorating the performative index of the plant like training of personnel coupled with regular operational maintenance were recommended.

The analysis of the performance of a 116MW gas turbine engine at Mahshahr (Iran) utilizing exergy technique was conducted by [5]. The study utilized the conservation of mass and energy laws to each element of the system. The results show that the huge amount of exergy destruction occurred in the air compressor, the

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turbine and the combustion chamber and that 60.97% of the total exergy ruined in the plant of which 55% was contributed by the combustion chamber.

The evaluation of how the ambient temperature affects the performance of the Trans-Amadi gas turbine engine plant was done by [6][20][21]. The investigation took thirteen months and the data were measured together with the logsheets used for operations study. The result shows that a 1^0C rise of the ambient temperature will be responsible to 0.12% decrement and increment of power output and power differential respectively,1.17% decrement in the thermal efficiency, 27.18% increment in the heat rate coupled with 3.57% increment of the SFC. The investigation further reveals that an ambient temperature of 30^0C will yield minimal fuel consumption.

The investigation of analyzing Egbin Thermal Power Station Performance was conducted by [7]. The station consists of Six (6) Units of steam turbine with installation capacity of 1320MW and is located in Lagos State, Nigeria, and the investigation studied the efficiency and reliability. The data were collated from the operational and maintenance records of the station for the period of 2000 – 2010. The result shows that the average overall efficiency and average reliability were 34.67% in opposite required standard of 40% to 50% and 80.92% in opposite to the best practice of 98% to 100%. The shortage in the performance level of the plant is caused by the low plant availability due to frequent breakdown, overdue overhauling of some units coupled with others.

Furthermore, the present work will study the parametric assessment of the performance of a gas turbine: Trans- Amadi Gas Turbine Engine Phase II using the comparative analysis of the performance criteria. This study entails comparing the actual performance criteria such as the work ratio (WR), thermal discharge index (TDI), net plant heat rate (NPHR), net work ratio (NWR) and actual thermal Efficiency (Ƞth) to their respective design values coupled with how the ambient temperature affects the performance criteria

II. METHODOLOGY

The research procedure entails collation of data from turbine logsheets, plant-auxiliaries logsheets and generator logsheets for thirteen months. Precisely, the appropriate thermodynamic equations and principles were used in determining parameters that cannot be determined straightforwardly from the logsheets utilized for the operations [8][9].The pressures, temperatures and mass flow rates at different points in the gas turbine engine were parameters investigated and put into consideration during the data collation (Figure 1).

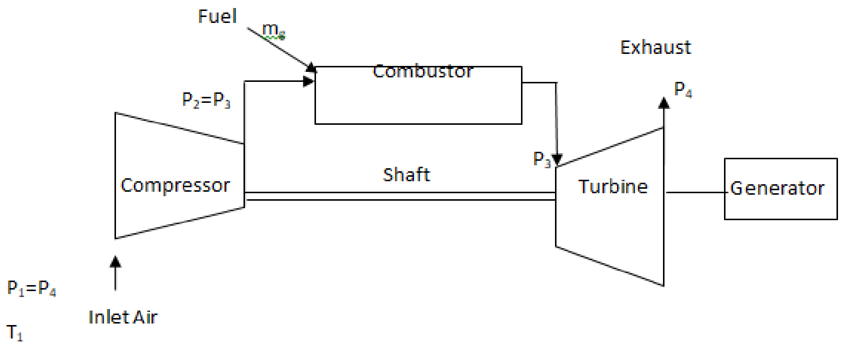

Figure 1: Single-Shaft Gas Turbine[10][11][12]21]

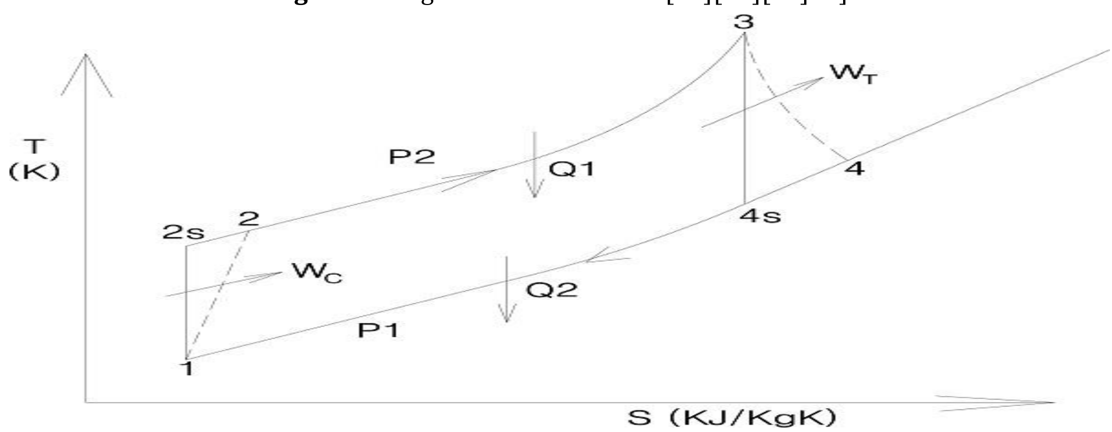

Figure 2: T-S Diagram for Brayton Cycle [13][12]

The detailed examination and handling of the data includes the computation of the monthly average of the mean values of the daily parameters. The performance of the plant was investigated using comparative analysis of the performance criteria[12][13][21].

From Figure 2: using the 1st thermodynamics law of an open system:

$$\dot{Q} - \dot{W}_{SHAFT} = \sum_{in} \dot{m}\left(h + \frac{v^2}{2} + gz\right)_{in} - \sum_{out} \dot{m}\left(h + \frac{v^2}{2} + gz\right)_{out} \quad (1)$$

If $v^2/2 = 0$ and $gz = 0$, The First Law will be:

$$0 = \dot{Q} - \dot{W}_{SHAFT} + \dot{m}(h_{in} - h_{out}) \quad (2)$$

The Turbine Work will be:

$$\dot{W}_T = \dot{m}_p C_p (T_4 - T_3) \quad (3)$$

The Net Work Output or Power Output;

$$\dot{W}_{Net} = \dot{W}_T - \dot{W}_C \quad (4)$$

the energy balance is given as [14]:

$$\dot{m}_a C_{pa} T_2 + \dot{m}_f \times LHV + \dot{m}_f C_{pf} T_f = (\dot{m}_a + \dot{m}_f) C_{pg} \times T_3 \quad (5)$$

Where: LHV = 47541.6KJ/Kg [15]

Re-arranging Eq. (5); the fuel ratio 'f' is given as:

$$f = \frac{\dot{m}_f}{\dot{m}_a} = \frac{C_{pa} \times T_3 - C_{pa} T_2}{LHV - C_{pg} T_3} \quad (6)$$

The Total Heat Supplied or Added is given as [16]:

$$\dot{Q}_{added} = (\dot{m}_a + \dot{m}_f) \times C_{pa}(T_3 - T_2) = \dot{m}_f \times CV \quad (7)$$

The Compressor Work is given as:

$$\dot{W}_c = \dot{m}_a C_{pa}(T_2 - T_1) = \rho_a v_a C_{pa}(T_2 - T_1) \quad (8)$$

Thermal Efficiency is expressed as:

$$\eta_{th} = \frac{Net\ Work}{Total\ Heat\ Supplied} = \frac{\dot{W}_{Net}}{\dot{Q}_{Added}} \quad (9)$$

Specific Fuel Consumption is expressed as:

$$SFC = \frac{3600 \times \dot{m}_f}{\dot{W}_{Net}} \quad (10)$$

Heat Rate

$$HR = \frac{Heat\ Supplied}{Power\ Generated} = \frac{1}{\eta_{th}} \quad (11)$$

Also from Eq. (10) the SFC is given as:

$$SFC = \frac{3600}{AFR \times \dot{W}_{Net}} \quad (12)$$

Therefore,

$$AFR = \frac{LHV}{\dot{Q}_{Added}} \quad (13)$$

Performance Criteria [17]:

1. Work Ratio

$$WR = \frac{Net\ Work\ Output}{Gross\ Work\ Output} \quad (14)$$

2. Thermal Discharge Index [18]:

$$TDI = \frac{Thermal\ Discharge\ to\ the\ Enviroment\,(MW)}{Electrical\ Output\,(MW)} = \frac{P_{th}(1 - \eta_{th})}{P_{th}\,\eta_{th}} = \frac{1}{\eta_{th}} - 1 \quad (15)$$

3. Net Plant Heat Rate[13]:

$$NPHR = \frac{3600}{\eta_{th}}. \quad (16)$$

4. Net Work Ratio [19]:

$$NWR = \frac{W_{Net}}{\dot{Q}_{Removed}} \quad (17)$$

Total Heat Removed: $\dot{Q}_{Removed} = (\dot{m}_a + \dot{m}_f)C_{pg}(T_3 - T_4)$

III. RESULTS AND DISCUSSION

Results: Table 1 contains values obtained straightforwardly from the omanual of MS5001 Nuovopignone Gas Turbine engine used for operations. Table 2 contains values of T_2, T_4, p_{Ouput} and $\dot{m}_f$ which were obtained directly from turbine , generator and plant-auxiliaries logsheets respectively. Table 3 contains values of T_3, $\dot{W}_c$, $\dot{W}_T$, $\dot{W}_{net}$, Q_{add}, AFR, η_{th}, SFC and HR and they were obtained by calculation : using Equations 6,8,3,4,7,8,9,12,and 11 respectively. Table 4 comprises of the values of the performance criteria namely WR, TD1, NPHR and NWR which were obtained by calculation using Equations 14, 15,16, and 17 respectively. Also, the average of each of the performance criteria is computed and compared with the respective design value.

Furthermore, the effects for 1 ^{0}C rise in the ambient temperature with the WR, TDI, NPHR , NWR and η_{th} is plotted utilizing the Computer based Excel Software as depicted in Figures 3- 7 respectively.

Table 1: Design Parameters With Their Data[20]

S/N	Parameters	Units	Design Data
1	P_{Output}	MW	25.0
2	η_{th}	%	26.6
3	HR	Kcal/W.h	2.833
4	SFC	Kg/KW.h	0.308
5	T_1	^{0}C	25.0-45.0
6	C_{pg}	KJ/KgK	1.155
7	C_{pa}	KJ/KgK	1.005
8	Y_a	None	1.40
9	Y_g	None	1.33
10	$\dot{m}_g$	Kg/s	122.9

Table 2: Parameters And Their Values Obtained From Direct Logsheets Reading[20]

S/N	T_1 (^{0}C)	T_2 (^{0}C)	T_4 (^{0}C)	$\dot{m}_f$ (kg/s)	P_{Output} (MW)
1	25	240	378	2.60	11.14
2	26	242	382	2.62	11.14
3	27	244	384	2.64	11.13
4	28	246	385	2.66	11.13
5	29	247	387	2.67	11.13
6	30	248	390	2.68	11.13
7	31	250	392	2.69	11.12
8	32	254	394	2.80	11.11
9	33	257	388	2.82	11.10
10	34	258	400	2.90	11.09
11	35	260	389	2.92	11.08
12	36	262	388	2.98	11.07
13	37	265	379	3.00	11.04

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Table 3: Calculated Turbine Actual working Parameters' Values[20]

S/N	T_3 (^{0}C)	$\dot{W}_c$ (KW)	$\dot{W}_T$ (KW)	$\dot{Q}_{Added}$ (KW)	$\dot{W}_{net}$ (KW)	AFR	η_h (%)	SFC (kg/KWh)	HR (KCal/W.h)
1	1017	26556	1670	98002	24886	0.485	25.39	0.298	3.94
2	1025	26679	1693	98774	24986	0.481	25.30	0.300	3.95
3	1032	26803	1719	99420	25084	0.478	25.23	0.300	3.96
4	1041	26926	2015	100319	24911	0.474	24.83	0.305	4.03
5	1045	26926	2029	100706	24897	0.472	24.72	0.306	4.05
6	1049	26926	2040	101093	24886	0.470	24.62	0.308	4.06
7	1054	27050	2054	101479	24996	0.470	24.60	0.308	4.06
8	1092	27420	2257	105863	25163	0.449	23.77	0.319	4.20
9	1101	27667	2322	106638	25345	0.445	23.77	0.319	4.20
10	1127	27667	2435	109867	25232	0.432	22.97	0.330	4.35
11	1135	28451	2516	110643	25935	0.430	23.44	0.322	4.27
12	1156	28591	2643	113099	25948	0.420	22.94	0.330	4.36
13	1165	28849	2724	113877	26125	0.418	22.94	0.330	4.36

Table 4: Performance Criteria With Their Values[20]

S/N	T_1^{0}C	WR	TDI	NPHR(MJ/KW)	NWR	η_{th} (%)
1	25	0.882	2.94	14.18	0.27	25.39
2	26	0.881	2.95	14.22	0.27	25.30
3	27	0.880	2.96	14.27	0.27	25.23
4	28	0.860	3.03	14.50	0.26	24.83
5	29	0.860	3.05	14.56	0.26	24.72
6	30	0.859	3.06	14.62	0.26	24.62
7	31	0.859	3.06	14.63	0.26	24.60
8	32	0.848	3.20	15.15	0.25	23.77
9	33	0.845	3.20	15.15	0.25	23.77
10	34	0.838	3.35	15.67	0.24	22.97
11	35	0.838	3.27	15.36	0.24	23.44
12	36	0.831	3.36	15.69	0.23	22.94
13	37	0.828	3.36	15.69	0.23	22.94
AVERAGE		**0.855**	**3.13**	**14.90**	**0.25**	**24.19**

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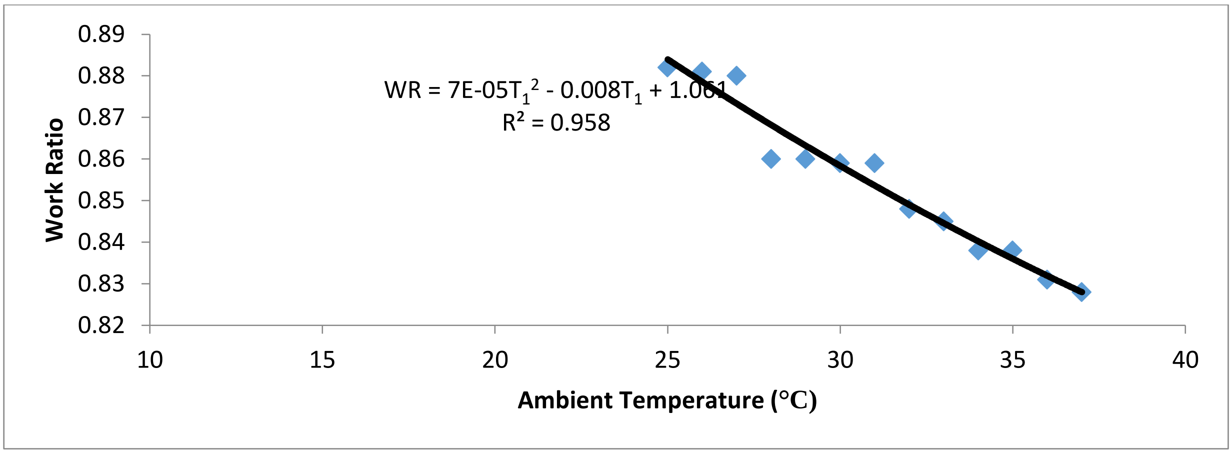

Figure 3: Effect of Ambient Temperature on the Work Ratio

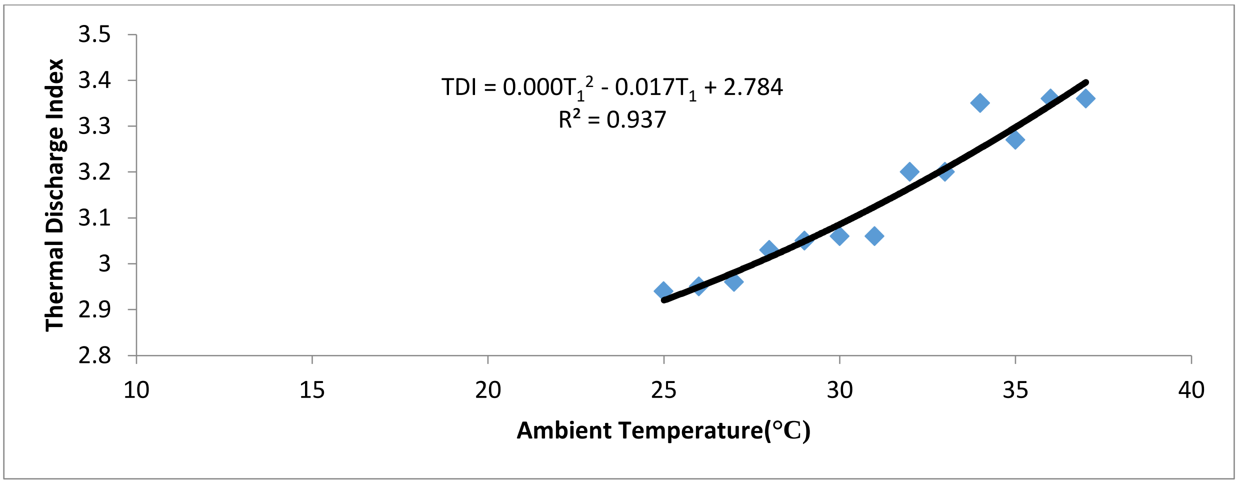

Figure 4: Effect of Ambient Temperature on the Thermal Discharge Index

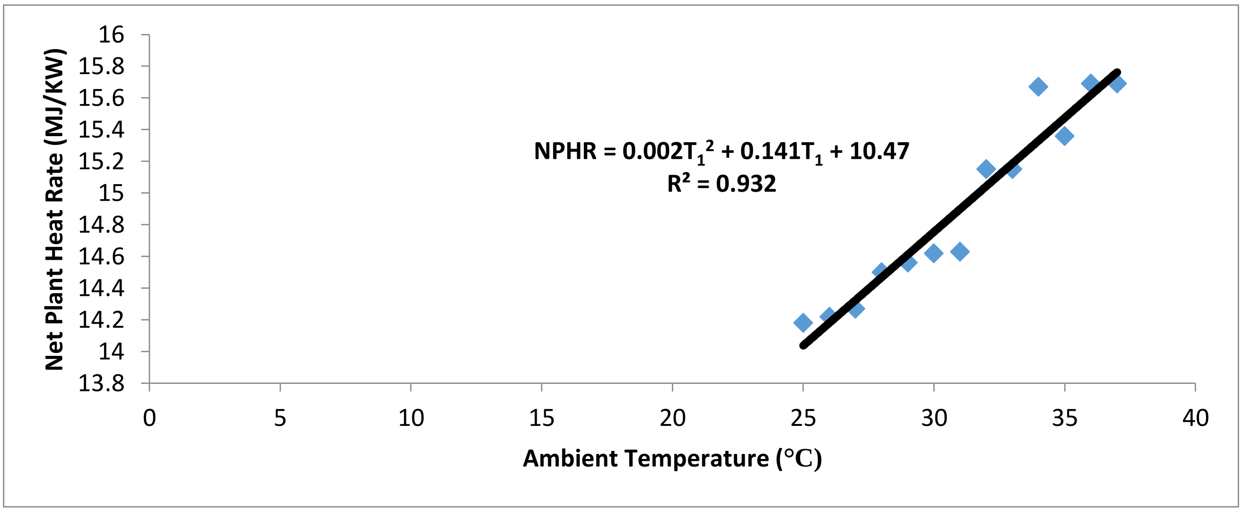

Figure 5: Effect of Ambient Temperature on Net Plant Heat Rate

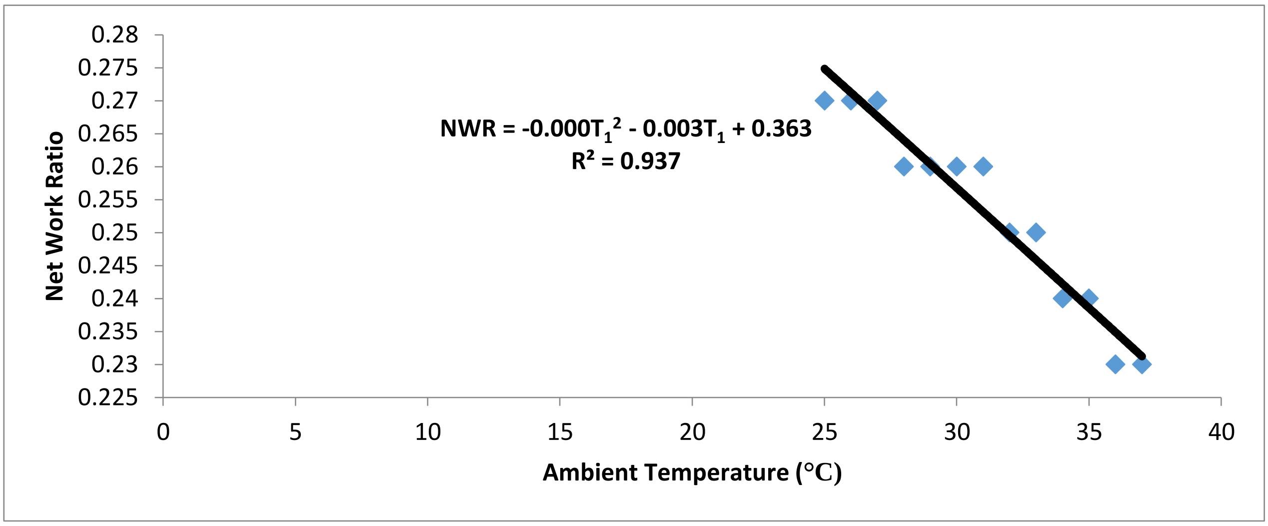

Figure 6: Effect of Ambient Temperature on the Net Work Ratio

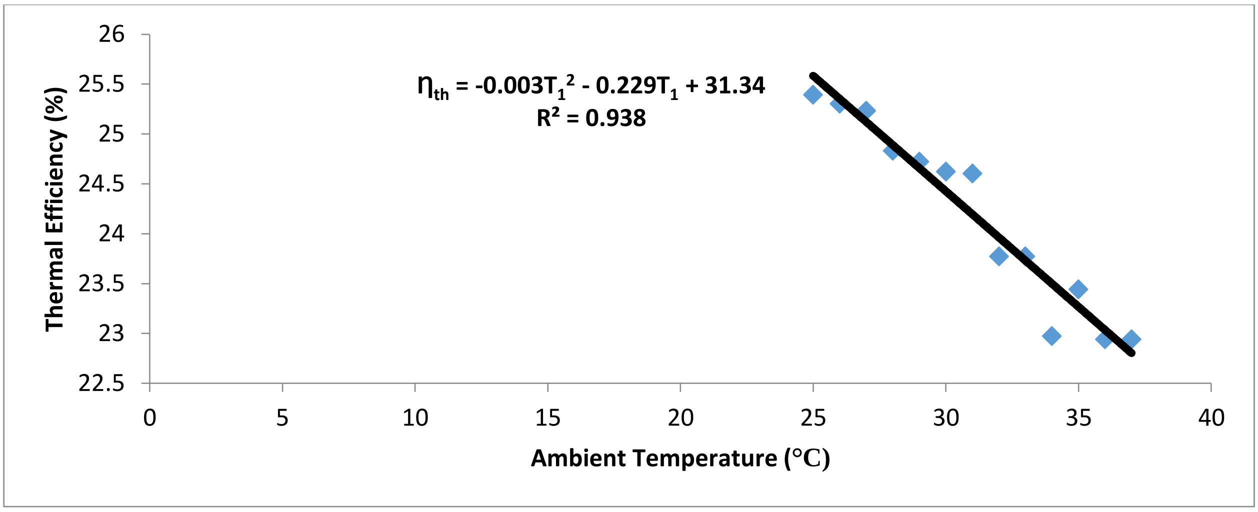

Figure 7: Effect of Ambient Temperature on the Actual Thermal Efficiency

Discussion:

Figure 3 shows how the ambient temperature affects the work ratio. It shows that an increment of the ambient temperature from 30^{o}C to 37^{o}C, the work ratio decreases from 0.86 to 0.828. Figure 4 depicts how the ambient temperature affects the TDI. It also depicts that an increment in the ambient temperature from 26^{o}C - 28^{o}C causes an increment the TDI from 2.96 - 3.06. Figure 5 illustrates how the ambient temperature affects the NPHR. The Figure 5 shows that an increment in ambient temperature from 26^{o}C to 34^{o}C will cause the net plant heat rate to increase from 14.20MJ/kW to 15.16MJ/kW. Figure 6 illustrates how the ambient temperature affects the network ratio. The figure 6 depicts that an increment of the ambient temperature from 26^{o}C to 35^{o}C causes the network ratio to drop from 0.269 to 0.238. Furthermore, Figure 7 shows the effect of the ambient temperature on the actual thermal efficiency. The figure 7 illustrates that an increment in the ambient temperature from 26^{o}C to 33^{o}C causes the thermal efficiency to reduce from 25.40% to 23.75%.

IV. CONCLUSION

The results show how the ambient temperature affects the performance criteria of the gas turbine engine. It further shows that 1^{o}C rise in the ambient temperature will cause 0 – 0.054 decrease in the work ratio, 0 – 0.42 increase in the thermal discharge index, 0 – 1.51MJ/kW increase in the NPHR, 0 – 0.04 decrease in the net work ratio and 0 – 2.45% decrease in the actual thermal efficiency. The average of the performance parameters such as thermal efficiency (24.19%), work ratio (0.855), thermal discharge index (3.13), net plant heat rate (14.90MJ/KW) and net work ratio (0.25) were computed as indicated and are in agreement with their respective design values (26.6% ,0.4-0.8,3.42, 10-20MJ/KW and 0.25).

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Nomenclature

[23] AFR = Air Fuel Ratio

[24] C_p= Specific Heat Capacity of the Product (KJ/KgK)
[25] C_{pa}= Specific Heat of Air at Constant Pressure (KJ/KgK)
[26] C_{pg}= Specific Heat of Gas at Constant Pressure (KJ/KgK)
[27] CV = Calorific Value of the Fuel
[28] $\frac{dE_{CV}}{dt}$ = change in energy within the control volume over time
[29] Σ = Summation
[30] f = Fuel Ratio
[31] g = Acceleration due to Gravity (g = 9.81m/s^2)
[32] GT = Gas Turbine
[33] h = Specific Enthalpy (KJ/KgK)
[34] HR = Heat Rate (Kcal/KW.h)
[35] LHV = Lower Heat Value (KJ/Kg)
[36] MW = Meggawatts
[37] NPHR = Net Plant Heat Rate (MJ/kW)
[38] NWR = Net Work Ratio
[39] $\dot{m}$ = Mass Flow Rate (Kg/s)
[40] $\dot{m}_p$= Mass Flow Rate of the Product (Kg/s)
[41] $\dot{m}_a$= Mass flow rate of air (Kg/s)
[42] $\dot{m}_g$ = Mass flow rate of gas (Kg/s)
[43] $\dot{m}_f$ = Mass flow rate of fuel (Kg/s)
[44] η_{th}= Thermal Efficiency (%)
[45] η_{ts} = Isentropic Efficiency of Turbine (%)
[46] P_{Output} = Power Output (MW)
[47] P_{th}= Thermal Energy (MW)
[48] ρ_a= Density of Air (Kg/m^3)
[49] $\dot{Q}$ = Quantity of Heat Transfer (KJ/Kg)
[50] Q_{added}= Heat Added or Heat Supplied (KJ/Kg)
[51] s = Specific Entropy (KJ/KgK)
[52] SFC = Specific Fuel Consumption (Kg/KW.h)
[53] TDI = Thermal Discharge Index
[54] T = Temperature {Degree Celsius (^{0}C) or Degree Kelvin (K)}
[55] T_f = Temperature of Fuel (^{0}C)
[56] T_1 = Ambient Temperature (^{0}C)
[57] T_2 = Compressor Exit Temperature (^{0}C)
[58] T_3 = Turbine Inlet Temperature (^{0}C)
[59] T_4 = Exhaust Temperature (^{0}C)
[60] T_{4S} = Exhaust Isentropic Temperature (^{o}C)
[61] v = Velocity (m/s)
[62] v_a = Specific Volume of air aspirated by the compressor(m^3/kg)
[63] WR = Work Ratio
[64] $\dot{W}_c$ = Compressor Work (KJ/Kg)
[65] $\dot{W}_{Net}$= Turbine Net Work (KJ/Kg)
[66] $\dot{W}_{SHAFT}$ = Shaft Work Transfer (KW or KJ/Kg)
[67] $\dot{W}_T$ = Turbine Work (KJ/Kg)
[68] Υ_a = Isentropic index of air
[69] Υ_g = Isentropic index of gas
[70] z = Distance (m)