RELATION BETWEEN EXHAUST TEMPERATURE AND POWER OUTPUT OF A TYPICAL POWER PLANT

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ABSTRACT

A study of the relation between the exhaust temperature and the Power output of the Akwa Ibom State Independent gas turbine Power Plant has been undertaken. The data for the study covers the period from December 2010 to June 2011. The objective was to determine the relationship between the exhaust temperature of a power plant and its power output. The investigation revealed that the greater the exhaust temperature, the greater the power output. The frame 9 turbine engine was used in generating the data in this study.

INTRODUCTION

Our industries such as in agriculture, transportation, oil and gas on their day to day need power supply to carry out their activities, hence the need for more power generation for their uses and increase in productivity. It is also true that home consumption of power is on the increase as the population increases, then the need for more independent power stations to be built to cater for this human population. This could be achieved from our vast natural gas and from the waste of such resources arising from gas flaring, of which Nigeria is said to have the highest amount of natural gas reserve and is being flared daily resulting in all economic loss of US $2.5 billion annually. This causes local pollution, environmental tragedy and an energy problem that can be solved (Mahmood and Mahdi, 2009; Mohanty and Palosa, 1995).

Gas flaring can be dealt with today through a variety of existing technologies at reasonable cost depending on the region power is generated and the gas injection to produce liquefied gas. This calls for more independent power plants to be built and using gas turbines to produce power. A turbine is basically a rotating device that uses a moving fluid such as water, wind and steam to produce a rotational force that can be applied to work, (Kamps, 2005; Essays, 2011).

The Gas Turbine

A gas turbine is a rotating device that uses a hot moving fluid to produce a rotational force that can be applied to work. It is a Power Plant that produces great amount of energy depending on its size and weight. The gas turbine is an internal combustion engine that uses air as the working fluid. It is also one of the cleanest means of generating electricity with the emission of oxides of nitrogen (NO_x) from some large turbines in the single digit of Part Per Million (PPM) with catalytic exhaust clean up because of their relatively high efficiency as reliance on natural gas as the primary fuel (Donald, 1991).

A gas turbine emits relatively less carbon dioxide than any other fossil technology. The engine extracts chemical energy from fuel and converts it to mechanical energy, using the gaseous energy of the working fluid (air) to drive the engine and propeller, which in turn propel the airplane (Charles *et al.,* 1991). The gas turbine power plant is basically divided into the compressor, combustion chamber and the generator (Whitaker, 2006; Wiser, 2000).

Gas Turbine Operating Principles

The classical gas turbine thermodynamic analysis permits the evaluation of the Georger Brayton's Cycle using such parameters as temperature, pressure and adiabatic compression. The operating principle and cycle of a gas turbine is basically developed from the Newton's law of motion and also from the Brayton's Cycle used in a single shaft combustion turbine application (General Electric, 2011).

Newton's laws of motion apply to the operation of the gas turbine and power generation, however, the third law of motion or reaction principle is fundamental to the output force that combustion turbines produce. In the combustion turbines the action of the hot combustion gases causes an equal and opposite reactions, the equal and opposite reactions in terms of thrust and the reaction is in terms of torque. The mechanical energy of a rotating shaft of the turbine is used in a land stationary application (General Electric, 2011).

Brayton's Cycle is the thermodynamic process in which all gas turbines operate. In Brayton's Cycle, the gases passing through an ideal gas turbine undergoes three thermodynamic processes, namely: Isentropic compression, Isobaric (constant pressure) combustion and Isentropic expansion. Isentropic expansion relates to increase in pressure and temperature of the gas, which Isentropic compression is on decrease in pressure and temperature. Isobaric combustion occurs at constant pressure (Fig. 1).

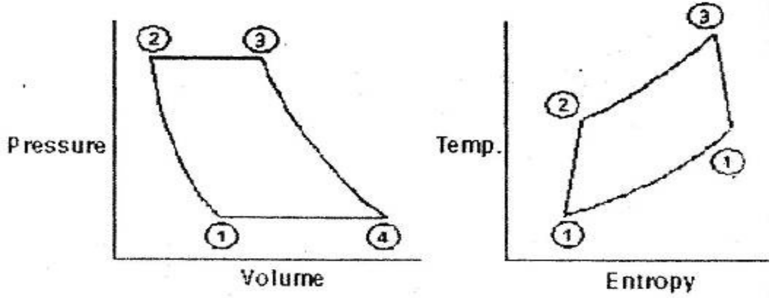

Fig. 1: The Brayton Cycle Showing Pressure Volume and Temperature diagram

Ambient Temperature

This is the temperature surrounding the environment. Ambient temperature could lead to a drop in net power output, and this is particularly relevant where temperature varies throughout the year (Boonasa *et al., 2006)*. The ambient temperature affects the power output by a great deal by changing air density and compression. Low ambient temperature will lead to high air density and low compression or work, which in turn gives a higher gas turbine power (Rahman *et al.,* 2010). The ambient conditions at which a gas turbine operates have a noticeable effect on the power output. At elevated inlet air temperature, the air mass flow decreases because the compressor requires more power to compress air at higher temperatures (Ameri *et al.,* 2007).

Turbine Firing Temperature

It is the highest temperature at which work is done. The temperature control system will limit fuel flow to the gas turbine to maintain internal operating temperatures within design limitations of turbines hot gas path parts. The highest temperature in the gas turbine occurs in the flame zone of the combustion chamber. The combustion gas in that zone is diluted by cooling air and flows into the turbine section through the first stage nozzle. The temperature of that gas as it exits the first stage nozzle is known as the "firing temperature" of the gas turbine. Firing temperature is a reference temperature not generally a temperature that exists in a gas turbine cycle; it is a calculated heat balance on the combustion system using certain parameters. The reference temperature will always be less than the firing temperature as defined by the General Electric energy. It is defined as mass-flow total temperature. The turbine firing temperature has a greater benefit in generating power output. Increases in firing temperature provide power increase output (Fig. 2).

Turbine Exhaust Temperature

After the gas has passed through the turbine, it is discharged through the exhaust. Though most of the gaseous energy are converted to mechanical energy by the turbine, a significant amount of power remains in the exhaust gas. This as energy is accelerated through the convergent duct shape of the exhaust to make it more useful. The exhaust temperature could also be a product of combustion expanded through the turbine which produces work and finally discharges to the atmosphere (Jonke and Mast, 2002). It is also called the turbine exit temperature. It influences the overall efficiency of the unit.

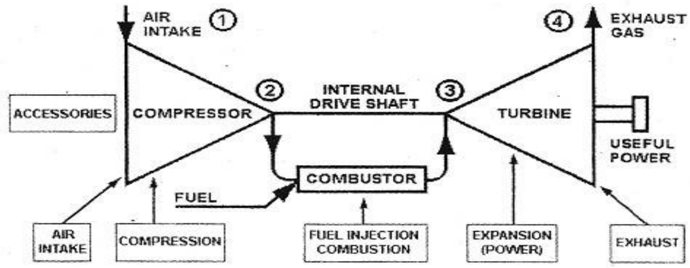

Fig. 2: A Simple Gas Turbine Cycle

After General Electric 2011

Thermodynamic Modeling of the Gas Turbine

Basically, the gas turbine power plant consists of four components including the compressor, Combustion Chamber (CC), turbine and generator. The fresh atmosphere air is drawn into the circuit continuously and energy is added by the combustion of the fuel in the working fluid itself. The products of combustion are expanded through the turbine which produces the work and finally discharges to the atmosphere.

The compressor compression ratio (r_p) can be defined as $R_p = \frac{P_2}{P_1}$

Where P_1 and P_2 are the compressor inlet and outlet pressure respectively.

The Isentropic efficiency for compressor and turbine in the range of 85 to 90% is expressed as

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

Where T_1 and T_2 are compressor inlet and outlet air temperatures respectively. T_{2s} is compressor isentropic outlet temperature.

The final temperature of the compressor is calculated from $T_2 = T_1 \left[1 + \frac{r_p \frac{\gamma_a - 1}{\gamma_a} - 1}{\eta_c}\right]$ (Rahman *et al.*, 2010)

Where $\gamma_a = 1.4$ is the molar heat capacity of air.

The work of the compressor (W_c) when blade cooling is not taken into account can be calculated from, $W_c = \frac{C_{pa} \times T_1 \left[r_p \frac{\gamma_a - 1}{\gamma_a} - 1\right]}{\eta_m \times \eta_c} = \frac{C_{pa} \times T_1 \times R_{pa}}{\eta_m}$

Where C_{pa} is the specific heat of air, η_m is the mechanical efficiency of the compressor and turbine.. The energy balance in the combustion chamber is given by $\dot{M} C_{pa} T_2 + \dot{m}f$ X LHV + $\dot{m}f$ $C_{pf} T_f = (\dot{m}a + \dot{m}f) C_{pa}$ X $T_I T$

Where, $\dot{m}f$ is fuel mass flow rate (Kg/s), $\dot{m}a$ is air mass flow rate (Kg/s), LHV is low heating value,

T_3 = TIT = Turbine Inlet Temperature, C_{pf} is specific heat of fuel and T_f, the temperature of fuel.

The fuel air ratio is therefore; $f = \frac{\dot{m}f}{\dot{m}a} = \frac{C_{pg}TIT - C_{pa}T_2}{LHV - C_{pg}\ X\ TIT}$

The exhaust gas temperature from the gas turbine is given by

$$T_4 = T_3\left[1 - \eta_t \times \left[1 - \frac{\frac{1}{r_g - 1}}{{r_p}^{r_g}}\right]\right] = T_3(1 - \eta_t \times R_{pg})$$

The shaft work (w_t) of the turbine is given by $W_t = C_{pg}$ X TIT X η_t X R_{pg} / η_m
The network of the gas turbine (w_{net}) is obtained from the equation $W_{net} = W_t - W_c$

The output power from the turbine (P) is expressed as P = $\dot{M}a \times W_{net}$

The specific fuel consumption (SPC) is determined by SPC = $\frac{3600f}{W_{net}}$

The heat supplied is also given by $Q_{add} = C_{pg}$ (TIT – T_1 (1+R_{pa})

The gas turbine efficiency (η_{th}) can therefore be obtained from $\eta_{th} = \frac{W_{net}}{Q_{add}}$ (Ibrahim *et al.,* 2010)
The Heat Rate (HR) is the consumed heat to generate unit energy of electricity, and is given as
HR = $\frac{3600}{\eta_{th}}$ (Savavanamuttoo *et al.,* 2009).

The Pearson Product Correlation Coefficient, r
The simple statistic that best describes the degree of relationship between two variables x and y is the product moment correlation coefficient; denoted by r.

The relation is given by r = $\frac{n\Sigma x\Sigma y - \Sigma xy}{\sqrt{[n(\Sigma x)^2 - \Sigma x^2(n(\Sigma y)^2 - \Sigma y^2)]}}$

Where x is the independent variable and y, the dependent variable.

The Correlation Coefficient ranges from -1 to +1. A value of +1 implies that a linear equation describes the relationship between x and y perfectly; with all data points lying on a line for which y increase as x increases. A value of -1 implies that all data point lie on a line for which y decreases as x increases. A value of 0 implies that there is no linear correlation between the variables (Pearson, 2011).

METHODOLOGY

The data for this study was obtained from the Ibom Power Company Limited (IPC). The data covered a period of seven months, from December 2010 to June 2011. Since the study is on the relation between the exhaust temperature and power output, the exhaust temperature (in ^{o}F), power output (in Megawatt) and the time of the day were extracted for analysis. Tables 1 - 6 gives some of the data and corresponding plots are shown in Figs. 3 - 8.

RESULTS

Tables 1 to 6 shows the value of the exhaust temperature and the power output of the gas turbine in the Ibom Power Plant for selected days from 1st December, 2010 to 30th June 2011. Also displayed are the corresponding plots of exhaust temperatures (^{0}F) against the power output (Mw), Figs. 3-8, for the period under study.

The general trend of the relation between the exhaust temperature and the power output, arising from the plots, is that, as the exhaust temperature increases, the power output increases.

Correlation of Results

Apart from the random plots of the relationship between the exhaust temperature and power output, obtained in this study, the correlation study was further undertaken to evaluate the degree of relation between the parameters statistically. The Pearson Product moment correlation coefficient, r, earlier presented was used for this analysis.

In this study, x is the independent variable, corresponding to the exhaust temperature, whereas y is the dependent variable corresponding to the power output of the gas turbine.

Tables 7 and 8 show examples of the Pearson's Correlation calculations for the variables x and y.

The general value of r obtained in this study is of the average, r = 0.93, giving a very strong positive correlation between output, that is as the exhaust temperature increases, the power output of the gas turbine also increase. There were also a few weak positive correlation of 0.3 to 0.4 and very strong negatively related values of -0.8 to -1.0.

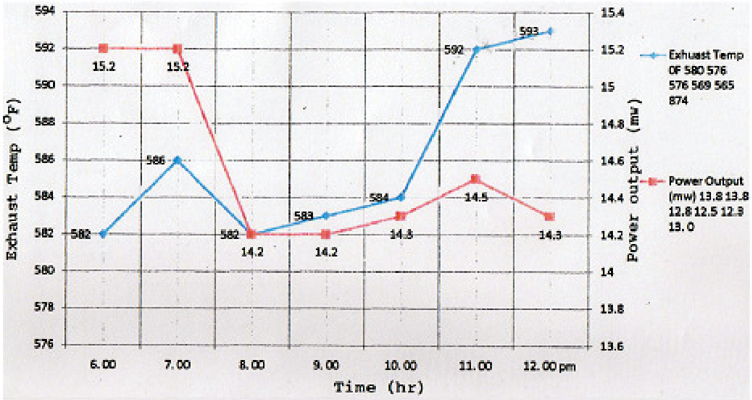

Fig. 3 Variation of Exhaust Temperature (F) against Power Output (MW)

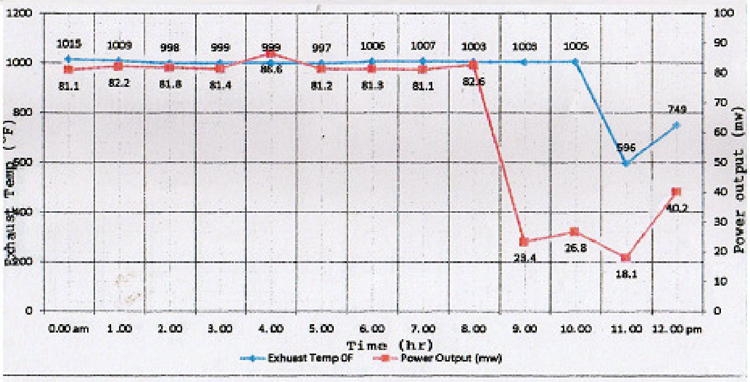

Fig. 4 Variation of Exhaust Temperature (F) against Power Output (MW)

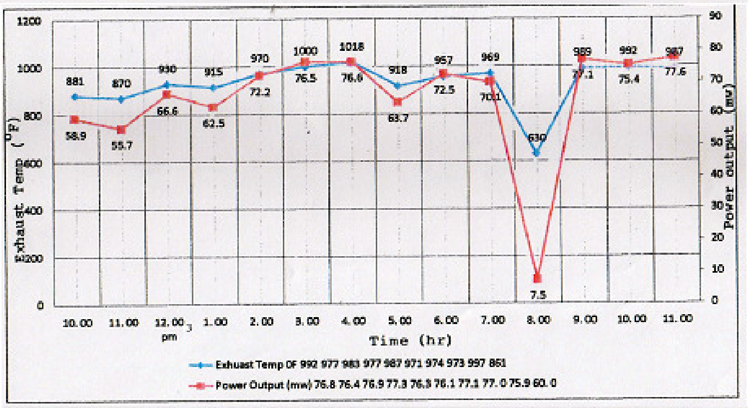

Fig. 5 Variation of Exhaust Temperature (°F) against Power Output (MW)

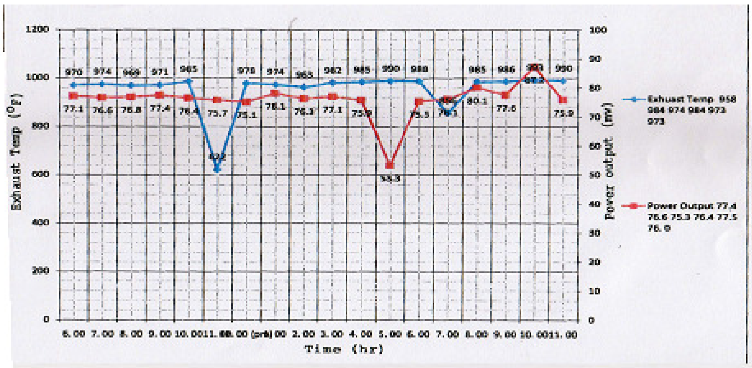

Fig. 6 Variation of Exhaust Temperature (°F) against Power Output (MW)

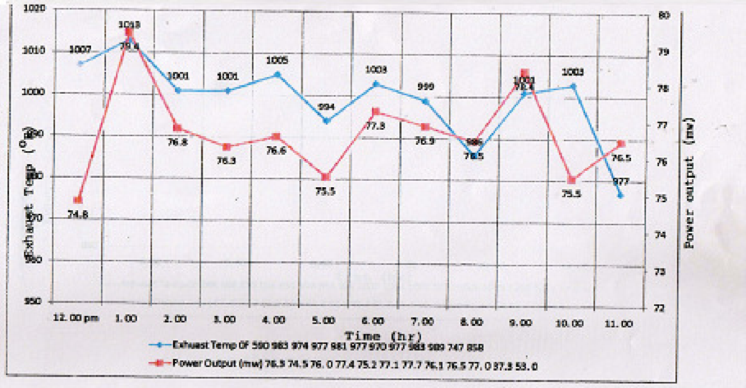

Fig. 6 Variation of Exhaust Temperature (°F) against Power Output (MW)

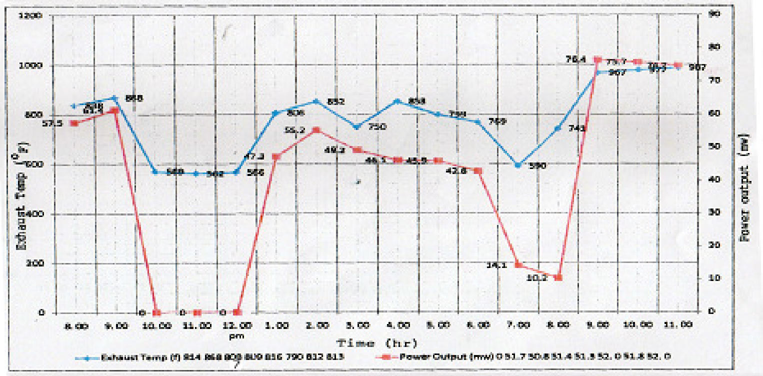

Fig. 8 Variation of Exhaust Temperature (F) against Power Output (MW)

5/12/2010

S/N	TIME (Hr)	ExH TEMP(X)	POWER OUTPUT (MW) (Y)
1	6	1038	81.3
2	7	1033	81.2
3	8	1033	81.4
4	9	1028	80.6
5	10	1032	80.5

Table 1: The value of the exhaust temperature and the power output of a gas turbine in Ibom Power Plant

16/02/2011

S/N	TIME (Hr)	ExH TEMP (X)	POWER OUTPUT (MW) (Y)
1	6	970	77.1
2	7	973	76.6
3	8	969	76.8
4	9	971	77.4
5	10	985	76.4
6	11	622	75.7
7	12	978	75.1
8	1	974	78.5
9	2	963	76.3
10	3	982	77.1
11	4	985	75.9
12	5	990	53.3
13	6	988	75.5
14	7	806	76.1
15	8	985	80.1
16	9	986	77.6
17	10	988	908
18	11	990	75.9

Table 4: The value of the exhaust temperature and the power output of a gas turbine in Ibom Power Plant

6/1/2011

S/N	TIME (Hr)	ExH TEMP (X)	POWER OUTPUT (MW) (Y)
1	0	1103	76.5
2	1	1095	76.6
3	2	1101	77.3
4	3	1093	76.7
5	4	1097	77.5
6	5	1101	76.9
7	6	1105	76.9
8	7	1094	76.2
9	8	1106	77.3
10	9	1094	76.9
11	10	1096	76.9
12	11	1094	76.6
13	12	1097	76.8

Table 2: The value of the exhaust temperature and the power output of a gas turbine in Ibom Power Plant

23/03/2011

S/N	TIME (Hr)	ExH TEMP (X)	POWER OUTPUT (MW) (Y)
1	3	992	75.5
2	4	21022	66.2
3	5	1011	75.1
4	6	981	78.9
5	7	958	77.9
6	8	971	82.6
7	9	971	78.4
8	10	967	76.2
9	11	983	75.2

Table 5: The value of the exhaust temperature and the power output of a gas turbine in Ibom Power Plant

11/1/2011

S/N	TIME (Hr)	ExH TEMP (X)	POWER OUTPUT (MW) (Y)
1	6	1021	62.8
2	7	1004	63.9
3	8	976	51.2
4	9	931	51.1
5	10	933	52.3
6	11	928	51.5

Table 3: The value of the exhaust temperature and the power outpt of a gas turbine in Ibom Power Plant

27/06/2011

S/N	TIME (Hr)	ExH TEMP (X)	POWER OUTPUT (MW) (Y)
1	0	1083	70.7
2	1	1080	71.4
3	2	1075	72.7
4	3	1086	71.5
5	4	1018	62.2
6	5	1007	61.4
7	6	1004	60.3
8	7	1008	60.6
9	8	1011	61.4
10	9	1005	61.5
11	10	1015	61.8
12	11	1041	63.3
13	12	1045	69.3
14	13	1080	70.2
15	14	1064	70.9
16	15	0	0
17	16	960	70.5
18	17	976	55.4

Table 6: The value of the exhaust temperature and the power output of a gas turbine in Ibom Power Plant

DISCUSSION

The study was on the relation between the exhaust temperature and the power output of the Ibom Power Plant in Akwa Ibom State, South-South Nigeria. The plots earlier presented in this study show the dependence of the power output in the plant on its exhaust temperature i.e. as the exhaust temperature in the power plant increases, the power output also increases. To further justify this finding, the Pearson Product moment Correlation Coefficient was used. The correlation study confirms the current result. Though a few weakly related values of r were recorded (namely, $r = 0.3$ to 0.4 and $r = -0.8$ to -1.0), the general occurrence of $r = 0.9$ and above support the current finding for the Akwa Ibom independent Power Plant. That is, the few non-correlated values could be attributed to the wear and tear of the turbine arising from long hour of usage without maintenance.

Table 7**:** Correlation between exhaust temperature and power output

7/4/2011

S/N	TIME (Hr)	ExH TEMP(X)	POWER OUTPUT (MW) (Y)	XY	X^2	Y^2
1	10	881	58.9	51890.9	776161	3469.21
2	11	870	55	47850	756900	3025
3	12	930	66.6	61938	864900	4435.56
4	1	915	62.5	57187.5	837225	3906.25
5	2	970	72.2	70034	940900	5212.84
6	3	1000	76.5	76500	1000000	5852.25
7	4	1018	76.6	77978.8	1036324	5867.56
8	5	918	63.7	58476.6	842724	4057.69
9	6	957	72.5	69382.5	915849	5256.25
10	7	969	70.1	67926.9	938961	4914.01
11	8	630	75	47250	396900	5625
12	9	989	77.1	76251.9	978121	5944.41
13	10	992	75.4	74796.8	984064	5685.16
14	11	987	77.6	76591.2	974169	6021.76

Correlation = 0.993069808

Table 8: Correlation between exhaust temperature and power output

27/06/2011

S/N	TIME (Hr)	ExH TEMP(X)	POWER OUTPUT (MW) (Y)	XY	$X\wedge^2$	$Y\wedge^2$
1	0	1083	70.7	76568.1	1172889	4998.49
2	1	1080	71.4	77112	1166400	5097.96
3	2	1075	72.7	78152.5	1155625	5285.29
4	3	1086	71.5	77649	1179396	5112.25
5	4	1018	62.2	63319.6	1036324	3868.84
6	5	1007	61.4	61829.8	1014049	3769.96
7	6	1004	60.3	60541.2	1008016	3636.09
8	7	1008	60.6	61084.8	1016064	3672.36
9	8	1011	61.4	62075.4	1022121	3769.96
10	9	1005	61.5	61807.5	1010025	3782.25
11	10	1015	61.8	62727	1030225	3819.24
12	11	1041	63.3	65895.3	1083681	4006.89
13	12	1045	69.3	72418.5	1092025	4802.49
14	13	1080	70.2	75816	1166400	4928.04
15	14	1064	70.9	75437.6	1132096	5026.81
16	15	0	0	0	0	0
17	16	960	70.5	67680	921600	4970.25
18	17	976	55.4	54070.4	952576	3069.16
Total		17558	1115.1	1154185	18159512	73616.33
Correlation =		0.9711674				

CONCLUSION

The study on the relation between the Ibom Independent Power Plant, has been carried out. The results reveal the dependence of the power output on the exhaust temperature of such a plant.

The indication is that if the power plant is given adequate maintenance, it will operate at its optimum capacity, hence making distribution adequate. A strong correlation coefficient of r = 9.0 and above can be maintained.

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