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Evaluation of operating characteristics of a HFO fired Diesel Engine Power Plant in Bangladesh

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Abstract: *This study aims at investigating the performance of a 50 MW capacity Diesel engine power plant run mostly byHFO (heavy fuel oil). The plant consists of six identical Diesel engines of 20 cylinders in each, arranged in V-shape. The variations in capacity factor, plant availability, plant reliability, BSFC (Break Specific Fuel Consumption), Generator efficiency have been analysed in different periods of a year. During January to March, BSFC has a minimum value of 217.72 g/kWh& it reaches at the peak (221.92 g/kWh) between July & September. During April to June, both plant availability (96.67%) & capacity factor (25.64%) have their highest magnitudes. Generator efficiency value fluctuates between a narrow limit of 40.88 to 42.94%. From exergy analyses, the highest exergy efficiency is found at compressor & lowest at boiler. Ensuring effective heat transfer between the fluids of heat exchanger, efficiency can be increased at a great extent.*
Keywords:*Availability,BSFC,Capacity factor, Exergy, Generator efficiency, Reliability, Turbocharger Nomenclature*

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I. Introduction

In todays' world, where fuel price is increasing as a consequence of spiraling demand & diminishing supply, everyone needs to choose a cost-effective fuel to meet their needs. The invention of Rudolph Diesel, the Diesel engine has proved to be extremely efficient & cost effective [1]. Also, because of less space requirement, quick starting capability and higher thermal efficiency than coal, the demand for Diesel engine power plant are increasing day by day [2]. Like many other countries, Bangladesh, having scarcity of coal & gas, also focuses generating power using Diesel engine, which provides 31.13% of total installed capacity of the country (5287 MW among 16982 MW) [3]. So, it plays a vital role in the power sector of Bangladesh.

Among the operating characteristics of an internal combustion engine power plant - power, fuel consumption, generator efficiency, exergy efficiency is evaluated here. Although, exergy analysis can be generally applied to energy & other systems, it appears to be a more powerful tool than energy analysis for power cycles because it helps to determine the true magnitude of losses and their causes & locations and improve the overall system & its components [4]. Many researchers have done their studies on diesel engine power plant to observe its various parameters' performance. Kanogˇlu, Isık, Abusoglu [5] have investigated the energy &exergy efficiency with emission values. They have shown that pollutant emissions from the engine can be greatly reduced by effective treatment system. They also showed that the engine irreversibilities are due mostly to the irreversible combustion process and account for 32% of the total exergy input and 57% of the total irreversibilities in the plant. Bourhis& Leduc [6] have done their experiments to evaluate the difference between the energy and exergy balances when heat recovery is considered in an internal combustion engine. In the first case, the entropy of the system is not taken into account so that, the maximum useful work recoverable from a system cannot beestimated. Then, the second case is much more adapted to estimate heat recovery potential. El-Awad [7] has analysed Combined Diesel-Brayton (CDB) cycle, which enables small-scale power generation & industrial cogeneration systems to attain high thermal efficiencies, while the fuel flexibilities of Diesel engine & gas turbine enable them to use heavy Diesel fuel, natural gas or renewable bio-fuel.

The goals of this research work are as follows:

(a) To scrutinize the performance of a diesel engine power plant with some parameters used before with some new parameters in various season from the monthly data.
(b) To find the impact of varying engine load with the speed of turbocharger and engine speed.
(c) To perform exergy analyses of the plant components.
(d) To examine the 'health' of the power plant and get an overview about the operational characteristics of such

power plant based on the data obtained from the inspections.

II. Power plant operation

(i) Description

The power plant is located 50-55 kms. away from Dhaka, the capital city of Bangladesh.It started to produce electricity in 2010 with a total power capacity of 52.084 MW, while it was intended that an average of 50 MW were to be produced. The plant has a total area of 20234.3 m^2. The annual electrical energy production is nearly76737 MWh, and the annual fuel consumption is about 16445 metric tons at designed operating conditions (based on the data from July-2015 to June-2016) [8].

The power house consists of six engine-generator sets or gensets, each of them generates maximum load of 8.4 MW (rated

power). The engines are dual fuel, four stroke, turbocharged, compression ignitionengine with 20 cylinders in V configuration. Furnace oil (Heavy Fuel Oil or HFO) & High Speed Diesel (Light Fuel oil or LFO) are used as Fuel. Usually, the plant is run by HFO, main components of which are alkanes, cycloalkanes and different carbon hydrides [9]. The boiling range is between 300°C and ~700°C. Due to its semi-fluid consistence, HFO has to be pre-heated to make it combustible in engines. Auxiliary Boiler is used to pre-heat this fuel which is not essential for LFO.

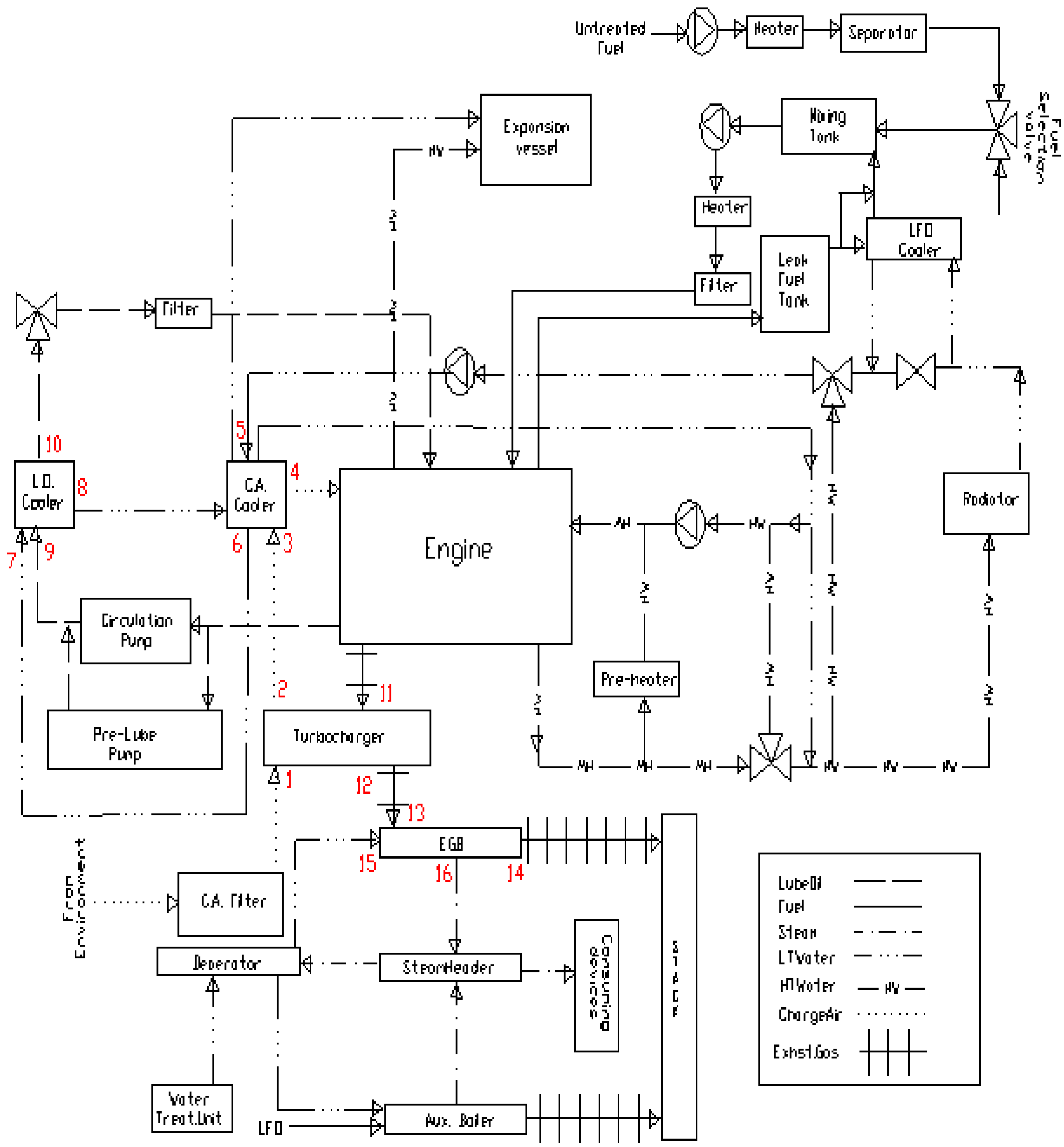


Fig. 2.1: Schematic of the power plant

(ii) Typical Properties of Furnace oil[10] **(iii) Properties of Lube oil**

Gross calorific value, kcal/ kg
10350
Viscosity class
SAE 40
Net calorific value, kcal/ kg 9600 Viscosity Index ≥ 95
Specific Gravity at 15° C 0.96 amount of lube oil needed to 0.4 g – 0.5 g
Flash point , °C 66 generate 1 kW electricity
Kinematic viscosity, cst at 50° C 125-180
Pour point, °C + 27

There are four power transformers (including one stand-by) of rating 11/132 kV & two auxiliary transformers (0.4/11 kV). Black start Diesel generator is used to supply own power in case of emergency. Fuel is unloaded by pump from cargo marine vehicle to the storage tank.Fuel separator unit contains centrifugal separator, which cleans the fuel by removing water & solid particles. Fuel is supplied to the engine by feeder unit through booster unit, where fuel temperature & pressure is 'boosted' up.

There are also lube oil separator to purify lube oil. Pre-lubrication pump has a pressure range of about 0.8 bar to 1.2 bar. Anti-Condensate heater is used to warm 'Generator' to make it free from moisture. Mixing tank, shown in the figure 2.1, removes air-lock to ensure proper injection of fuel. A large amount of heat is lost through the exhaust gas. Fraction of this heat is utilised by exhaust gas boiler (EGB). Here, the exhaust gas is used to heat up water. The steam produced from EGB & auxiliary boiler is used to preheat the fuel, lube oil, cooling water & feed water before entering the boiler. The cooling circuit is 'closed'. High Temperature (HT) water is used to cool cylinder, cylinder head etc. Low Temperature (LT) water is used for charge air cooler, lube oil cooler etc. More soot & sludge form in lower load than the higher. At lower load, Sulphur, contained in the fuel (HFO) produces SO_2, SO_3 which in terms reacting with H_2O, produce H_2SO_4 which is very harmful. So, in normal condition, engines run at a load of 7 MW or more.

HT water is pre-heated to 60 ^{0}C before circulation, to avoid thermal shock. Also, lube oil temperature is kept to 40 ^{0}C before entering the engine. Water, used in the plant, is treated by adding chemical at water treatment unit. The plant is used as 'Peak load plant'. It is normally operated at an average of 4.5 hours per day. During the first half of the month of Ramadan, demand grows much and even 9-10 hours is common. It gets 'rest' in the winter (December to February); when only 1-2 hours operation is enough to fulfil the demand required.

With the varying engine loads, the resulting effect of turbocharger speed is one of our concerns. In this plant, single pipe exhaust turbochargers are used which has speed between 25,000 & 27,000 rpm. There are 2 turbochargers for the V- engines, 1 for each bank. In every turbocharger, there are a single stage radial flow turbine & a centrifugal air compressor. In dirty turbine, exhaust gas temperature increases & higher stress developed due to imbalance. To maintain the turbocharger in good operating conditions & prevent the unexpected occurrence, 'Turbowash' is done at a certain interval, which is a cost effective & efficient process.

Table 2.1: Exergy & other properties of flow streams (state no.s refer to fig. 2.1)

State no.	Fluid	Phase	Temp. (^{0}C)	Exergy change (kJ)	Component
1	Air	Gas	28.4	73.8143	Compressor of TC
2	Air	Gas	60.2		
3	Air	Gas	150	18.0966	Charge air cooler
4	Air	Gas	62		
5	Water	Liquid	49	9.5158	
6	Water	Liquid	78		
7	Water	Liquid	49	2.9612	Lube oil cooler
8	Water	Liquid	62		
9	Lube oil	Liquid	83	4.5801	
10	Lube oil	Liquid	64		
11	Exhaust	Gas	570	209.1107	Turbine of TC
12	Exhaust	Gas	394		
13	Exhaust	Gas	394	224.0908	Boiler
14	Exhaust	Gas	200		
15	Water	Liquid	65	22.6888	
16	Steam	Sat. vapour	100		

(ii) Typical Properties of Furnace oil[10]

Gross calorific value, kcal/ kg	10350
Net calorific value, kcal/ kg	9600
Specific Gravity at 15° C	0.96
Flash point , °C	66
Kinematic viscosity, cst at 50° C	125-180
Pour point, °C	+ 27

(iii) Properties of Lube oil

Viscosity class	SAE 40
Viscosity Index	≥ 95
amount of lube oil needed to generate 1 kW electricity	0.4 g – 0.5 g

(iv) Engine & Generator Specification

Cylinder bore	320 mm
Stroke	400 mm
Piston displacement per cylinder	32.17 litre
Compression ratio	16:1
No. of cylinder per engine	20
Cylinder arrangement	V-type
Firing order	1-4-3-2-6-10-7-8-9-5 (with Resonator) 1-7-3-9-5-10-4-8-2-6 (without Resonator)
Direction of rotation	clockwise
Nominal Speed	750 rpm
Piston speed	10 ms^{-1}
Exhaust gas temperature (avg.)	550 ^0C
Frequency	50 Hz
Electrical power	8924 kW(maximum)
No. of pole in Generator	8
Power Output Per Displacement (OPD)	13.0556 kW/L
Capacity of cooling water circuit	HT water: 940 L LT water: 310 L

III. Energy&Exergy Analysis

(i) Energy Analysis

Several parameters, used for energy analysis are defined as follows:

- **Brake specific fuel consumption (BSFC)** is a measure of fuel efficiency within a shaft reciprocating engine. [11].

$$\mathrm{BSFC} = \frac{\mathrm{m}}{\mathrm{P}} \qquad (3a)$$

Where, m = fuel consumption rate,P = power produced.

- **Availability factor** of a power plant is the amount of time that it is able to produce electricity over a certain period, divided by the amount of the time in the period [12].

$$\text{Plant availability} = \frac{\text{Total no. of hrs.} - (\text{ Planned hrs.} + \text{Forced hrs.})}{\text{Total no. of hrs.}} \qquad (3b)$$

Forced outages arethe shutdown condition of a power station, transmission line or distribution line when the generating unit is unavailable to produce power due to unexpected breakdown caused by equipment failures, disruption in the power plant fuel supply chain, operator error etc. [13]. While, planned outages are interruptions prearranged on relatively short notice [14].

- **Reliability factor** is a similar term of availability factor. In this case, planned outages are excluded from the consideration. Mathematically,

$$\text{Plant reliability} = \frac{\text{Total no. of hrs.} - \text{ Forced hrs.}}{\text{Total no. of hrs.}} \qquad (3c)$$

- **Capacity factor** of a power plant is defined as the ratio of actual energy production to the maximum possible energy that might have been produced during the same period [15].

$$\text{Capacity factor} = \frac{\text{Net Energy Generation}}{\text{Capacity of the plant x Total no.of hrs.}} \qquad (3d)$$

- **Generator efficiency** is determined by the power of the load circuit and the total watts produced by the generator [16].The losses that are incurred typically arise from the transformer, the copper windings, magnetizing losses in the core and the rotational friction of the generator**.** It is calculated by following formula.

$$\text{Generator efficiency} = \frac{\text{Net Energy Generation}}{\text{Input energy of fuel}} \qquad (3e)$$

(ii) Exergy Analysis

Exergy, may be defined as the useful work potential of a system at some specified state [17]. It is simply the maximum useful work that can be obtained from the system. Like energy, exergy can be transferred to or from a system in three forms: heat, work & mass flow. The equations are as follows:
Exergy transfer by heat:

$$X_{heat} = \left(1 - \frac{To}{T}\right) \qquad (3f)$$

Exergy transfer by mass: $X_{mass} = m\psi$ (3g)
Exergy transfer by work: $X_{work} = W$ (3h)

The specific flow exergy, ψ is given by [5]-

$$\psi = (h - h_0) - T_0(s - s_0) \qquad (3i)$$

Change in Specific Exergy,

$$\Delta\Psi = (h_2 - h_1) - T_0(s_2 - s_1) \qquad (3j)$$

Wherethesubscript0 stands for the restricted dead state. A system that is in equilibrium with its environment (same temperature & pressure) is said to be at the dead state. At this state, the useful work potential (exergy) of a system is zero [17]. For calculation, we consider 27.1^0 C& 101.325 kPa as T_0 & P_0 (environment temperature & pressure respectively of the specified day). The system is considered as 'Closed' one& K.E., P.E. are negligible.
The second law (exergy) efficiency of a turbine can be defined as a measure of how well the stream availability of the fluid is converted into shaft work output [5] -

$$\eta_{T,II} = \text{Wactual} / \text{Wrev} \qquad (3k)$$

where, W_{rev}(reversible work) = W_{actual}(actual shaft-work) + I (Irreversibility)

and $W_{actual} = \frac{kR\ (T_1 - T_2)}{k-1}$ (3l)

Where, k = ratio of specific heats
The maximum work we can get out of a given set of flows & heat transfers or, alternatively, the minimum work we have to put into the device is called reversible work [18].

The exergy efficiency of the compressor is defined similarly as-

$$\eta_{C,II} = \text{Wrev} / \text{Wactual} \qquad (3m)$$

where, $W_{rev} = W_{actual} - I$

Again, $W_{actual} = \frac{mR\ (T_1 - T_2)}{n-1}$ (3n)

for compression process, the index of compression 'n' is given by [19] -

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{[(n-1)/n]}$$

Or, $\frac{(n-1)}{n} = \frac{\ln\ (T_2/T_1)}{\ln(p_2/p_1)}$ (3o)

The exergy efficiency of the heat exchangers in the power plant is measured by the increase in the exergy of the cold stream divided by the decrease in the exergy of the hot stream [5] –

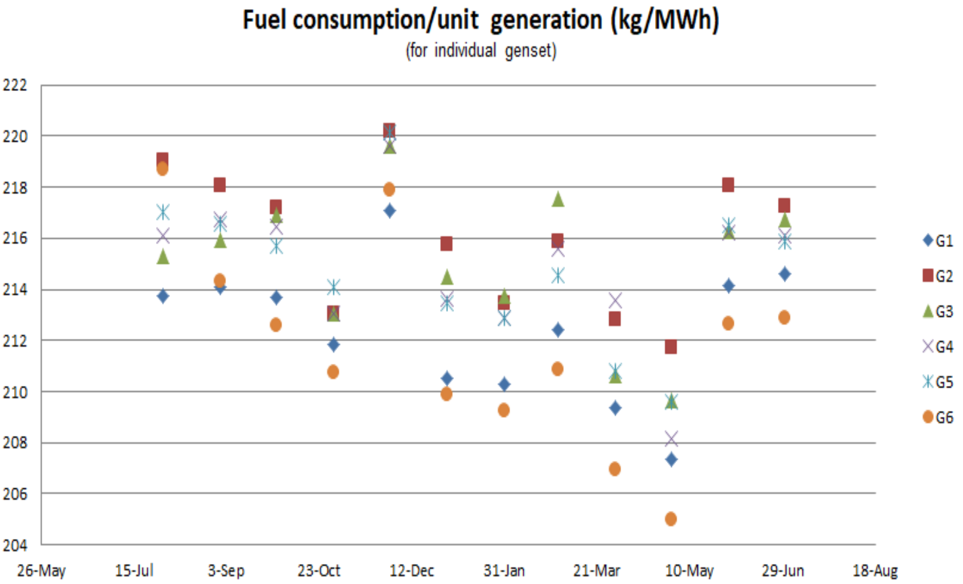
$$\eta_{HE,II} = \frac{\dot{m}_c\ (\psi e - \psi i)c}{\dot{m}_h\ (\psi i - \psi e)h} \qquad (3p)$$

where, $\dot{m}_c$&$\dot{m}_h$ are the mass flow rates of the cold & hot streams respectively.

IV. Results& Discussion

4.1 Energy Analysis

The performance of a Diesel engine power plant is evaluated based on the data & graphs of last 1 year by using various parameters. From the observation (fig. 4.1.1), it is found that the amount of fuel consumption per unit generation increases during October to January during winter, Demand becomes less & plant runs only few hours. This is because of the fact that at the beginning when engine runs, the fuel consumption rate is high. After a certain period, the rate becomes almost steady. So, when plant runs for longer period, the average fuel consumption gets decrease.



Generator efficiency has less effect of season; the values are pretty close during every one month interval. In spite of that it has the highest value (42.9383%) in April and lowest (40.8784%) in November (Table 1.1.3 in appendix), that is also for the similar reason of the variation of fuel consumption rate. Plant availability (96.67%) & capacity factor (25.64%) have maximum values during April to June (Table 1.1.4 in Appendix). Availability shows, how much the plant is available for use. Higher availability means the plant is 'ready to use' for more times. Capacity factor represents the amount of energy generation during certain period. The more is the capacity factor, the more is the generation in that period. So, from April to June, plant remains more available to use & generates more electricity than any other periods of the year. Plant reliability is higher during the months of January to March (99.53%).

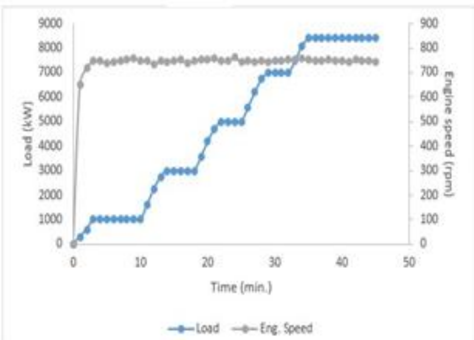


Fig. 4.1.2: Relation between load & enginespeed

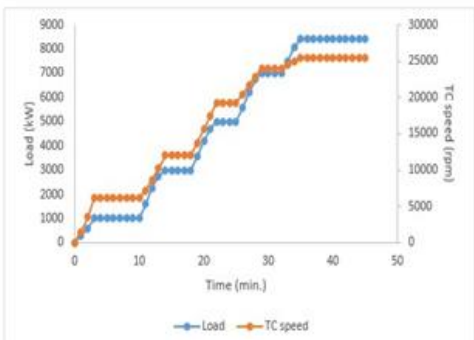


Fig. 4.1.3: Relation between load& turbocharger speed

From Fig. 4.1.2 & 4.1.3, it is clear that engine speed has no dependency on load (electric power). It remains almost constant after reaching a constant value instantly. However, the speed of turbocharger varies with load proportionally.

Based on the air standard Diesel cycle analysis, Mean Effective Pressure (MEP), Indicated power, Indicated thermal efficiency obtained are 20.8891 bar, 16800.058 kW & 84.1037 % respectively (see appendix 1.1). Peak pressure (obtained from the instrument) of the engine is 160 bar (avg.) which is ideally 195 bar.

Thermal efficiency obtained from the formula (theoretical) is 63.33 % (with a cut-off ratio = 1.62, obtained from calculation).

The magnitude of BSFC changes for different engine design, compression ratio & power rating. Engine of different classes have different BSFC value ranging from less than 200 g/kWh (Diesel at low speed & high torque) to 1000 g/kWh (turboprop at low power level) [20]. For a turbocharged Diesel car engine, this minimum value of BSFC is 205 g/kWh.

4.2 Exergy Analysis

Exergy analyses are done for different plant components. In the compressor of TC, exergy efficiency is the highest. Most of the exergy destructed are found in boiler (η_{II} = 13.49%). Kanogˇlu, Isık&Abusoglu [5], found the value of second law efficiency of boiler as 18.5%. The reason of less exergy efficiency in the boiler is that, exergy change or exergy destruction is proportional to temperature difference. The more is the temperature difference between two working fluids or between two states (initial & final), more is the amount of exergy change or destruction occurs (see appendix 1.2).

Table 4.2.1: values obtained from exergy analysis:

Component	Exergy change (kJ)	Exergy destruction (kJ)	Exergy Efficiency (%)
Compressor of TC	73.8143	2.9443	96.16
Turbine of TC	209.1107	32.3187	84.54
Lube Oil Cooler	4.5801	1.6189	40.69
Boiler (E.G.B.)	224.0908	201.3908	13.49
Charge Air Cooler (Intercooler)	18.0966	8.5808	38.36

4.3 Regression Analysis Results

Regression analysis helps one understand how the typical value of thedependent variable (or 'criterion variable') changes when any one of the independent variables is varied, while the other independent variables are held fixed [21]. For higher value of R^2, the variables become predictable.

From fig. 4.3.1 & 4.3.2, both plant availability and plant reliability show scattered appearance during the period of 1 year. By plotting the curve of 6th order, the R^2values are obtained which are quite low and the prediction become tough.On the other hand, the capacity factor curve (fig. 4.3.3) shows more uniform trend than those above. R^2 is equal to 0.9571 which means almost 95.71% variations are explained by the definite month. Apart from regression analysis, the availability & reliability are also near to each other (fig. 4.3.4). Even in July, December of 2015 & in January, June of 2016, the values are coincided. This is because of no or negligible planned outage hours in these months.

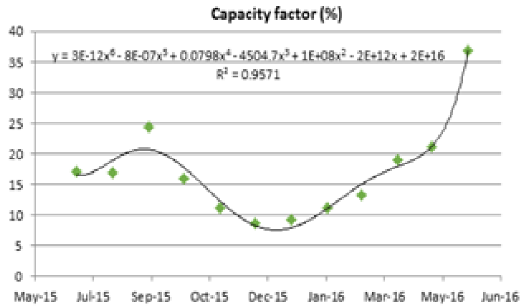


Fig. 4.3.3.: Plot of Capacity factor in different months

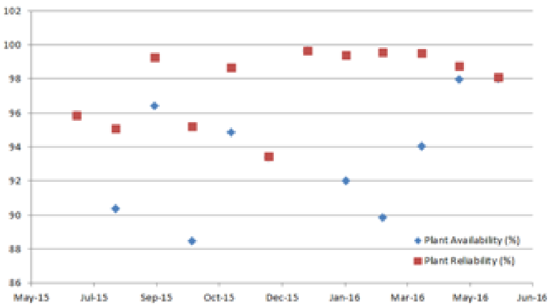


Fig. 4.3.4.: Comparison of plant availability & reliability

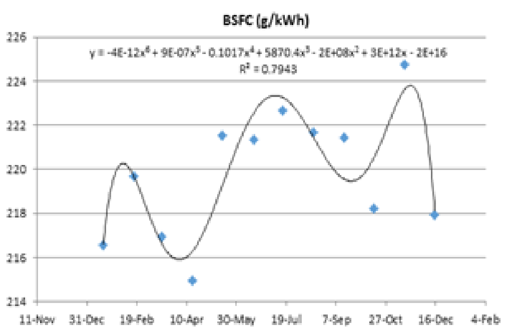


Fig. 4.3.5.: Plot of BSFC in different months

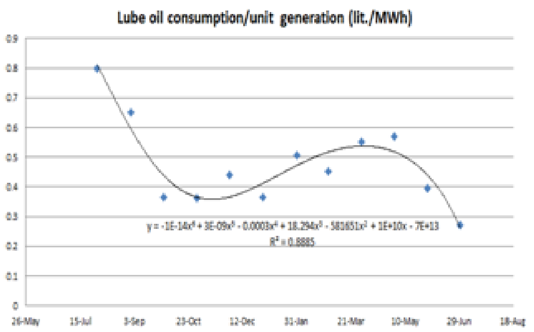


Fig. 4.3.6.: Plot of lube oil consumption rate in different months

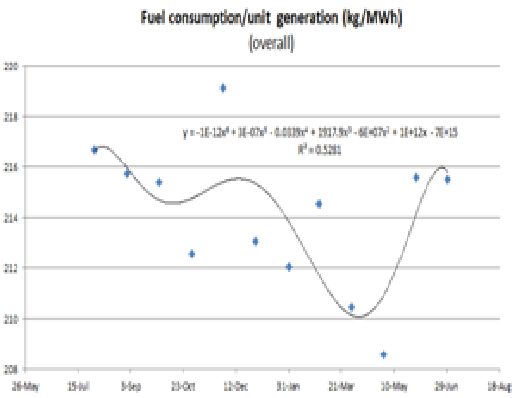


Fig. 4.3.7.: Plot of fuel consumption rate in different months

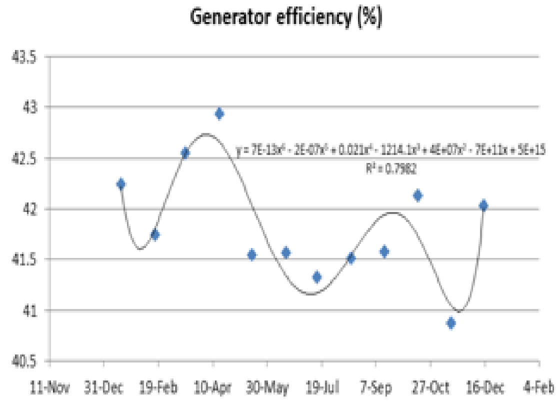


Fig. 4.3.8.: Plot of generator efficiency in different months

In case of Brake Specific Fuel Consumption (BSFC) seen from fig. 4.3.5, this value is well enough (0.7943). It shows upward & downward flow, repeats through the year. Also, the graph of lubricant consumption in every MWh electricity generation (fig. 4.3.6) depicts a great R^2 value (0.8885).Values decrease gradually, then increases slowly. The pattern follows a smooth curve. However, there are lots of sharp changes in the graph of fuel consumption per unit generation (fig. 4.3.7). This becomes too unpredictable having an R^2 value of 0.5281. On the other hand, curve of Generator efficiency has completely opposite trend of BSFC graph with a close R^2 value of it (0.7982) shown in fig. 4.3.8.

V. Closing Remarks

Various parameters related to energy &exergy are analysed and the verification of their effect on the power plant are presented here. Engine load is a key factor that controls turbocharger speed. A turbocharged engine can't take 100% load instantly, because of the air deficiency before reaching steady state of turbocharger. There are plenty of areas where improvements of 'Quantity' (energy) & 'Quality' (exergy) can be made. In this plant, there are six engines but three exhaust boiler. The thermal energy of the exhaust gas of those three engines, contains no E.G.B., can be utilised by setting boiler before the exhaust leaving through the stack. Thermal efficiency also can be improved by heating & pressurize the fuel close to ideal temperature & pressure. It can be ensured by the effective use of thebooster unit. Plant availability and reliability has a higher value of more than 88.4% in every month, which indicates that the outage hours are few and did not interrupt that much in power supply. Generator efficiency varies within a short range of 40.88 to 42.94%. Boiler is the main source of exergy destruction. 201.4 kJ exergy is diminished here. Whether, only 2.9 kJ exergy destruction happens in the turbocharger compressor. Considering efficiency and consumption of fuel & lube oil, it is found that the plant runs well from January to March (Table 1.1.3; fig.4.3.6 to 4.3.8) when the weather converts from winter to summer.Nothing can be said firmly for the rest of the months.In regression analysis, narrower prediction intervals always indicate more precise predictions. The values were taken in every single month. It would give more precise result if the data of every week could be taken. Decision can be taken more accurately if study of 4-5 years were considered. As Diesel engine power plant provides a huge amount of electricity throughout the country, this study may assist future researchers to examine any other characteristics of this type of plant, yet to investigate.

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Appendix 1.1 (Energy Analysis)

Table 1.1.1

Total fuel consumption (kg)						
Month	G1	G2	G3	G4	G5	G6
Jul-15	265839	223992	162314	236818	228355	294207
Aug-15	251705	142207	242341	254466	232561	268197
Sep-15	363524	311065	280532	345064	362215	279606
Oct-15	255658	260241	160371	138476	236746	240034
Nov-15	129218	145364	148785	161198	146981	166001
Dec-15	120833	112224	124896	115544	138096	87144
Jan-16	122393	120464	115627	124592	137456	130810
Feb-16	150823	153838	139572	164255	124877	119032
Mar-16	189995	198511	135050	146099	182022	214437
Apr-16	168064	267293	259847	268618	233368	269213
May-16	289811	268919	290164	294522	301387	299392
Jun-16	502382	468575	420436	479376	530179	530927

Table 1.1.2

Generation (MWh)						
Month	G1	G2	G3	G4	G5	G6
Jul-15	1243.6	1022.5	754	1095.9	1052.2	1345.2
Aug-15	1175.7	652.2	1122.2	1174.2	1073.9	1251.5
Sep-15	1701.3	1432.1	1293.3	1594.2	1679.4	1315.2
Oct-15	1206.7	1221.6	752.7	649.9	1105.8	1139
Nov-15	595.3	660.2	677.4	733.9	667.7	761.9
Dec-15	574	520.1	582.3	540.8	647	415.2
Jan-16	582	564.3	540.9	585.2	645.7	625.2

Feb-16	710.1	712.6	641.5	762	582.1	564.5
Mar-16	907.4	932.7	641.2	684.1	863.5	1036.2
Apr-16	810.6	1262.6	1239.5	1290.6	1113.4	1313.2
May-16	1353.4	1233.2	1341.7	1362	1392.2	1408
Jun-16	2341.1	2156.9	1939.6	2218	2456.2	2493.8

Table 1.1.3

- Generation & Consumption

Month	Electricity Generation (MWh)	Fuel consumption (kg)	BSFC (g/kWh)	Lube oil consumption(m^3)	Generator efficiency (%)
15-Jul	6513.4	1411525	221.32	5.2	41.3303
15-Aug	6449.7	1391477	221.54	4.2	41.5157
15-Sep	9015.5	1942006	214.95	3.3	41.5804
15-Oct	6075.7	1291526	216.92	2.2	42.1349
15-Nov	4096.4	897547	219.67	1.8	40.8784
15-Dec	3279.4	698737	216.58	1.2	42.0368
16-Jan	3543.3	751342	217.92	1.8	42.2396
16-Feb	3972.8	852397	224.74	1.8	41.7449
16-Mar	5065.1	1066114	218.20	2.8	42.5533
16-Apr	7029.9	1466403	221.42	4.0	42.9383
16-May	8090.5	1744195	221.67	3.2	41.546
16-Jun	13605.6	2931875	222.66	3.7	41.5644
Total	76737.3	16445144	------	35.2	------
Average	6394.775	1370429	219.80	2.9	41.8386

Table 1.1.4

- Plant operating hour related data

Month	Avg. op. hrs./day	Plant Availability (%)	Plant Reliability (%)	Capacity factor
15-Jul	9.807	98.00	98.10	36.80
15-Aug	5.514	97.99	98.73	21.16
15-Sep	5.605	94.03	99.54	18.95
15-Oct	3.821	89.84	99.56	13.21
15-Nov	2.937	92.00	99.38	11.15
15-Dec	2.422	99.64	99.66	9.33
16-Jan	2.272	93.42	93.44	8.62
16-Feb	2.957	94.88	98.66	11.09
16-Mar	4.128	88.48	95.21	15.91
16-Apr	6.383	96.40	99.27	24.36
16-May	4.344	90.39	95.06	16.87
16-Jun	4.433	95.85	95.85	17.05
Average	4.552	94.23	97.71	17.04

- Mean Effective Pressure (MEP) = $\frac{\text{PC x } 1.2\text{x}10^9}{D^2 \text{ x } \pi LN}$
- Indicative Power (IP) = $\frac{\text{MEP x V x N x n}}{60}$
- Indicated thermal efficiency = $\frac{\text{IP x 4500}}{\text{W x Cv x J}}$
- Thermal efficiency of Diesel cycle = $1 - \frac{1}{r^{k-1}} [\frac{r_c^k - 1}{k\,(r_c - 1)}]$

Where, P = output/cylinder (kW)
N = engine speed (rpm)
D = cylinder diameter (mm)
L = stroke (mm)
C = operating cycle stroke (= 4)
n = no. of cylinder

V = displacement volume (m^3)
r = compression ratio
r_c = cut-off ratio
k = specific heat ratio

Table 1.1.5

- Table of relation between load, turbo charger speed & engine speed

Time (s)	Eng. Speed (rpm)	Load (kW)	TC speed (rpm)	Time (s)	Eng. Speed (rpm)	Load (kW)	TC speed (rpm)
0	0	0	0	23	750	5000	19300
1	650	300	1500	24	762	5000	19300
2	720	600	3550	25	745	5000	19300
3	748	1000	6100	26	751	5600	20400
4	750	1000	6100	27	746	6200	21700
5	739	1000	6100	28	747	6750	22850
6	746	1000	6100	29	746	7000	24000
7	748	1000	6100	30	749	7000	24000
8	752	1000	6100	31	750	7000	24000
9	760	1000	6100	32	754	7000	24000
10	750	1000	6100	33	754	7500	24450
11	750	1600	7200	34	761	8100	24950
12	735	2250	8650	35	752	8400	25500
13	748	2750	10200	36	748	8400	25500
14	746	3000	12000	37	751	8400	25500
15	749	3000	12000	38	754	8400	25500
16	752	3000	12000	39	751	8400	25500
17	741	3000	12000	40	750	8400	25500
18	750	3000	12000	41	742	8400	25500
19	752	3550	13750	42	755	8400	25500
20	755	4200	15600	43	750	8400	25500
21	757	4700	17500	44	750	8400	25500
22	750	5000	19300	45	744	8400	25500

Appendix 1.2 (Exergy Analysis)
1. Compressor of Turbo Charger
Working fluid: Air

State no.	Flow direction	Temperature, ^{0}C (K)	Pressure, (bar)
1	inlet	28.4 (301.4)	1
2	exit	60.2 (333.2)	2.57

Specific heat values: Cp = 1.005 kJ/kg-K, Cv = 0.716 kJ/kg-K

Change in availability (exergy) = $(h_i – h_e) - T_o (S_i – S_e)$
$= Cv (Tc_i – Tc_e) - T_o (R(\ln(p_{Ce}/p_{Ci})) – Cp (\ln(Tc_e/Tc_i)))$
= 73.8143 kJ/kg; [R = 0.287 kJ/kg-K]

Considering unit mass, W_{rev} = 73.8143 kJ

From eq^n(3l)& (3m), n = 1.1189 &W_{act} = 76.7586 kJ

Irreversibility (exergy destruction), I = $W_{act} - W_{rev}$ = 2.9443 kJ

From eq^n(3k),
$\eta_{C,II}= W_{rev} / W_{act}$ = 96.16 %

2. Turbine of Turbo Charger
Working fluid: Exhaust Gas
(As an approximation, the properties of air can be used for diesel exhaust gas calculations. The error associated with neglecting the combustion products is usually no more than about 2%. [22])

State no.	Flow direction	Temperature, ^{0}C (K)	Pressure, (bar)
11	inlet	570 (843)	3.3
12	exit	394 (667)	1

Change in availability (exergy) = $(h_i - h_e) - T_o (S_i - S_e)$
$= Cp (T_{Ti} - T_{Te}) - T_o (R(\ln(p_{Te}/p_{Ti})) - Cp (\ln(T_{Te} / T_{Ti})))$
= 209.1107 kJ/kg; [R = 0.287 kJ/kg-K]
Considering unit mass, W_{rev} = 209.1107 kJ

From eq^n(3jb) Actual Work, W_{act} = 176.792 [k = 1..4]

Irreversibility (exergy destruction), $I = W_{rev} - W_{act}$ = 32.3187 kJ

From eq^n(3j),
$\eta_{T,II} = W_{actual} / W_{rev}$ = 84.54 %

3. Lube Oil Cooler
Cold fluid: Water
Hot fluid: Lube Oil (LO)

State no.	Flow direction	Temperature, ^{0}C (K)
7	Water inlet, T_{WLi}	49 (322)
8	Water exit, T_{WLe}	62 (335)
9	LO inlet, T_{Li}	83 (356)
10	LO exit, T_{Le}	64 (337)

Specific heat: lube oil = 1.8 kJ/kg-K [23], water = 4.18 kJ/kg-K
Considering unit mass of lube oil,

Heat lost by LO = Heat gained by water
$m_L C_{pL}(T_{Le} - T_{Li}) = m_{WL} C_{pWL}(T_{WLe} - T_{WLi})$
$1 \times 1.8 \times (83 - 64) = m_{WL} \times 4.18 \times (62 - 49)$
m_{WL} = 0.6294 kg

Entropy change of water, $\Delta S_{WL} = m_{WL} C_{pWL}(\ln(T_{WLe}/ T_{WLi}))$ = 0.1041 kJ/K
Entropy change of LO, $\Delta S_L = m_L C_{pL}(\ln(T_{Le}/ T_{Li}))$ = -0.0987 kJ/K

Change in availability (exergy) of water = $m_{WL} C_{pWL}(T_{WLe} - T_{WLi}) - T_0(\Delta S_{WL})$ = 2.9612 kJ
Change in availability (exergy) of LO = $m_L C_{pL}(T_{Le} - T_{Li}) - T_0(\Delta S_L)$ = -4.5801 kJ

Loss in availability (exergy destruction) = (4.5801 – 2.9612) kJ = 1.6189 kJ

$\eta_{HE,II} = \dot{m}_c (\psi_e - \psi_i)_c / \dot{m}_h (\psi_i - \psi_e)_h$ = (0.6294 x 2.9612) / (1 x 4.5801) = 40.69 %

4. Charge Air Cooler (Intercooler)

Cold fluid: Water
Hot fluid: Air

State no.	Flow direction	Temperature, ^{0}C (K)
5	Water inlet, T_{WAi}	49 (322)
6	Water exit, T_{WAe}	78 (351)
3	Air inlet, T_{Ai}	150 (423)
4	Air exit, T_{Ae}	62 (335)

Specific heat: air = 1.005 kJ/kg-K, water = 4.18 kJ/kg-K
Considering unit mass of air,

Heat lost by air = Heat gained by water

$m_A C_{pA}(T_{Ae} - T_{Ai}) = m_{WA} C_{pWA}(T_{WAe} - T_{WAi})$
$1 \times 1.005 \times (150 - 62) = m_{WA} \times 4.18 \times (78 - 49)$
$m_{WA} = 0.7296$ kg

Entropy change of water, $\Delta S_{WA} = m_{WA} C_{pWA}(\ln(T_{WAe}/ T_{WAi})) = 0.263$ kJ/K
Entropy change of air, $\Delta S_A = m_A C_{pA}(\ln(T_{Ae}/ T_{Ai})) = -0.2344$ kJ/K

Change in availability (exergy) of water = $m_{WA} C_{pWA}(T_{WAe} - T_{WAi}) - T_0(\Delta S_{WA}) = 9.5158$ kJ
Change in availability (exergy) of air = $m_A C_{pA}(T_{Ae} - T_{Ai}) - T_0(\Delta S_A) = -18.0966$ kJ

Loss in availability (exergy destruction) = (18.0966 – 9.5158) kJ = 8.5808 kJ

$\eta_{HE,II} = \dot{m}_c (\psi_e - \psi_i)_c / \dot{m}_h (\psi_i - \psi_e)_h = (0.7296 \times 9.5158) / (1 \times 18.0966) = 38.36$ %

5. Boiler (E.G.B)

Cold fluid: Water
Hot fluid: Exhaust Gas (EG, treated as air)

State no.	Flow direction	Temperature, ^{0}C (K)
15	Water inlet, T_{WBi}	65 (338)
16	Water exit, T_{WBe}	100 (373)
13	EG inlet, T_{Gi}	394(667)
14	EG exit, T_{Ge}	200 (473)

Specific heat: air = 1.005 kJ/kg-K, water = 4.18 kJ/kg-K
Considering unit mass of water,

Heat lost by EG = Heat gained by water
$m_G C_{pG}(T_{Ge} - T_{Gi}) = m_{WB} C_{pWB}(T_{WBe} - T_{WBi})$
$m_G \times 1.005 \times (394 - 200) = 1 \times 4.18 \times (100 - 65)$
$m_G = 0.7504$ kg

Entropy change of water, $\Delta S_{WB} = m_{WB} C_{pWB}(\ln(T_{WBe}/ T_{WBi})) = 0.4119$ kJ/K
Entropy change of EG, $\Delta S_G = m_G C_{pG}(\ln(T_{Ge}/ T_{Gi})) = -0.2592$ kJ/K

Change in availability (exergy) of water, = $m_{WB} C_{pWB}(T_{WBe} - T_{WBi}) - T_0(\Delta S_{WB}) = 22.7$ kJ
Change in availability (exergy) of EG = $m_G C_{pG}(T_{Ge} - T_{Gi}) - T_0(\Delta S_G) = -224.0908$ kJ

Loss in availability (exergy destruction) = (224.0908 – 22.7) kJ = 201.3908 kJ

$\eta_{HE,II} = \dot{m}_c (\psi_e - \psi_i)_c / \dot{m}_h (\psi_i - \psi_e)_h = (1 \times 22.7) / (0.7504 \times 224.0908) = 13.49$ %

h	Enthalpy (kJ/kg)
I	Irreversibility (exergy destruction) (kJ)
$\dot{m}$	Mass flow rate (kg/s)
P	Pressure (kPa)
s	Entropy (kJ/kg-K)
T	Temperature (K)
W_{rev}	Reversible work (kJ)
W_{act}	Actual work (kJ)
X	Exergy transfer (kW)
η_{II}	Exergy efficiency
ψ	Specific flow exergy (kJ)

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