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Performance Evaluation of a Cogeneration Based Fertilizer Plant: A Case Study

Devendra Kumar Pathak [a *], Deevesh Sharma [a], Harshit Kumar Khandelwal [b]
[a] Department of Mechanical Engineering, ITM University Gurgaon, India
[b] Research Scholar, Bhabha Atomic Research Centre, Mumbai, India

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Abstract

This paper attempts to show the performance evaluation of natural gas-fired cogeneration based fertilizer plant in India. The fertilizer industry is an energy intensive industry consuming about 29 GJ/MT of Urea Produced. It has observed that large amount of input energy is being lost as the waste heat through the flue gases, if it is not substantially utilized. A steam cycle is used to recover the heat from the flue gases using a waste heat recovery steam generator. A thorough study has been carried out to show the performance evaluation of IIFCO AONLA, Bareilly (U.P.) fertilizer plant. The key performance parameters for present study have been considered as thermal efficiency and heat rate. Their values are calculated for different sections of the fertilizer plant. On the basis of analysis performed in the present study, thermal efficiency is calculated by taking cogeneration into account and without considering it. Finally results have shown that overall thermal efficiency of the plant without considering Co-Generation is 20.162 % while overall thermal efficiency of the Plant when considering Co-Generation is 78.552 %. Therefore, Cogeneration may also be called as thermodynamically efficient utilization of fuel.

1. Introduction

Fertilizer Industries are having their utmost importance in Indian economy as they provide an important product as input to agriculture. As far as the operation of any fertilizer industry is considered, the demand for energy is very high. The main focus of fertilizer industry is to enhance its performance in terms of capacity utilization and specific energy consumption. In India there are about 121 fertilizers plant including large, medium and small scale units. Annual production from Indian fertilizer plants is 121.10 lakh MT, which ranks it third in the world of Fertilizer production (1).

In India, almost all urea/ ammonia production based fertilizer plants are equipped with captive power generation. In earlier plants, High Pressure (HP) boilers were used to generate power as well as to provide specific amount of steam to Urea plant for driving CO2 compressor and process steam was used to supply through extraction from steam turbine. Now a day in ammonia/ urea plants, captive power is generated by operating Gas Turbine and steam is generated through Heat Recovery Steam Generator (HRSG). The steam generated through HRSG is used in urea plant. In nitric acid production, the reaction of oxidation of ammonia to produce nitric acid is exothermic. The heat of reaction is used to generate medium pressure (MP) steam, which is partially used to drive process air compressor and rest is exported to other processes in plant. By using cogeneration technology, the energy consumption in Indian fertilizer plants is near to 7 GCal/ MT which is at par with international standards.

Cogeneration (also Known as combined heat and power, CHP technology) is defined as utilization of heat engine or a power station to sequentially produce High Grade Energy (Work) and Low Grade Energy (Heat)

Corresponding Author,
E-mail address: pathakdev15@gmail.com

Conventional power plants (Based on Gas Turbine) emit the heat created as a by-product of electricity generation into the environment through cooling towers, flue gas, or by other means. CHP or a bottoming cycle utilizes heat from by-products for other specific purposes (2). Cogeneration may also be treated as thermodynamically efficient utilization of fuel. In separate production of electricity some energy must be rejected as waste heat, but in cogeneration this thermal energy is being further utilized.

1.1 Conventional Gas Turbine Cycle

The conventional power plant based on the gas turbine, consists of mainly 4 units, these are compressor, combustion chamber, a single /multi stage gas turbine, an electricity generator (dc / ac) .In these simple gas turbine cycle (Brayton cycle), the compressor is used to suck the air from atmosphere. And further this air is compressed to a high pressure .This high pressure & high temperature air will move to the combustion chamber .In the combustion chamber the fuel will be injected (most commonly a gaseous or a liquid fuel). Due to this the combustion will take place and high temperature & high pressure gas (generated due to combustion of fuel) will be supplied over the blades of gas turbine. Due to this the turbine rotor will start to rotate. When this gas turbine rotor shaft is connected to the electricity generator (dc/ ac), the electricity will generate, due to change in the flux between magnets inside generator. After this whole process the exhaust gases (coming out after expansion from gas turbine) are supposed to be wasted. But these gases have very high temperature (approx. 500°C generally) which will contribute in wastage of high amount of thermal energy in to the atmosphere (3). This not only affects the entire efficiency of the plant, but also increases the surrounding temperature.

Cogeneration is the solution of the above mentioned problem. The cogeneration based fertilizer plant selected for present study is having a HRSG unit, in which the high temperature exhaust gases, coming out from the gas turbine section will pass through the tubes of HRSG. In the HRSG unit, the supply of water will also take place. Due to the temperature difference between the hot exhaust gas & the feed water, the heat transfer will take place between both of them. Due to this the water will be transformed to the steam phase. Now this steam can be utilized in various ways. A Schematic diagram for cogeneration based plant is shown in figure 1.

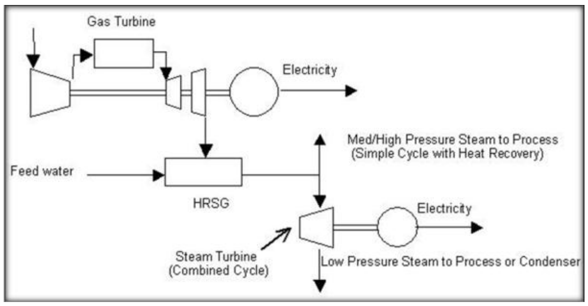

Fig: 1 Schematic Diagram for a Cogeneration based Plant

1.2 Types of Co-Generation Plants

Topping cycle plants primarily produce electricity from a steam turbine. The exhausted steam is then condensed, and the low temperature heat released from this condensation is utilized for e.g. district heating.

Bottoming cycle plants produce high temperature heat for industrial processes, and then a waste heat recovery boiler feeds an electrical plant. Bottoming cycle plants are only used when the industrial process requires very high temperatures, such as furnaces for glass and metal manufacturing, so they are less common.

2. CO-GENERATION AT IFFCO, AONLA (UP)

The IFFCO, Aonla, plant consists of a gas turbine based power plant, which also utilizes cogeneration technology. A schematic diagram for representing structure of IFFCO Aonla is being shown in figure 2. This power plant is divided into 3 parts. These sub structures of the power plant is as written below ;

1) Gas Turbine -1 + Heat recovery steam generator-1 (GTG.-1 +HRSG.-1) unit
2) Gas Turbine -2 + Heat recovery steam generator-2 (GTG.-2 +HRSG-2) unit
3) Steam generator (SG)

Among the above mentioned sub structures of power plant, only first two (i.e. GTG 1 + HRSG 1 unit & GTG -2 + HRSG -2 unit) units produces the electric power. The steam generator (SG) is just a type of boiler which is used to produce the steam from the feed water, and not used for the electricity generation.

Both the GTG-1 + HRSG-1 and GTG -2 + HRSG-2 produce electricity, either simultaneously and one of them remains in Stand –by condition, depending upon the amount of electricity required. Most of the electricity generated is used in the IFFCO plant itself (most commonly used in processing of ammonia (NH3) & processing of the urea (NH2COONH2) in the AMMONIA-1, AMMONIA-2, UREA-1, UREA-2 plants). The remaining part of this electricity is sent for its own township. Since all of this electric energy is consumed by IFFCO itself, so this plant will act like a Captive Power Plant.

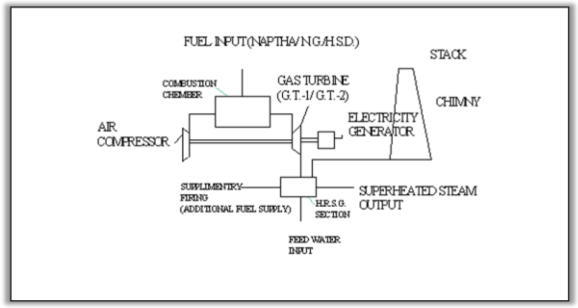

Fig: 2. Structure of IFFCO, Aonla Plant

2.1 Equipment Details and Specification

The basic unit of the IFFCO plant (GTG +HRSG) mainly consists of following equipments:

1) The compressor
2) Combustion section
3) Gas turbine
4) Heat recovery steam generator (HRSG)
5) Electric generator

2.1.1 Compressor

The IFFCO plant consists of axial flow compressor with compression ratio of 10.15:1 and which is having compressor rotor & the enclosing stator casing. This compressor is manufactured by M/S HITACHI, LIMITED .This compressor has 17 stages of compressor blades, inlet & exit guide vanes with maximum speed of rotation as 5100 rpm. In the compressor, air is compressed in stages by a series of alternate rotating (rotor) and stationary (stator) air-foil shaped blades. The compressed air is extracted from the compressor for the turbine, turbine shell & exhaust frame cooling, for bearing sealing and for compressor pulsation control during start up. One row of stator blades (inlet guide vanes) are variable to aid in limiting the air flow during start up and to improve the part load efficiency of combined cycle plants.

a) Rotor of Compressor

The compressor rotor assembly consists of

I. A forward stub shaft, on which first stage rotor blades are mounted.
II. 16 blades and wheel assemblies (rotor stages 2 to 17 inclusive)

Each stage of the compressor is an individual bladed disk. The disks are held together axially by a number of through bolts arranged around the bolting circle. The wheels are positioned radically by a riveted fit near the centre of the disk & do not contact at the rim.

Note: The starting of the compressor will be done with the help of a 12 cylinder diesel engine. After starting the compressor, the diesel engine will get stopped. And there will not be any role of the diesel engine in the plant.

2.1.2 Combustion Chamber

The overall function of the gas turbine combustion system is to supply heat energy in the gas turbine cycle by having combustion of the fuel (Naphtha/N.G./HIGH SPEED DIESEL).This is done by burning fuel in the air downstream of the compressor & diluting the combustion products with excess air to achieve the desired gas temperature at the inlet of the first stage turbine nozzle. Ten numbers of combustors are being used with having its design temperature as 957°C

This combustion system is made up of the following components:

a) **Igniters:** The main function of the igniters is to start the combustion process, for starting the gas turbine. Once the combustion process has been started, the flame itself generated, unless fuel /air flow is interrupted. This is presently done with the help of two 15000 volts spark plugs. These are spring injected (i.e. spring is used to insert the spark plugs inside the combustion chamber.

Basically when the combustion of the fuel take place, the pressure inside the chamber rises due to gas generated. Due to this, the spark plug piston will come out from the combustion chamber. The spring used to return piston back automatically.

b) Cross Fire Tube: After one of the spark plug combustion is ignited, it is necessary to propagate the flame to the other chambers on a multiple combustor machine. This is done by using CROSS-FIRE TUBES, located in the primary/reaction zone to interconnect the combustion chambers. The flame from ignited chamber, flow through the cross-fire tube by virtue of the pressure difference between fired and unfired chambers.

Note: Due to this tube, there is no requirement of spark plug in each combustion chamber.

c) Fuel Nozzle: The function of the fuel nozzle is to deliver atomized fuel to reaction zone of combustor. Since the ignition required occurs at about 8% of the fuel flow at rated condition, so the fuel nozzles must operate over a flow rate ratio of approximately 12:1.
d) Cap and Liner Assembly: The cap and liner assembly is a device in which the fuel from nozzle, mixes with the air from compressor and is burnt prior to being delivered to the turbine.

If the fuel is mixed with all the air available in the combustor, it would be impossible to have combustion, because of the low (fuel /air ratio).For this reason, the fuel is injected into the reaction zone, where it get mixed and burned with a fraction of the air. The hot combustion gases are then mixed with the air outside the reaction zone, so that the gas temperature should become a bit lower, so that the turbine metal will tolerate the gas.

2.1.3 Gas Turbine Section

In the IFFCO plant, there are 2 units of gas turbine. Each of them is of 2-stage, Impulse type and having rating as 18020 kW. When the high velocity flue gas strikes over the turbine blades, it applies a force on the turbine to rotate the turbine rotor. The flue gases coming out from the turbine are at 516 °C with having mass flow rate as 101.7 kg/s. This turbine section include following parts:

a) Turbine rotor: The turbine rotor assembly consists of a distance piece, first & second stage turbine wheels and buckets, one turbine spacers, and turbine wheel shaft. Concentricity control is achieved with mating rabbets on the distance pieces, turbine wheels, spacers & wheel shaft. The turbine rotor is held together with the help of bolts.
b) Stator of turbine: The turbine shell and exhaust frame completes the major portion of the gas turbine stator structure. The turbine nozzles, shrouds and turbine exhaust diffuser are internally supported from these components.

2.1.4 Heat Recovery Steam Generator (HRSG)

The HRSG is very important component in the power plant, because this is the only unit, which is used to generate cogeneration effect in any power plant. Basically, this unit is used as a waste heat recovery unit. The exhaust gases which are coming out from the gas turbine unit have very high temperature and hence high heat energy with them. If this large amount of heat is disposed off to atmosphere, it will severely affect plant efficiency as well as surrounding temperature will also get increased. Therefore in HRSG these high temperature exhaust gases will be used to further produce the steam from feed water (4) .This steam will be used for other purposes.

This HRSG unit consists of 3 main components. These are as follows:

1) Economizer
2) Evaporator & steam drum unit
3) Superheater

a) Economizer: The economizer is used to increase the temperature of the feed water, entering into it, by utilizing the heat from the exhaust gas. As we know that the exhaust gases coming out from the gas turbine are at 500 °C. These gases will be further treated by using the supplementary firing and their temperature will rise to 700 °C. These gases after moving through super heater and evaporator, reaches to the economizer unit .This section has counter flow, drainable vertical tubes with spiral fins.
b) Evaporator and Steam Drum: Evaporator section is composed of several components, which consists of tube with spiral fin and each inlet and outlet header. Each component is made up with a different water circulation circuit. Evaporator elements are bottom supported by lower header holding plates.

Steam drum is of all welded construction, fabricated from carbon steel material and equipped with steam purifier of baffle screen type in the steam drum and necessary nozzle and connections. The drum is mounted above the boiler & is supported with down comer pipes.

c) Super heater: Super heater is a convection type, counter flow, drainable inverted U-looped tubes with spiral fins. Superheated section is located in the highest gas temperature zone and materials are designed to satisfy the requirement of operation conditions. Its elements are supported at bottom by lower holding plates.

3. Data Collection And Analysis

In this section data required to perform analysis for the present study is being shown in the following tables. General specifications regarding operation are being shown in Table 1, while working data of plant on 20/01/2014 is being shown in Table 2 and 3. Table 4 shows unit wise consumption of natural gas

Table: 1. General Specifications Regarding Operation

HRSG capacity	**80 T/hr. at 125 N/m^2 and 515 °C**
Exhaust gas temp. after the gas turbine	500 °C
Exhaust gas temp. after the supplementary firing ,entering into the super heater	707 °C
Exhaust gas temp. when entering into the evaporator	573 °C
Exhaust gas temp. ,when entering into the economizer	336 °C
Exhaust gas temp. ,when leaving the economizer	161 °C
Exhaust gas temp. going out from chimney	160 °C
Temp. of feed water at inlet to economizer	126°C
Temp. of water& steam mixture coming out from economizer	310°C
Temp. of steam input to super heater	323°C
Temp. of steam output from super heater	412°C
Pressure of the feed water input to economizer	121.2 N/m^2
Pressure of water & steam mixture entering to steam drum	117.6 N/m^2
Pressure of Water/steam entering to super heater	117.6 N/m^2
Feed water flow rate	81600 kg/hr.
Final Steam outlet flow rate	80000 kg/hr.
Pressure of Flue Gas at turbine outlet	33.5 N/m^2

Table: 2. Working Data for 20/01/2014

DESCRIPTION	**UNIT**	**TOTAL PRODUCTION**	**HOURLY PRODUCTION**
Total steam generation	MT	6756	281.5
Steam generator	MT	2865	119.4
HRSG-1	MT	1945	81.0
HRSG-2	MT	1946	81.1
HP Export	MT	6164	256.8
MP Export	MT	240	10.0
LP Export	MT	264	11.0
Total Power Generation	MWh	665	27.7
GTG-1	MWh	319.6	13.3
GTG-2	MWh	345.4	14.4
LOWER CALORIFIC VALUE (LCV) of NG	kCal/Sm^3	8372.15	N.A.

Table: 3. Working Data for 20/01/2014

UNIT	**Specific fuel Consumption (Sm^3/MT)**	**Energy (Gcal/T/ MWh)**
SG	89.4	0.75
HRSG-1	41.5	0.35
HRSG-2	37.8	0.32
GTG-1	520.4	4.36
GTG-2	498.6	4.17

Table: 4. Unit Wise Natural Gas Consumption

UNIT	**Nm^3**	**Sm^3**	**Actual values at prevailing condition**	**Hourly Consumption**
HRSG-1	76873	81255	80624	3359
HRSG-2	70183	74183	73608	3067
GTG-1	158580	167619	166318	6930
GTG-2	164220	173581	172234	7176
SG	242220	256027	252425	10517

4. Results

Thermal Efficiency and Heat Rate calculations are being done in section 4.1 and 4.2 respectively.

4.1 Calculation for Thermal Efficiencies

From the data collected, Thermal efficiency calculations are done for GTG-1 along with HRSG-1, GTG-2 along with HRSG-2, overall efficiency with cogeneration and overall efficiency without cogeneration by using equation (1), (2), (3) and (4) respectively.

a) For GTG -1 +HRSG -1 Unit

Total electric energy generated by GTG-1 = 319.6 MWh
Fuel consumed in GTG-1 unit = 166318 Sm^3
Fuel consumed in HRSG-1 unit for supplementary firing= 80624 Sm^3
Enthalpy of feed water for HRSG-1 unit = 126.0 kcal/MT
Enthalpy of steam produced in HRSG-1 unit = 811.0 kcal/MT
Total steam production in HRSG-1 unit =1945 MT
LCV for Natural Gas = 8372.15 kcal/Sm^3

$$\text{Efficiency} = \frac{(\text{total energy generated by GTG}-1)+(\text{total energy contained with steam})}{(\text{Total Natural Gas consumed})\times(\text{LCV of Natural Gas})} \times 100 \quad (1)$$

$$= \frac{(860\times 319.6\times 1000)+[1945\times(811-126)\times 1000]}{(166318+80624)\times 8372.15} \times 100$$

$$= 77.73\,\%$$

b) For GTG-2 +HRSG-2 Unit

Total electric energy generated by GTG-2 = 345.4 MWh
Fuel consumed in GTG-2 unit = 172234 Sm^3
Fuel consumed in HRSG-2 unit for supplementary firing = 73608 Sm^3
Enthalpy of feed water for HRSG-2 unit = 126.0 kcal/MT
Enthalpy of steam produced in HRSG-2 unit = 811.0 kcal/MT
Total steam production in HRSG-2 unit =1946 MT
LCV for Natural Gas = 8372.15 kcal/Sm^3

$$\text{Efficiency} = \frac{(\text{total energy generated by GTG}-1)+(\text{total energy contained with steam})}{(\text{Total Natural Gas consumed})\times(\text{LCV of Natural Gas})} \times 100 \quad (2)$$

$$= \frac{(860 \times 345.4 \times 1000) + [1946 \times (811-126) \times 1000]}{(172234 + 73608) \times 8372.15} \times 100$$

$$= 79.2\%$$

c) For Overall Efficiency with Cogeneration (without considering SG unit):

Total electric energy generated by (GTG-1 +GTG-2) = 665 MWh

Fuel consumed in (GTG-1 + GTG-2) units = (166318+ 172234=338552) Sm^3

Fuel consumed in (HRSG-1 +HRSG-2) units for supplementary firing = (80624+ 73608= 154232) Sm^3

Enthalpy of feed water for (HRSG-1/HRSG-2) unit = 126 kcal/MT

Enthalpy of steam produced in (HRSG-1/HRSG-2) unit = 811.0 kcal/MT

Total steam production in (HRSG-1 +HRSG-2) units = (1945 +1946 = 3891) MT

LCV for Natural Gas = 8372.15 kcal/Sm^3

$$\text{Efficiency} = \frac{(\text{total energy generated by GTG}-1\ \&\ GTG-2)+(\text{total energy contained with steam})}{(\text{Total Natural Gas consumed})\times(\text{LCV of Natural Gas})} \times 100 \quad (3)$$

$$= \frac{(860 \times 665 \times 1000) + [3891 \times (811-126) \times 1000]}{(338552 + 154232) \times 8372.15} \times 100$$

$$= 78.46\%$$

Note: While calculating the efficiency for the over-all power plant, we have not considered the SG (Steam Generator) performance, because it is a separate unit within the power plant & it has no relation with the cogeneration technique.

d) For Overall Efficiency Without Co-Generation:

Total electric energy generated by (GTG-1+ GTG-2) units = 665 MWh

Fuel consumed in (GTG-1 +GTG-2) units = (166318 +172234 = 338552) Sm^3

LCV for Natural Gas = 8372.15 kcal/Sm^3

$$\text{Efficiency} = \frac{(\text{total energy generated by GTG}-1\ \&\ GTG-2)}{(\text{Total Natural Gas consumed by GTG.}-1+\text{GTG}-2)\times(\text{LCV of Natural Gas})} \times 100 \quad (4)$$

$$= \frac{(860 \times 665 \times 1000)}{(338552) \times 8372.15} \times 100$$

$$= 20.17\%$$

Note: IFFCO, Aonla fertilizer plant in a cogeneration plant by birth. So we have calculated the above efficiency by neglecting the effects of the HRSG-1 & HRSG-2 units in the plant.

From the above results, it has found that thermal efficiency for GTG-1 along with HRSG-1is 77.73% while for GTG-2 along with HRSG-2 is 79.2%. Overall Thermal efficiency when considering cogeneration is 78.46% while overall thermal efficiency without cogeneration is 20.17%.

4.2 Calculation for Heat Rate

From the data collected, Heat rate calculations are done for GTG-1 and GTG-2 by using equation (5) and (6)

a) Heat Rate Calculation For GTG-1:

Total electric energy generated by GTG-1 unit = 319.6 MWh

Fuel consumed in GTG-1 unit = 166318 Sm^3

LCV for Natural Gas = 8372.15 kcal/Sm^3

$$\text{Heat Rate} = \frac{(\text{Total Natural Gas consumed by GTG}-1)\times \text{LCV of N.G}}{\text{Total electric energy generated by GTG}-1\ \text{unit}} \quad (5)$$

$$= \frac{166318 \times 8372.15 \times 4.18}{319.6 \times 1000}$$

$$= 18211.502 \ \text{kJ/kWh}$$

b) Heat Rate Calculation For GTG-2:

Total electric energy generated by GTG-2 unit = 345.4 MWh

Fuel consumed in GTG-2 unit = 172234 Sm^3

LCV for Natural Gas = 8372.15 Kcal/Sm^3

$$\text{Heat Rate} = \frac{(\text{Total Natural Gas consumed by GTG}-2)\times \text{LCV of N.G}}{\text{Total electric energy generated by GTG}-2\ \text{unit}} \quad (6)$$

$$= \frac{172234 \times 8372.15 \times 4.18}{345.4 \times 1000}$$

$$= 17450.58 \ \text{kJ/kWh}$$

From the above results, it has found that heat rate for GTG-1is higher than that of GTG-2.

Performance analysis of IFFCO Fertilizer Plant for all the five working days have been done as mentioned in the above analysis and being shown in Table 5. Figure 3 and 4 shows the daily variation of thermal efficiency for GTG-1 along with HRSG-1 and GTG-2 along with HRSG-2 respectively.

Table: 5. Performance Analysis for Five continuous working Days

Performance Parameters	20/01 /2014	21/01 /2014	22/01/ 2014	23/01/ 2014	24/01/2 014
GTG-1+HRSG-1 unit efficiency	77.78 %	77.6 %	77.7 %	77.6 %	78.1 %
GTG-2 + HRSG-2 unit efficiency	79.2 %	79.7 %	79.8 %	79.7 %	79.8 %
Overall plant efficiency (considering Co-Generation)	78.46 %	77.97 3 %	78.74 3 %	78.63 6 %	78.95 %
Overall plant efficiency (without Co-Generation)	20.17 %	20.41 5 %	20.13 3 %	20.08 %	20.01 %
Heat Rate of					

GTG-1 unit (kJ/kWh)	18211.502	18439.69	18327.41	18459.614	18431.38
Heat Rate of GTG-2 unit (kJ/kWh)	17450.58	17374.033	17426.017	17409.64	17409.59

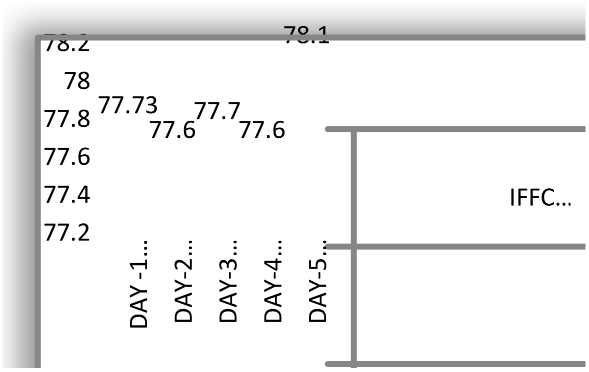

Fig: 3. Daily Variation of Efficiencies for GTG-1 + HRSG-1 in IFFCO Fertilizer Plant

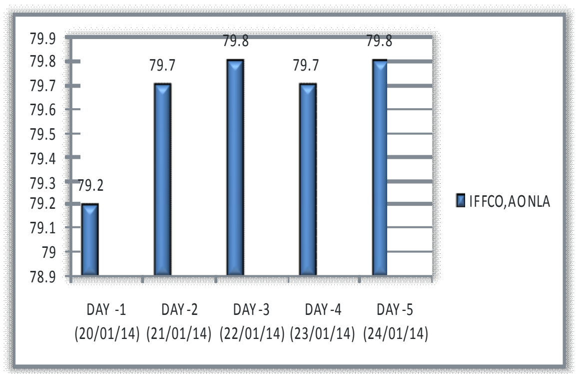

Fig: 4. Daily Variations of Efficiencies for GTG-2 + HRSG-2 in IFFCO Fertilizer Plant

5. Conclusions

The data collected from IFFCO Aonla, Plant was used to perform required analysis. From the results it is revealed that thermal efficiency of GTG-2 along with HRSG-2 is more than the thermal efficiency of GTG-1 along with HRSG-1. The overall thermal efficiency of the plant considering cogeneration was found to be 78.55%, while the overall thermal efficiency of the plant without considering cogeneration was found to be 20.16%. From the heat rate calculation made for GTG-1 and GTG-2 unit, it has revealed that heat rate value for GTG-1 is higher than GTG-2. Therefore we can say that by supplying some additional amount of heat to HRSG, steam will be generated sequentially along with electrical energy by GTG, which will further increase the overall plant thermal efficiency from 20.16% to 78.55%. The Flue gas temperature at the inlet of gas turbine in the IFFCO, Aonla Plant is found to be 957 °C while compressor Pressure Ratio is 10.15. For further improving thermal efficiency, steps can be taken for increasing these temperature limit and pressure limit.

Acknowledgement

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