**Unit 5: Cogeneration**

**Objectives:** At the end of this chapter the reader would be able to describe what cogeneration is, why cogeneration is required, how cogeneration can be carried out in different ways, what are the different factors that influence the selection of a cogeneration cycle, how the performance assessment of a cogeneration system can be carried out.

**Pre-requisites:** Understanding of basic thermodynamic principles, gas power cycles, vapour and compound power cycles.

**5.1 Principle and need for cogeneration**

The energy requirement of most industries can be categorised into *thermal energy requirement* and *electrical energy requirement*. The electrical energy requirement is met by either directly connecting to the *national electricity grid* or by having an own *power generating unit* also known as a captive power plant. The captive power generation in India stands at 31,516.87 MW as on 30/04/2012 (Central Electricity Authority).

Various power generating units work on different power generating cycles. A review of the various power cycles would indicate that the sole purpose of these cycles is to generate some form of useful work from the heat that is transferred to the working fluid. The remaining portion of the heat is rejected as waste heat to rivers, lakes, oceans or atmosphere as its quality (or grade) is too low to be of any practical use. Most of these industries are also in requirement of *process heat*. The process heat in these industries is usually supplied by steam at 5 to 7 bar and 150 to 200°C[[1]](#footnote-1)

Thus as energy professionals it will be worthwhile for us to find means to use the waste heat of the captive power plants for process heating. The method used for this purpose is known as *combined heat and power (CHP) generation* or simply *co-generation*. In other words cogeneration is the simultaneous generation of multiple forms of energy from a single integrated system.

**5.2 Technical options of cogeneration; Classifications of cogeneration systems**

A cogeneration plant uses either a Rankine cycle (Section 5.2.1) or a Brayton cycle (Section 5.2.2) or a reciprocating engine cycle (Section 5.2.3).

**5.2.1 Steam turbine cogeneration system**

The schematic of an ideal steam-turbine cogeneration plant is shown in Fig. 5.1.

It is observed that in the ideal steam turbine cogeneration plant the condenser is replaced with a process heater. Thus no waste heat is produced in this type of plant. Thus all the energy transferred to the steam in the boiler is utilised in producing power and for process heating.

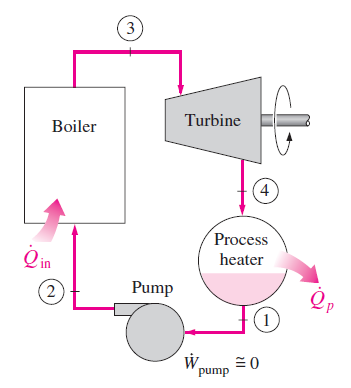


Figure 5.1: Ideal Steam Turbine Cogeneration Plant[[2]](#footnote-2)

Steam is extracted from the exit of the turbine and the configuration is also known as a back pressure turbine as the steam exits the turbine at a pressure higher or at least equal to the atmospheric pressure, which depends on the needs of the thermal load. Although the ideal steam turbine cogeneration plant seems to be the most efficient but it has its limitations. It cannot adjust to the variations in power and process-heat loads. Figure 5.2 shows the schematic of a more practical cogeneration plant.

Under normal conditions when both power and process-heat are required, some amount of steam is extracted from the turbine at the required process-heating pressure and the rest expands to the condenser pressure and is then cooled. The steam is extracted from one or more intermediate stages at the appropriate pressure and temperature and the configuration is also known as an extraction condensing steam turbine. The heat rejected in the condenser goes out as the waste heat. When the process heating requirement is high, all the steam is routed to the process-heating units and none to the condenser.



**Figure 5.2: Practical Steam Turbine Cogeneration Plant[[3]](#footnote-3)**

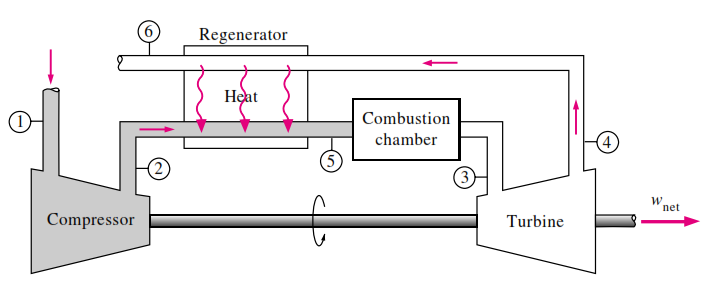
The waste heat becomes practically zero. If still the process heating requirement is not satisfied, an expansion or pressure-reducing valve is used to throttle some of the steam leaving the boiler to the process-heating unit. The power produced in this case becomes practically zero. When the process heating requirement is nil, all the steam passes through the turbine and the condenser and the cogeneration plant operates as an ordinary steam power plant.

**5.2.2** **Gas turbine cogeneration system**

The gas turbine based cogeneration system works on the basic principle of Brayton cycle. The gas turbine system consists of a compressor, combustion chamber, turbine and generator. In the combustion chamber air from the compressor is drawn and mixed with the fuel. The fuel air mixture is then ignited. The flue gases with a very high temperature from the combustor are expanded through a gas turbine, which drives the electric generator and the air compressor. Some portion of the mechanical power is utilised for running the compressor and the balance is converted into electric power. The Brayton cycle can be of two types *viz.* open cycle Brayton cycle and closed cycle Brayton cycle and accordingly the gas turbine cogeneration systems are classified as open cycle gas turbine cogeneration system and closed cycle gas turbine cogeneration system.

In the open cycle cogeneration system the exhaust flue gases from the gas turbine which are typically at a high temperature of 480-540 °C acts as a heat source from which the heat is recovered in the form of steam or hot air for process heating. Figure 5.3 shows a schematic of an open cycle based cogeneration system.

Although the industrial gas turbine based power plants operate at thermal efficiency of 25-35% only depending of type and size of gas turbine, a cogeneration system deriving energy from the high temperature flue gases helps in increasing the overall plant efficiency to around 85-90%. The heat of the exhaust flue gases can also be used alternatively by diverting it to heat exchanger to generate hot water or hot air (District Heating purpose in foreign countries) instead of generating steam.



**Figure 5.3: Open Cycle Gas Turbine Cogeneration System[[4]](#footnote-4)**

In the closed-cycle system (Figure 5.4), helium or air acts as the working fluid which circulates in a closed circuit. A heat exchanger is used to heat the working fluid before entering the turbine, and it is cooled down after the exit of the turbine releasing useful heat. The working fluid when used in this manner remains clean and it does not cause corrosion or erosion.

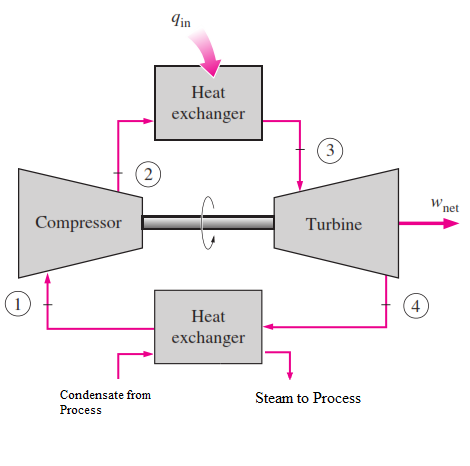
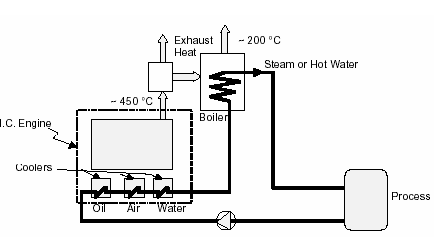


Figure 5.4: Closed Cycle Gas Turbine Cogeneration System[[5]](#footnote-5)

**5.2.3 Reciprocating Engine Cogeneration System**

Reciprocating engines are used extensively in industries as they start quickly, follow load well, have good part- load efficiencies, and generally have high reliabilities. Also, the fuel-related operating costs of reciprocating engines are lower than that of gas turbines of comparable sizes because of their high electrical efficiencies.

****

**Figure 5.4: Reciprocating Engine Cogeneration System**

There are four sources of usable waste heat from a reciprocating engine: exhaust gas, engine jacket-cooling water, lube oil cooling water, and turbocharger cooling. Recovered heat is generally in the form of hot water or low-pressure steam. The high temperature exhaust can generate medium pressure steam, but the hot exhaust gas contains only about one half of the available thermal energy from a reciprocating engine[[6]](#footnote-6).

Cogeneration systems are also classified according to the sequence of energy use and the operating schemes adopted. On this basis cogeneration systems can be classified as either a topping or a bottoming cycle.

In a topping cycle, the fuel is first used to produce power and then the residual or waste energy is used to generate thermal energy, which is used to satisfy process heat or other thermal requirements. Topping cycle cogeneration is widely used and is the most popular method of cogeneration.

In a bottoming cycle, the primary fuel is first used to produces high temperature thermal energy and the heat rejected from the process is used to generate power through a recovery boiler and a turbine generator. Bottoming cycles are suitable for manufacturing processes that require heat at high temperature in furnaces and kilns, and reject heat at significantly high temperatures. Typical areas of application include cement, steel, ceramic, gas and petrochemical industries. Bottoming cycle plants are much less common than topping cycle plants.

Table 5.1 lists the advantages and disadvantages of the various types of cogeneration systems discussed in the previous sections.

Table 5.1: Comparison of Cogeneration Systems[[7]](#footnote-7)

|  |  |  |
| --- | --- | --- |
| **Variant** | **Advantages** | **Disadvantages** |
| Back Pressure Steam Turbine and Fuel firing in Conventional Boiler | - High fuel efficiency rating | - Little flexibility in design and operation |
| - Very simple Plant | - More impact on environment in case of use of low quality fuel |
| - Well suited to all types of fuels of high or low quality | - Higher civil construction cost due to complicated foundations |
| - Good part load efficiency |  |
| - Moderate relative specific capital cost |  |
| Extraction-cum- Condensing Steam Turbine and fuel firing in Conventional Boiler | - High flexibility in design andoperation | - More specific capital cost |
| - Well suited to all types of fuels, high quality or low quality | - Low fuel efficiency rating, in case of more condensing |
| - Good part load efficiency | - More impact on environment in case of use of low quality fuel |
| - More suitable for varying steam demand | - Higher civil construction cost |
| **Variant** | **Advantages** | **Disadvantages** |
| Gas Turbine with Waste Heat Recovery Boiler | - High fuel efficiency at full load operation | - Moderate part load efficiency |
| - Very simple plant | - Limited suitability for low quality fuels |
| - Low specific capital cost | - Not economical, if constant steam load is a problem |
| - Lowest delivery period, hence low gestation period |  |
| - Less impact on environment (with use of clean fuels) |  |
| - Least maintenance option |  |
| - Quick start and stop |  |
| - Still better efficiency with supplementary firing in Waste heat recovery boiler |  |
| - Least cooling water requirement |  |
| Reciprocating Engine and Waste Heat Recovery Boiler with Heat Exchanger | - Low civil construction cost due to block type foundations and least nos. of auxiliaries | - Low overall plant efficiency in cogeneration mode |
| - High electrical power efficiency | - Suitability for low quality fuels with high cleaning cost |
| - Better suitability as emergency standby plant | - High maintenance cost |
| - Least specific capital cost | - More impact on environment with low quality fuel |
| - Low cooling water demand | - Least potential for waste heat recovery |

**5.3 Factors influencing selection of a cogeneration cycle**

Heat-to-power ratio is one of the most vital technical parameters influencing the selection of cogeneration system. If the heat-to-power ratio of industry can be matched with the characteristics of the cogeneration system being considered, the system optimisation would be achieved in real sense.

Heat-to-power ratio is defined as the ratio of the thermal energy to electrical energy required by the industry. Basic heat-to power ratios of the cogeneration system variants are shown in Table 5.2 below along with the power output and overall plane efficiency. It is observed that the steam turbine based cogeneration system can be considered over a large range of heat-to-power ratios.

Table 5.2: Cogeneration System Performance Parameters

|  |  |  |  |
| --- | --- | --- | --- |
| **Cogeneration System** | **Heat-to-**  **power ratio (kWth/kWe)** | **Power Output**  **(as percent of fuel input)** | **Overall**  **Efficiency**  **%** |
| Back-pressure steam turbine | 4.0 – 14.3 | 14 – 28 | 84 – 92 |
| Extraction-condensing steam turbine | 2.0 – 10 | 22 – 40 | 60 – 80 |
| Gas turbine | 1.3 – 2.0 | 24 – 35 | 70 – 85 |
| Combined cycle (Gas plus steam turbine) | 1.0 – 1.7 | 34 – 40 | 69 – 83 |
| Reciprocating engine | 1.1 – 2.5 | 33 - 53 | 75 - 85 |

Following factors should be given a due consideration in selecting the most appropriate cogeneration system for a particular industry[[8]](#footnote-8).

* Normal as well as maximum/minimum power load and steam load in the plant, and duration for which the process can tolerate without these utilities, i.e. criticality and essentiality of inputs.
* What is more critical - whether power or steam, to decide about emergency back-up availability of power or steam.
* Anticipated fluctuations in power and steam load and pattern of fluctuation, sudden rise and fall in demand with their time duration and response time required to meet the same.
* Under normal process conditions, the step by step rate of increase in drawl of power and steam as the process picks up - whether the rise in demand of one utility is rapid than the other, same or vice-versa.
* Type of fuel available - whether clean fuel like natural gas, naphtha or high speed diesel or high ash bearing fuels like furnace oil, LSHS, etc. or worst fuels like coal, lignite, etc., long term availability of fuels and fuel pricing.
* Commercial availability of various system alternatives, life span of various systems and corresponding outlay for maintenance.
* Influence exerted by local conditions at plant site, i.e. space available, soil conditions, raw water availability, infrastructure and environment.
* Project completion time.
* Project cost and long term benefits.

**5.4 Cogeneration performance parameters, Case study[[9]](#footnote-9)**

**5.4.1 Performance Terms & Definitions**

***Overall Plant Performance***

* ---------- (5.1)

Where,

Ms = Mass Flow Rate of Steam (kg/hr)

hs = Enthalpy of Steam (kCal/kg)

hw = Enthalpy of Feed Water (kCal/kg)

* ----------(5.2)

***Steam turbine performance***

----------(5.3)

***Gas turbine performance***

----------(5.4)

***Heat recovery steam generator (hrsg) performance***

----------(5.5)

Where,

Ms = Steam Generated (kg/hr)

hs = Enthalpy of Steam (kCal/kg)

hw = Enthalpy of Feed Water (kCal/kg)

Mf = Mass flow of Flue Gas (kg/hr)

tin = Inlet Temperature of Flue Gas (0C)

tout = Outlet Temperature of Flue Gas (0C)

Maux = Auxiliary Fuel Consumption (kg/hr)

Let us now try and use the above mentioned formulas to evaluate the performance of steam turbine cogeneration system as shown in figure 5.5.

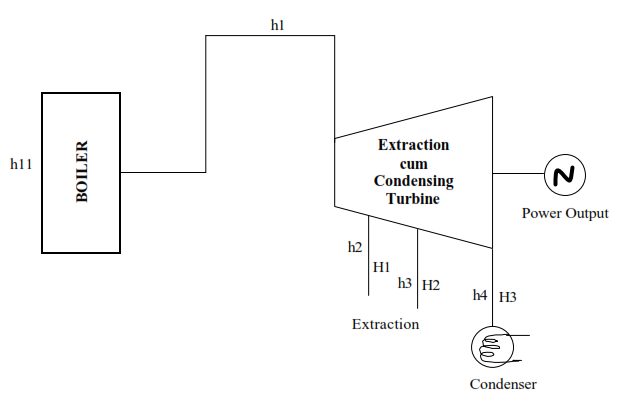


Figure 5.5 Steam Turbine Cogeneration System

The calculation in carried out in four steps

***Step 1: Calculate the actual heat extraction in turbine at each stage***

Steam Enthalpy at Turbine Inlet : h1, kCal/kg

Steam Enthalpy at stage 1 extraction : h2, kCal/kg

Steam Enthalpy at stage 2 extraction : h3, kCal/kg

Steam Enthalpy Condenser : h4\*, kCal/kg

\* Due to wetness of steam in the condensing stage, the enthalpy of steam cannot be considered as equivalent to saturated steam. Typical dryness value is 0.88 – 0.92. This dryness value can be used as first approximation to estimate heat drop in the last stage. However it is suggested to calculate the last stage efficiency from the overall turbine efficiency and other stage efficiency.

Heat extraction from inlet to Stage 1 extraction (h5):

*h5 = (h1 –h2) kCal/kg*  ----------(5.6)

Heat extraction from stage 1 to stage 2 extraction (h6):

*h6 = (h2 –h3) kCal/kg* ----------(5.7)

Heat extraction from stage 2 extraction to condenser (h7):

*h7 = (h3 –h4) kCal/kg*  ----------(5.8)

***Step 2: Estimate theoretical heat extraction***

From the Mollier diagram (H-f Diagram) estimate the theoretical heat extraction for the conditions mentioned in Step 1. This is done as follows:

* Plot the turbine inlet condition point in the Mollier chart – corresponding to steam pressure and temperature.
* Since expansion in turbine is an adiabatic process, the entropy is constant. Hence draw a vertical line from inlet point (parallel to y-axis) up to the condensing conditions.
* Read the enthalpy at points where the extraction and condensing pressure lines meet the vertical line drawn.
* Compute the theoretical heat drop for different stages of expansion.

Theoretical Enthalpy after 1st Extraction : H1

Theoretical Enthalpy after 2nd Extraction : H2

Theoretical Enthalpy at Condenser Condition : H3

Theoretical Heat Extraction from Inlet to Stage 1 Extraction (h8):

*h8 = h1 –H1*----------(5.9)

Theoretical Heat Extraction from Stage 1 to Stage 2 Extraction (h9):

*h9 = H1 –H2* ----------(5.10)

Theoretical Heat Extraction from Stage 2 Extraction Condensation (h10):

*h10 = H2 –H3* ----------(5.11)

**Step 3: Compute Turbine Efficiency**

----------(5.12)

-----------(5.13)

---------(5.14)

**Step 4: Calculate the plant heat rate**

-----------(5.15)

Where,

M = Mass flow rate of steam (kg/hr)

h1 = Enthalpy of inlet steam (kCal/kg)

h11 = Enthalpy of feed water (kCal/kg)

P = Average power generated (kW)

**Case Study**

**Reciprocating engine System- Chlor Alkali Industry**

Generally, in continuous process industries requiring more electric power than steam, power: heat ration more than 1, the cogeneration systems having configuration of reciprocating engine generator and unfired, or supplementary fired, or fully fired waste heat recovery boilers are found working providing the best performance results among various cogeneration configurations. Moreover, in such type of cogeneration systems, it is possible to achieve number of combinations to meet the industry’s specific needs of energy in different forms besides achieving optimum cogeneration efficiency. The examples of such plants can be seen in the chemical process plants or in foundry units.

The case study provided below is based on the actual system working in one of the largest Chlor-alkali manufacturing plants in Gujarat state.

**Equipments**

The captive power plant (CPP) consists of major equipment detailed below.

a. 3 x 7510 kVA (3 X 6000 kW) industrial heavy duty reciprocating engine generator sets as per ratings provided below.

b. 3 nos. of 3.5 TPH, 11 Kg/cm2, 250 0C unfired waste heat recovery boilers as per ratings provided below.

Cogeneration equipment data is mentioned below.

**Table 5.3: Cogeneration equipment data**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Reciprocating engine generator data** | | | | | |
| **Parameter** | | **Unit** | | **Quantity** | |
| **Engine data** | | | | | |
| Type | | Industrial heavy duty | | | |
|  | | Wartsila, 18V32 | | | |
| Nos. of units installed | | Nos. | | 3 | |
| Rating | | bhp | | 8160 | |
| Speed of engine | | RPM | | 750 | |
| Engine inlet design conditions | | | | | |
| air temperature | | 0C | | 35 | |
| Pressure | | Kg/cm2 | | 1.0332 | |
| Altitude | | Above MSL | | 51.5 metre | |
| relative humidity | | % | | 60 | |
| diff. pressure - inlet air filter | | mbar | | 75 | |
| Fuel fired – Primary | | Heavy fuel oil | | | |
| Engine heat rate at designed conditions | | kCal/kWh | | 2042.21 | |
| Specific fuel consumption | | grams/kWh | | 180.5 | |
| Specific lube-oil consumption | | grams/kWh | | 0.8±0.3 | |
| Exhaust flue gas flow | | Kg/sec | | NA | |
| Exhaust flue gas temperature at engine outlet | | 0C | | 405 | |
| **Parameter** | | **Unit** | | **Quantity** | |
| **Generator data** | | | | | |
| Rating for apparent power | | kVA | | 7510 | |
| Power output at rated power factor and site conditions | | kW | | 6015 | |
| Generation voltage | | kV | | 11 | |
| Full load current | | Amp | | 394.6 | |
| Rated power factor (lag) | |  | | 0.8 | |
| Frequency | | Hz | | 50 | |
| Generator shaft speed | | RPM | | 750 | |
| Excitation | | Self excited, brushless | | | |
| **Waste heat recovery boiler data** | | | | | |
| Type of WHRB | | Water tube, single pass, vertical unfired, single pressure, waste heat recovery boiler | | | |
| Nos. installed | | Nos. | | 3 | |
| Exhaust gas temp at WHRB inlet | | 0C | | 405 | |
| Exhaust gas temp entering chimney | | 0C | | 140 | |
| Steam parameters at boiler exit | | | | | |
| Flow | | MT/hour | | 3 x 3.5 TPH | |
| Temperature | | 0C | | 200 | |
| pressure (g) | | Kg/cm2 | | 10.5 | |

The fuel specification and other relevant technical data are provided below.

**Table 5.4: Fuel composition data**

|  |  |  |
| --- | --- | --- |
| **Main fuel – Heavy fuel oil** | | |
| Higher heating value (Gross cal value) | kCal/Kg | 10200 |
| Lower heating value (LHV) | kCal/kg | 9200 |
| Moisture | % w/w | 1.0 |
| Viscosity, max. | cSt @ 1000C  cSt @ 500C | 55  730 |
| Density, max @ 15 0C | gms/ml | 0.991 |
| Vanadium, max. | mg/kg | 600 |
| Sodium, max. | mg/kg | 20-50 |
| Sulphur, max. | % w/w | 5.0 |
| Flash Point | 0C min. | 60 |
| Pour Point, upper max. | 0C | 30 |
| Sediment, Percent by Mass, | w/w%, max. | 0.1 |
| Ash | % w/w | 0.1 |
| **Start-up fuel – High speed diesel** | | |
| Fuel flow | Kg/hour |  |
| Higher heating value | kCal/kg | 11200 |
| Lower heating value | kCal/kg | 10500 |

The lube-oil used is SAE40 grade.

Normal operating philosophy

i. The Chlor-alkali plant works round the clock for the production of caustic soda (Sodium hydroxide, NaOH) as main product. Byproducts such as Hydrogen, Hydrochloric acid, Chlorine, etc, are also produced. The process, continuous in nature, is highly energy intensive and critical. In view of explosive nature of some products, it is essential to maintain uninterrupted electric power supply from safety angle. The system is bound to experience some variation in the demand of power and steam from time to time depending on production level. Moreover, even in case of continuous process, the demand of power and steam is based on simultaneous operation of number of plant sections and utilities. With the use of membrane based technology in place of conventional cell based electrolysis process, significant saving is achieved in electrical energy consumption.

ii. In the case study provided, 3 nos. of 6015 kW reciprocating engine generators along with 3.5 TPH unfired WHRB are operated at around 80-85% of their rated capacities with no back up for electric power from the state utility. The existing fired boilers, used prior to installation of CPP, have been retained to operate during extreme emergency situations.

iii. The reciprocating engine generators are run in parallel with each other. In fact, there is no provision of the gird supply at all. Such philosophy may prove disadvantageous to the plant, as in the event of tripping of one of the engines, there would be shortage of electric power. Moreover, due to sudden imposition of overload on remaining engines, they may also trip. To avert such situation, the load management scheme is placed in service, which immediately isolates the non-essential services in the first instant so as to save other running engines to maintain essential plant power supply. For meeting short fall in the steam supply, fuel oil fired existing boiler is taken into service to generate the steam. Whole process takes very nominal time without disturbance of any sort to the critical chemical manufacturing process.

**Utilisation of power**

i. The electrical energy generated from the CPP is totally utilised in operating the process equipment such as membrane process for electrolysis, large HT motor driven equipment, agitators, mixers, pumps, utilities and plant/office/area illumination. The production of caustic soda is extremely critical continuous chemical process along with other byproducts. In order to optimise the performance of CPP, minimum 80% load is maintained on all 3 engine generators in operation. In the vent of low production level, more load is taken on 2 generators with stoppage of 3rd one so as to maintain the plant performance. The configuration is designed to achieve optimum performance from the CPP under varied loading conditions.

ii. When the engines are operated nearly at 80-100% load, they maintain optimum heat rate and thereby efficiency. Moreover, the steam availability from WHRB is also maintained to as per the process plant requirements. No fired boiler is operated under normal plant running situation. This plant has been found working at excellent efficiency level maintaining attractive economics for the cost of power and steam.

**Utilisation of steam**

i. Maximum steam availability is 10.5 TPH from the cogeneration power plant. Major quantity of steam is utilized in the process for different purposes such as heating, membrane process, etc. the steam is utilised to its condensing temperature in the process. This shows good use of heat energy available as secondary product from the CPP. The condensate is taken back to deaerator to again use as boiler feed water.

ii. The steam is also utilised for heating of heavy fuel oil fired in the reciprocating engines. Earlier, electrical heaters were used for this purpose. With availability of steam from the CPP, the steam heaters are deployed, which has resulted into good saving of electrical energy. The condensate is recovered from FO heaters and sent back to the cogeneration plant for recycling. Thus the losses are minimised to great extent.

**Power Plant Performance Analysis**

i. The plant performance data is not available. However, based on the plant configuration and utilisation of energy in different forms to optimum available from the cogeneration facility, the performance indices can be theoretically derived as follows.

**Table 5.5: Energy-input & output**

|  |  |  |
| --- | --- | --- |
| **Parameter** | **Qty** | **Unit** |
| Fuel oil | 3.63 | MT/hour |
|  | 3630 | Kg/hr |
| Fuel Cal value | 9100 | kCal/kg |
| Energy input | 330.33 | lakh kCal/hr |
| Energy output |  |  |
| Ave. power | 14780 | kWh |
| Heat output | 127.108 | lakh kCal/hr |
| Electrical efficiency | 38.48 | % |
| Steam generated and used | 8.2 | TPH |
| Enthalpy | 664.18 | kCal/kg |
| Energy used | 54.46276 | lakh kCal/hr |
| Total energy used | 181.57076 | lakh kCal/hr |
| Overall Cogen efficiency | 181.57076/330.33 | |
|  | 55 | % |

Plant Load Overall

Factor Efficiency

3 x 6015 kW Reciprocating engine generators 90-95%

3 x 3.5 TPH Waste heat recovery boilers 65-70%

ii. Another point to be worth noted is the maintaining of CPP performance and the plant production levels even without back-up from the state grid for electric power supply. This is very good example of efforts made by this company to supplement the cause of energy conservation.

iii. The average age of the reciprocating engines and waste heat boilers is around 6 years.

iv. There is latest instrumentation system installed for individual engine for the measurement of HFO quantity, which is the essential requirement to monitor the performance. Actual data for steam generation vis-à-vis fuel is also generated precisely.

v. The measurement and monitoring of generator parameters is carried out using latest solid state metering system. The data base is generated for important performance indices such as kWh so as to keep close watch on the performance for all the time.

**Self-Assessment Exercise**

**Q1.** Why cogeneration is required?

**Q2.** What are the different methods of cogeneration? Discuss each of them in brief.

**Q3.** “Topping cycle cogeneration systems are more effective than bottoming cycle cogeneration system”. Explain briefly if the above statement is true or false.

**Q4.** Explain briefly thevarious parameters associated with the performance evaluation of a cogeneration system.

1. . Cengel, Y. A., Turner, R. H., *Fundamentals of Thermal-Fluid Sciences*, Second Edition, Tata McGraw Hill [↑](#footnote-ref-1)
2. . Cengel, Y. A., *Thermodynamics: An Engineering Approach*, 5th Edition, Tata McGraw Hill [↑](#footnote-ref-2)
3. . Cengel, Y. A., *Thermodynamics: An Engineering Approach*, 5th Edition, Tata McGraw Hill [↑](#footnote-ref-3)
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5. . Cengel, Y. A., *Thermodynamics: An Engineering Approach*, 5th Edition, Tata McGraw Hill [↑](#footnote-ref-5)
6. . This section has been adapted from *Energy Efficiency Guide for Industry in Asia,* UNEP [↑](#footnote-ref-6)
7. . Adapted from *Energy Efficiency Guide for Industry in Asia,* UNEP [↑](#footnote-ref-7)
8. . Adapted from *Best Practice Manual: Cogeneration* prepared by Devki Energy Consultancy Pvt. Ltd. [↑](#footnote-ref-8)
9. . This section has been adapted from *Energy Efficiency Guide for Industry in Asia, UNEP* [↑](#footnote-ref-9)