3. ENERGY PERFORMANCE ASSESSMENT OF COGENERATION AND TURBINES (GAS, STEAM)

3.1 Introduction

Cogeneration systems can be broadly classified as those using steam turbines, Gas turbines and DG sets. Steam turbine cogeneration systems involve different types of configurations with respect to mode of power generation such as extraction, back pressure or a combination of back-pressure, extraction and condensing.

Gas turbines with heat recovery steam generators is another mode of cogeneration. Depending on power and steam load variations in the plant the entire system is dynamic. A performance assessment would yield valuable insights into cogeneration system performance and need for further optimisation.

3.2 Purpose of the Performance Test

The purpose of the cogeneration plant performance test is to determine the power output and plant heat rate. In certain cases, the efficiency of individual components like steam turbine is addressed specifically where performance deterioration is suspected. In general, the plant performance will be compared with the base line values arrived at for the plant operating condition rather than the design values. The other purpose of the performance test is to show the maintenance accomplishment after a major overhaul. In some cases the purpose of evaluation could even be for a total plant revamp.

3.3 Performance Terms and Definitions

Overall Plant Performance

1. Overall plant heat rate, kCal/kWh

$$= \frac{\text{Mass flow rate of steam x (Enthalpy of steam, kCal/kg - Enthalpy of feed water, kCal/kg)}}{\text{Power output, kW}}$$

$$\text{2. Overall plant fuel rate kg/kWh} = \frac{\text{Fuel consumption* in kg/hr}}{\text{Power output,kW}}$$

*Total fuel consumption for turbine and steam

Steam Turbine Performance

$$\text{Turbine cylinder efficiency,\%} = \frac{\text{Actual enthalpy drop across the turbine, kCal/kg}}{\text{Isentropic (theoretical) enthalpy drop across the turbine, kCal/kg}} \times 100$$

Gas Turbine Performance

$$\text{Air Compressor efficiency, \%} = \frac{\text{Theoretical temperature rise across the compressor, } ^\circ\text{C}}{\text{Actual temperature rise, } ^\circ\text{C}} \times 100$$

$$\text{Overall Gas turbine efficiency (Compressor + Gas turbine), \%} = \frac{\text{Power output, kW x 860}}{\text{Fuel input for Gas turbine, kg/hr x GCV of fuel, kCal/kg}} \times 100$$

Heat Recovery Steam Generator (HRSG) Performance

Heat Recovery Steam Generator efficiency, %

$$= \frac{\text{steam generated, kg/hr x } (h_s\text{, kCal/kg} - h_w\text{,kCal/kg}) \times 100}{[\text{Mass flow of flue gas, kg/hr x Cp x } (t_{in} - t_{out})] + [\text{ auxiliary fuel consumption, kg/hr x GCV of fuel, kCal/kg}]}$$

where, h_s = Enthalpy of steam
h_w = Enthalpy of feed water
t_{in} = inlet temperature of flue gas
t_{out} = outlet temperature of flue gas

3.4 Reference standards

Modern power station practices by British electricity International (Pergamon Press) ASME PTC 22 - Gas turbine performance test.

3.5 Field Testing Procedure

The test procedure for each cogeneration plant will be developed individually taking into consideration the plant configuration, instrumentation and plant operating conditions. A method is outlined in the following section for the measurement of heat rate and efficiency of a co-generation plant. This part provides performance-testing procedure for a coal fired steam based co-generation plant, which is common in Indian industries.

3.5.1 Test Duration

The test duration is site specific and in a continuous process industry, 8-hour test data should give reasonably reliable data. In case of an industry with fluctuating electrical/steam load profile a set 24-hour data sampling for a representative period.

3.5.2 Measurements and Data Collection

The suggested instrumentation (online/ field instruments) for the performance measurement is as under:

Steam flow measurement : Orifice flow meters
Fuel flow measurements : Volumetric measurements / Mass flow meters
Air flow / Flue gas flow : Venturi / Orifice flow meter / Ion gun / Pitot tubes
Flue gas Analysis : Zirconium Probe Oxygen analyser
Unburnt Analysis : Gravimetric Analysis
Temperature : Thermocouple
Cooling water flow : Orifice flow meter / weir /channel flow/ non-contact flow meters
Pressure : Bourdon Pressure Gauges
Power : Trivector meter / Energy meter
Condensate : Orifice flow meter

It is essential to ensure that the data is collected during steady state plant running conditions. Among others the following are essential details to be collected for cogeneration plant performance evaluation.

I. Thermal Energy :				
		Flow	**Pressure**	**Temperature**
1	Steam inlet to turbine	✓	✓	✓
2	Fuel input to Boiler /Gas turbine	✓	-	-
3	Combustion air	✓	✓	✓
4	Extraction steam to process	✓	✓	✓
5	Back Pressure Steam to Process	✓	✓	✓
6	Condensing steam	✓	✓	✓
7	Condensate from turbine	✓	-	✓
8	Turbine bypass steam	✓	-	-
9	Flue gas to HRSG	-	✓	✓
10	Exit flue gas	-	-	✓ + composition
11	Cooling water to condenser	✓	✓	✓

II. Electrical Energy:

1. Total power generation for the trial period from individual turbines.
2. Hourly average power generation
3. Quantity of power import from utility (Grid)*
4. Quantity of power generation from DG sets.*
5. Auxiliaries power consumption

* Necessary only when overall cogeneration plant adequacy and system optimization / upgradation are the objectives of the study.

3.5.3 Calculations for Steam Turbine Cogeneration System

The process flow diagram for cogeneration plant is shown in figure 3.1. The following calculation procedures have been provided in this section.

- Turbine cylinder efficiency.
- Overall plant heat rate

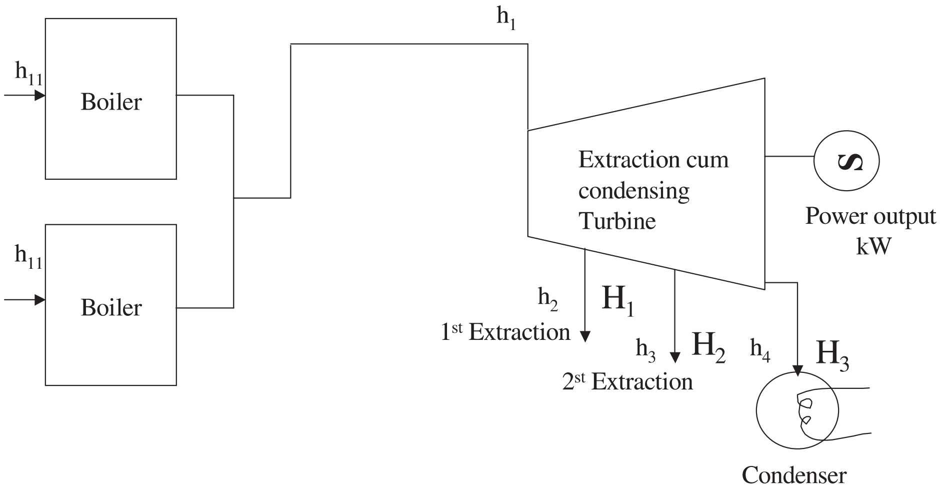

Figure 3.1 Process Flow Diagram for Cogeneration Plant

Step 1 :

Calculate the **actual** heat extraction in turbine at each stage,

Steam Enthalpy at turbine inlet : h_1 kCal / kg
Steam Enthalpy at 1st extraction : h_2 kCal / kg
Steam Enthalpy at 2nd extraction : h_3 kCal / kg
Steam Enthalpy at Condenser : h_{4*} 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 efficiencies.

Heat extraction from inlet to stage –1 extraction (h_5) : $h_1 - h_2$ kCal / kg

Heat extraction from 1^{st} –2^{nd} extraction (h_6) : $h_2 - h_3$ kCal / kg

Heat extraction from 2nd Extraction – condenser (h_7) : $h_3 - h_4$ kCal / kg

Step 2:

From Mollier diagram (H-S Diagram) estimate the theoretical heat extraction for the conditions mentioned in Step 1. Towards this:

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

Theoretical Enthalpy after 1^{st} extraction : H_1
Theoretical Enthalpy after 2^{nd} extraction : H_2
Theoretical Enthalpy at condenser conditions H_3

Theoretical heat extraction from inlet to stage 1 extraction, h_8 : $h_1 - H_1$

Theoretical heat extraction from 1^{st} – 2^{nd} extraction, h_9 : $H_1 - H_2$

Theoretical heat extraction from 2^{nd} extraction – condensation, h_{10} : $H_2 - H_3$

Step 3 :

Compute turbine cylinder efficiency

$$Efficiency\ of\ 1^{st}\ stage\left(\frac{h_5}{h_8}\right) = \frac{Heat\ extraction\ actual}{Heat\ extraction\ theoritical} = \frac{h_1 - h_2}{h_1 - H_1}$$

$$Efficiency\ of\ 2^{nd}\ stage\left(\frac{h_6}{h_9}\right) = \frac{Heat\ extraction\ actual}{Heat\ extraction\ theoritical} = \frac{h_2 - h_3}{H_1 - H_2}$$

Efficiency of condensing stage : $\frac{h_7}{h_{10}}$

Step 4 :

Calculate plant heat rate*

$$\text{Heat rate, kCal / kWh} = \frac{M \times (h_1 - h_{11})}{P}$$

M – Mass flow rate of steam in kg/hr
h_1 – Enthalpy of inlet steam in kCal/kg
h_{11} – Enthalpy of feed water in kCal/kg
P – Average Power generated in kW

*Alternatively the following guiding parameter can be utilised

$$\text{Plant heat consumption} = \frac{\text{fuel consumed for power generation, kg/hr}}{\text{Power generated, kW}}$$

3.6 Example

3.6.1 Small Cogeneration Plant

A distillery plant having an average production of 40 kilolitres of ethanol is having a cogeneration system with a backpressure turbine. The plant steam and electrical demand are 5.1 Tons/hr and 100 kW. The process flow diagram is shown in figure 3.2.Gross calorific value of Indian coal is 4000kCal/kg

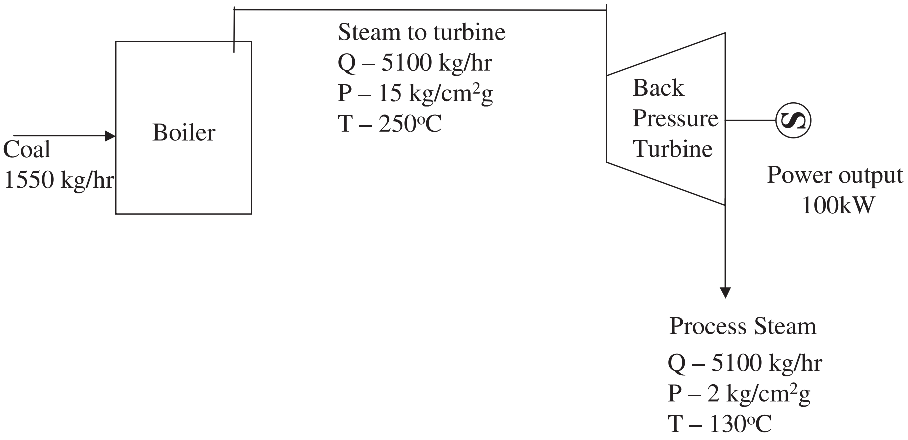

Figure 3.2 Process Flow Diagram for Small Cogeneration Plant

Calculations :

Step 1 :

Total heat of steam at turbine inlet conditions at 15kg / cm^2 and 250°C, h_1 =698 kCal/kg

Step 2 :

Total heat of steam at turbine outlet conditions at 2 kg/cm^2 and 130°C, h_2 = 648 kCal/kg

Step 3 :

Heat energy input to turbine per kg of inlet steam ($h_1 - h_2$) = (698-648) = 50 kCal/kg

Step 4 :

Total steam flow rate, Q_1 = 5100 kg/hr
Power generation = 100 kW
Equivalent thermal energy = 100 x 860 = 86,000 kCal /hr

Step 5 :

Energy input to the turbine = 5100 x 50 = 2,55,000 kCal/hr.

Step 6 :

$$\text{Power generation efficiency of the turbo alternator} = \frac{\text{Energy output}}{\text{Energy Input}} \times 100$$

$$= \frac{86,000}{2,55,000} \times 100 = 34\%$$

Step 7 :

Efficiency of the turbo alternator = 34%
Efficiency of Alternator = 92 %
Efficiency of gear transmission = 98 %

$$\mathit{Efficiency\ of\ Turbine} = \frac{\mathit{Power\ generation\ efficiency\ of\ turbo\ alternator}}{\mathit{Efficiency\ of\ gear\ transmission} * \mathit{Efficiency\ of\ Alternator}}$$

$$= \frac{0.34}{0.98 * 0.92} = 0.38$$

Step 8 :

Quantity of steam bypassing the turbine = Nil

Step 9 :

Coal consumption of the boiler = 1550 kg/hr.

Step 10:

Overall plant heat rate, kCal/kWh

$$= \text{Mass flow rate of steam} \times \frac{(\text{(Enthalpy of steam, kCal/kg} - \text{Enthalpy of feed water, kCal/kg)}}{\text{Power output, kW}}$$

$$= \frac{5100 \times (698 - 30)}{100}$$

$$= 34068 \text{ kCal/kWh*}$$

*Note: The plant heat rate is in the order of 34000 kCal/kWh because of the use of backpressure turbine. This value will be around 3000 kcal/kWh while operating on fully condensing mode. However with backpressure turbine, the energy in the steam is not wasted, as it is utilised in the process.

Overall plant fuel rate including boiler = 1550/100
= 15.5 kg coal / kW

Analysis of Results:

The efficiency of the turbine generator set is as per manufacturer design specification. There is no steam bypass indicating that the power generation potential of process steam is fully utilized. At present the power generation from the process steam completely meets the process electrical demand or in other words, the system is balanced.

Remarks: Similar steps can be followed for the evaluation of performance of gas turbine based cogeneration system.

QUESTIONS

1. What is meant by plant heat rate? What is its significance?
2. What is meant by turbine cylinder efficiency? How is it different from turbo-generator efficiency?
3. What parameters should be monitored for evaluating the efficiency of the turbine?
4. What is the need for performance assessment of a cogeneration plant?
5. The parameters for back pressure steam turbine cogeneration plant is given below

   Inlet Steam: P =16 kg/cm^2, T = 310°C, Q = 9000kg/hr
   Outlet Steam: P = 5.0 kg/cm^2, T = 235°C, Q = 9000kg/hr
   Find out the turbine cylinder efficiency?
6. Explain why heat rate for back pressure turbine is greater than condensing turbine.
7. Explain the methodology of evaluating performance of a gas turbine with a heat recovery steam generator.

REFERENCES

1. NPC report on 'Assessing cogeneration potential in Indian Industries'
2. Energy Cogeneration Handbook, George Polimeros, Industrial Press Inc.