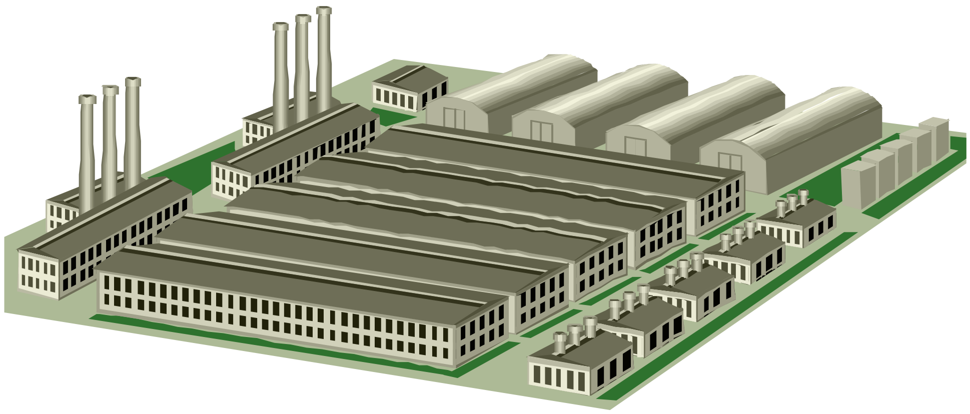
BEST PRACTICE MANUAL



COGENERATION

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2006

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1. INTRODUCTION

1.1 Background

Cogeneration first appeared in late 1880s in Europe and in the U.S.A. during the early parts of the 20th century, when most industrial plants generated their own electricity using coal-fired boilers and steam-turbine generators. Many of the plants used the exhaust steam for industrial processes.

When central electric power plants and reliable utility grids were constructed and the costs of electricity decreased, many industrial plants began purchasing electricity and stopped producing their own. Other factors that contributed to the decline of industrial cogeneration were the increasing regulation of electric generation, low energy costs which represent a small percentage of industrial costs, advances in technology such as packaged boilers, availability of liquid or gaseous fuels at low prices, and tightening environmental restrictions.

The aforementioned trend in cogeneration started being inverted after the first dramatic rise of fuel costs in 1973. Systems that are efficient and can utilise alternative fuels have become more important in the face of price rises and uncertainty of fuel supplies. In addition to decreased fuel consumption, cogeneration results in a decrease of pollutant emissions. For these reasons, governments in Europe, U.S.A. South East Asia and Japan are taking an active role in the increased use of cogeneration. In India, the policy changes resulting from modernized electricity regulatory rules have induced 710 MW of new local power generation projects in Sugar Industry. Other core sector industries are also already moving towards complete self generation of heat and electricity.

This manual discusses selection & operational issues in common cogeneration systems. Case studies are presented in Chapter-7 to give more insight into the operating parameters of cogeneration systems exist in core industrial sectors.

2 WHAT IS COGENERATION?

2.1 Introduction

By definition, Cogeneration is on-site generation and utilisation of energy in different forms simultaneously by utilising fuel energy at optimum efficiency in a cost-effective and environmentally responsible way. Cogeneration systems are of several types and almost all types primarily generate electricity along with making the best practical use of the heat, which is an inevitable by-product.

The most prevalent example of cogeneration is the generation of electric power and heat. The heat may be used for generating steam, hot water, or for cooling through absorption chillers. In a broad sense, the system, that produces useful energy in several forms by utilising the energy in the fuel such that overall efficiency of the system is very high, can be classified as Cogeneration System or as a Total Energy System. The concept is very simple to understand as can be seen from following points.

- Conventional utility power plants utilise the high potential energy available in the fuels at the end of combustion process to generate electric power. However, substantial portion of the low-end residual energy goes to waste by rejection to cooling tower and in the form of high temperature flue gases.
- On the other hand, a cogeneration process utilises first the high-end potential energy to generate electric power and then capitalises on the low-end residual energy to work for heating process, equipment or such similar use.
- Consider the following scenario. A plant require 24 units of electrical energy and 34 units of steam for its processes. If the electricity requirement is to be met from a centralised power plant (grid power) and steam from a fuel fired steam boiler, the total fuel input needed is 100 units. Refer figure-2.1 (top)

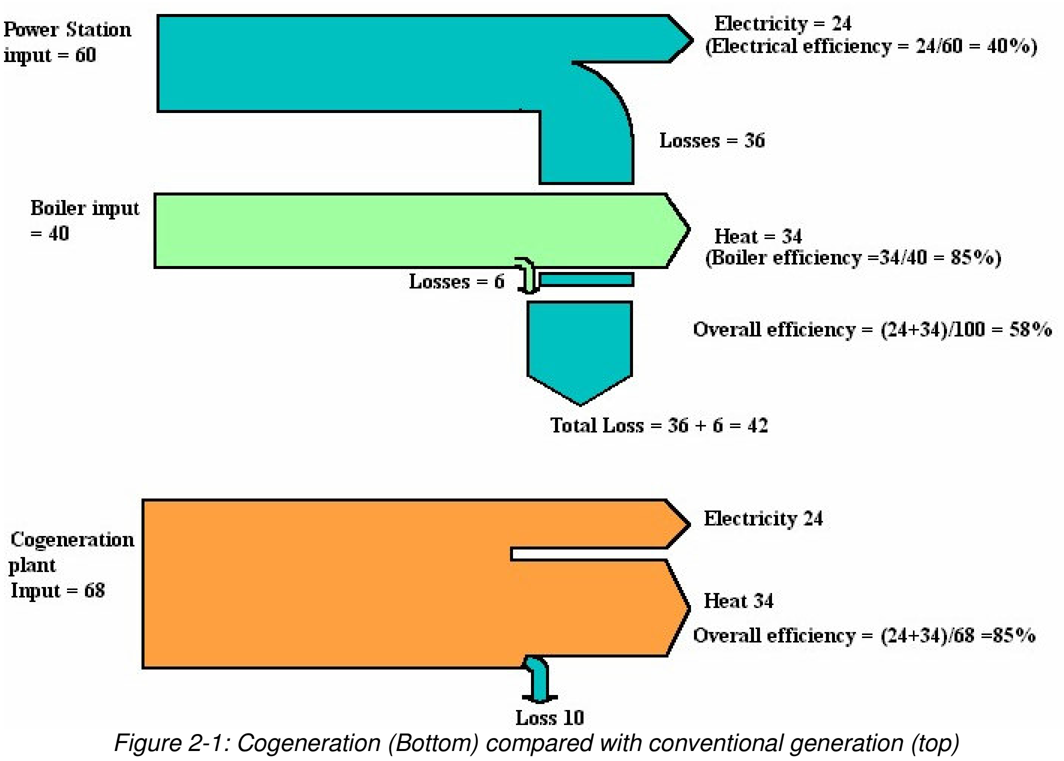


Figure 2-1: Cogeneration (Bottom) compared with conventional generation (top)

If the same end use of 24 units of electricity and 34 units of heat, by opting for the cogeneration route , as in fig 2.1 (bottom), fuel input requirement would be only 68 units compared to 100 units with conventional generation.

For the industries in need of energy in different forms such as electricity and steam, (most widely used form of heat energy), the cogeneration is the right solution due to its viability from technical, economical as well as environmental angle.

2.2 Heat-to-Power ratio

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.

Definition of heat-to-power ratio is thermal energy to electrical energy required by the industry. Basic heat-to power ratios of the cogeneration system variants are shown in Table 2.1 below along with some technical parameters. The steam turbine based cogeneration system can be considered over a large range of heat-to-power ratios.

Table 2-1: Heat-to-Power ratios and other Parameters of Cogen Systems

Cogeneration System	Heat-to-power ratio (kW_{th}/kW_e)	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

2.3 Cogeneration equipment - combinations

Cogeneration technology uses different combinations of power and heat producing equipment, which are numerous. Most widely used combinations are mentioned below.

i. **Steam turbine & fired boiler based cogeneration system**

Boiler	Steam turbine
Coal/Lignite fired plant	Back-pressure steam turbine
Liquid Fuel fired plant	Extraction & condensing steam turbine
Natural gas fired plant	Extraction & back-pressure steam turbine
Bagasse/Husk fired plant	

ii. **Gas turbine based cogeneration system**

Gas turbine generator	Waste heat recovery
Natural gas fired plant	Steam generation in unfired/supplementary
Liquid fuel fired plant	fired/fully fired waste heat recovery boiler
	Utilisation of steam directly in process
	Utilisation of steam for power generation
	From steam turbine generator
	[Cogeneration-cum-combined cycle]
	Absorption Chiller [CHP System]
	Utilisation of heat for direct heating

iii. **Reciprocating engine based cogeneration system**

Reciprocating engine	Waste heat recovery
Liquid fuel fired plant	Steam generation in unfired/supplementary
Natural gas fired plant	fired waste heat recovery boiler
	Absorption Chiller [CHP System]
	Utilisation of steam directly in process
	Utilisation of heat for direct heating

3 TYPES OF COGENERATION SYSTEMS

3.1 Introduction

It is needless to mention that unless all required aspects are considered at the conceptual stage of cogeneration system by the industry, no best practice would be able to provide and maintain the optimum performance at its operational stage. Hence, it is essential to conduct detailed feasibility study while selecting the cogeneration system for particular type of industry. The cogeneration system suitable to one industry would not be found suitable for another industry, though both would be manufacturing the same product. Choosing of right type of cogeneration system would boost the industry's economics, provide energy in reliable way, improve environmental performance, etc. The feasibility study at conceptual stage is better known as the optimisation study.

3.2 Cogeneration in industries

All continuous process chemical plants such as fertilizers, petrochemicals, hydrocarbon refineries, paper and pulp manufacturing units, food processing, dairy plants, pharmaceuticals, sugar mills, etc always require an uninterrupted input of energy in the form of electric power and steam to sustain the critical chemical processes. It is established fact that if these types of industrial plants set up the cogeneration systems with an appropriate power-and-heat balance, they would be able to achieve optimum cogeneration plant efficiency with best possible use of fuel, the primary source of energy.

Small continuous process chemical industrial units generally depend on the grid power, while generating process steam through conventional fired industrial boilers. Large and medium scale chemical industries can implement duly engineered feasible cogeneration system to meet their requirement of essential energy inputs - power and steam (at a desired parameters) achieving better availability, reliability and economics of the plant operations.

3.3 Cogeneration technology

A proper selection of a cogeneration system configuration, from a few basic system configurations described below, makes it feasible to produce first either electrical energy or thermal energy.

1 Steam turbine based cogeneration system
2 Gas turbine based cogeneration system
3 Combined steam/gas turbine based cogeneration system
4 Reciprocating engine based cogeneration system

Most widely used cogeneration systems in the chemical process industrial plants are based on steam turbine, gas turbine or combined steam/gas turbine configurations with installations based on reciprocating engine configuration in moderate number. These configurations are widely accepted by the industries due to their proven track record and easy commercial availability of required equipment. The cogeneration system based on sterling engine concept is still under development stage and hence not described in further detail.

All combinations of cogeneration systems are based on the First and Second Laws of Thermodynamics. Basic concepts of possible different configurations of cogeneration systems, consisting of a primary energy source, a prime mover driven electric power generator and arrangement to use the waste heat energy rejected from the prime mover, are briefly described along with the system schematic diagrams.

3.3.1 Steam turbine based cogeneration system

This system works on the principle of Rankine cycle of heat balance. In Rankine cycle, the fuel is first fired in a suitable boiler to generate high-pressure steam at predetermined parameters. The steam so produced is then expanded through a steam turbine to produce mechanical power/ electricity and a low-pressure steam. The steam turbine could be of backpressure type, extraction-cum-condensed type or extraction-cum-back pressure type depending on different levels and parameters at which the steam is required by the chemical process in that particular plant. Cogeneration system with backpressure steam turbine is schematically represented in Fig.3.1.

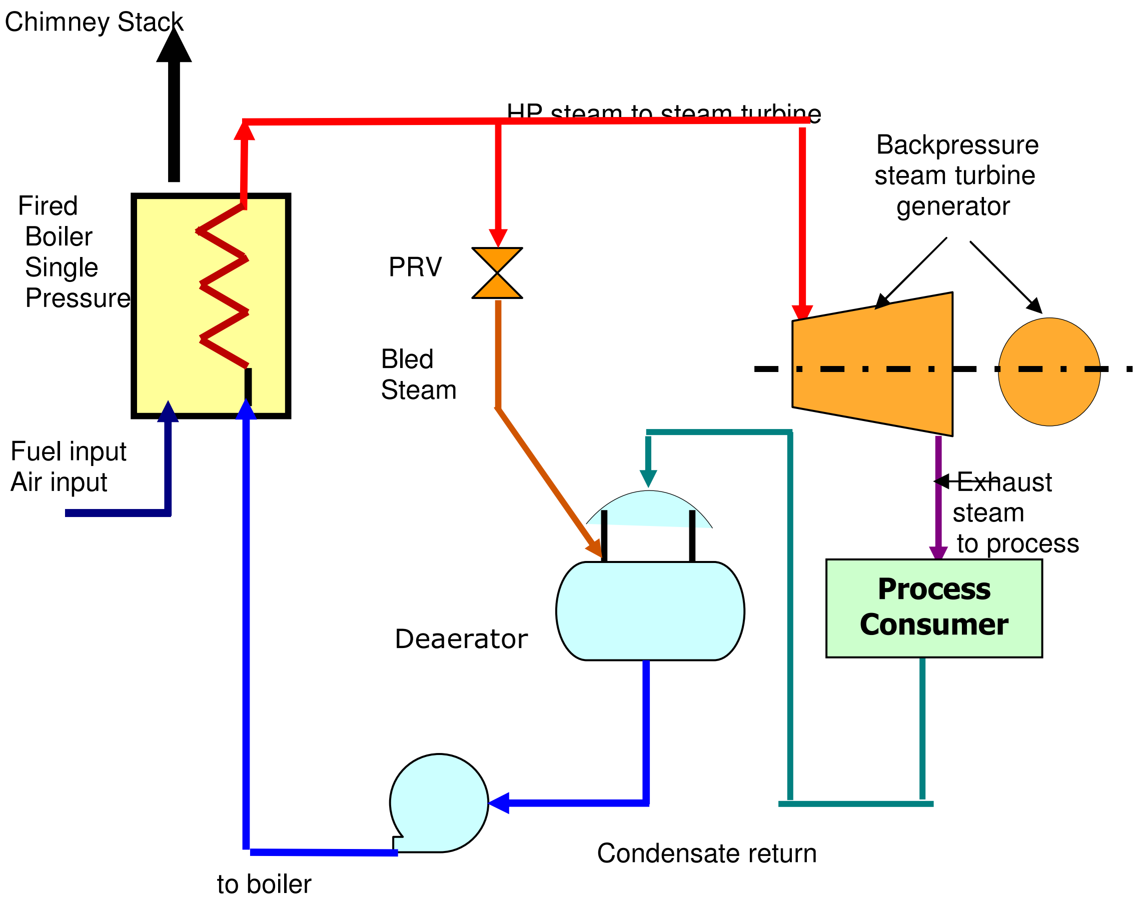


Figure 3-1: Backpressure steam turbine based cogeneration system

In a conventional fossil fuel fired power plant, maximum fuel efficiency of about 35% is achieved. Maximum heat loss occurs by way of the heat rejection in a steam condenser where a straight condensing steam turbine is used. Some improvement in the efficiency could be attained through extraction-cum-condensing steam turbine instead of straight condensing type as shown in Fig.3.2. The steam so extracted could be supplied to either process consumer or to heat the feed water before it enters into boiler. As seen from above, the rejected heat energy from the steam turbine is most efficiently used to meet the thermal energy requirement of that particular chemical process by adopting non-condensing steam turbine based cogeneration system. The overall efficiency of around 80-85% is achieved in this type of plant configuration.

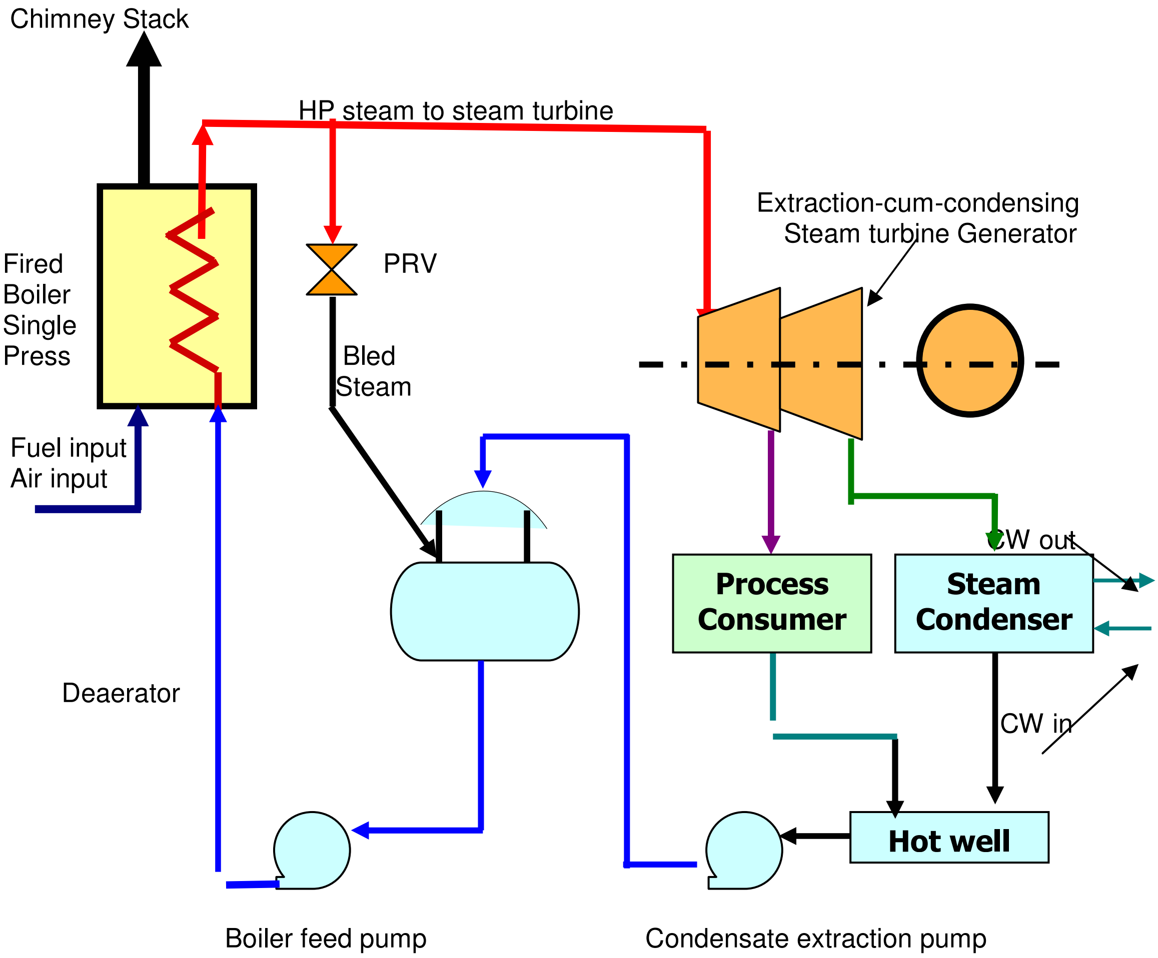


Figure 3-2 Extraction-cum-condensing steam turbine based cogeneration system

The selection of steam turbine for a particular cogeneration application depends on process steam demand at one or more pressure/temperature levels, the electric load to be driven, power and steam demand variations, essentiality of steam for process, etc. The steam to power ratio also plays a role in selection of the steam turbine. Generation of very high-pressure steam and low back pressure at steam turbine exhaust would result into small steam to power ratio. Smaller value of ratio would indicate the lower utilisation value of steam for heating or process purpose. The flexibility in steam to power ratio can be obtained by using steam turbines with regulated extraction.

Steam turbine based cogeneration systems can be fired with variety of fossil fuels like coal, lignite, furnace oil, residual fuel oil, natural gas or non-conventional fuels like bio-gas, bagasse, municipal waste, husk, etc. Hence, the fuel flexibility for this type of system is excellent. However, this configuration is not recommended for smaller installations as it is more expensive and maintenance oriented. It is also not feasible to adopt this system if the chemical industry is located nearer to a populated area, as it becomes a major source of environmental pollution depending upon type of fuel used, i.e. coal, lignite or furnace oil.

3.3.2 Gas turbine based cogeneration system

This type of system works on the basic principle of Bryton cycle of thermodynamics. Air drawn from the atmosphere is compressed and mixed in a predetermined proportion with the fuel in a combustor, in which the combustion takes place. The flue gases with a very high temperature from the combustor are expanded through a gas turbine, which drives electric generator and air compressor. A portion of mechanical power is used for compression of the combustion air: the balance is converted into electric power. The exhaust flue gases from the gas turbine, typically at a high temperature of 480-540 ^{0} C, acts as a heat source from which the heat is recovered in the form of steam or hot air for any desired industrial application.

Industrial gas turbine based power plants installed to generate only electric power operate at the thermal efficiency of 25-35% only depending of type and size of gas turbine. Aero derivative gas turbines operate at marginal higher efficiency than the conventional industrial heavy-duty machines. With recovery of heat in exhaust flue gases in a waste heat recovery boiler (WHRB) or heat recovery steam generator (HRSG) to generate the steam, overall plant efficiency of around 85-90% is easily achieved. As an alternative, the heat of exhaust flue gases can also be diverted to heat exchanger to generate hot water or hot air (District Heating purpose in foreign countries) instead of generating steam. Figure 3.3 shows a schematic of Gas Turbine based cogeneration system.

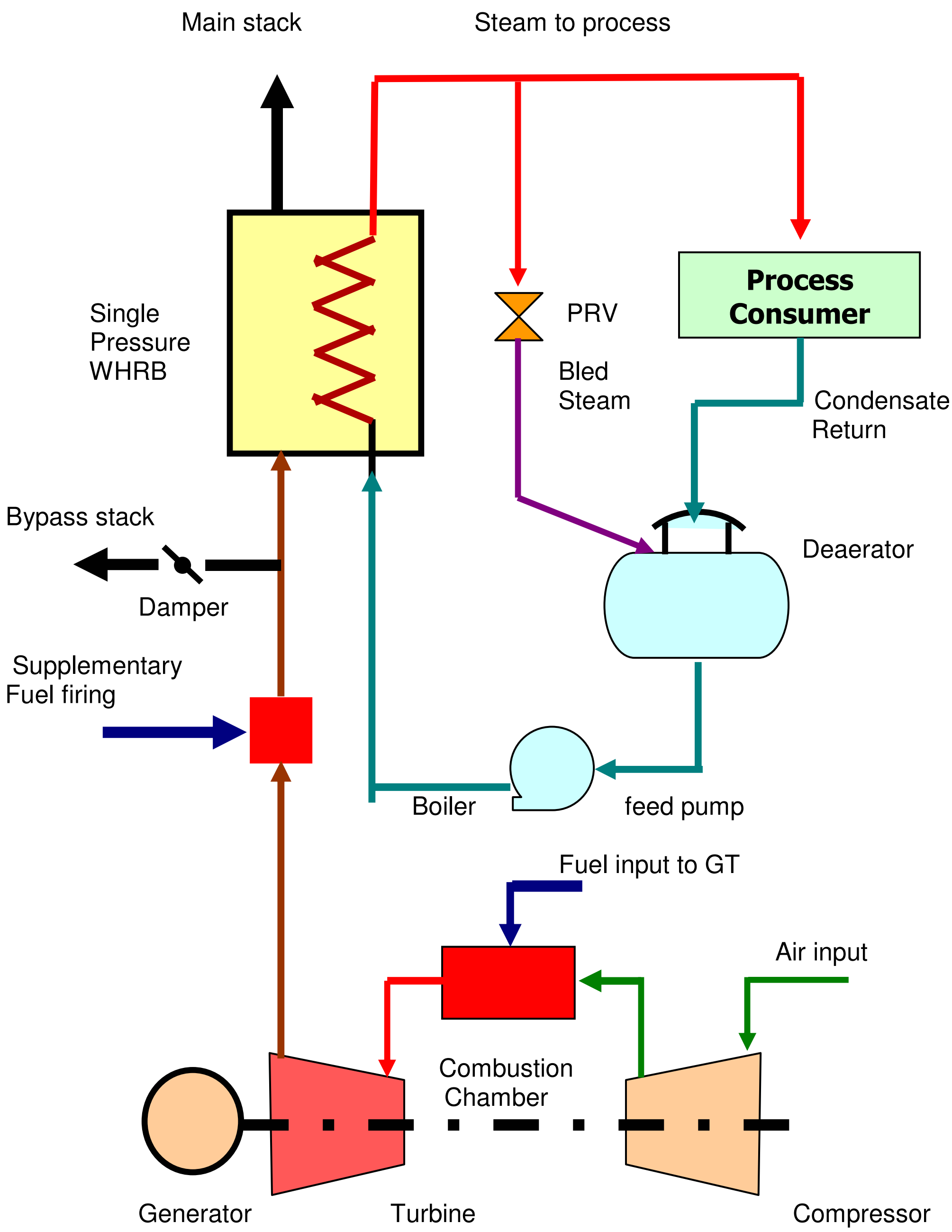


Figure 3-3: Gas turbine based cogeneration system with supplementary fired WHRB

Compared to steam turbine based cogeneration system, the gas turbine based cogeneration system is ideal for the chemical process industries where the demand of steam is relatively high and fairly constant in comparison to that of steam.

Gas turbine based cogeneration system gives a better performance with clean fuels like natural gas, or non-ash bearing or low ash bearing liquid hydrocarbon fuels like Naphtha, High speed diesel, etc. Though high ash bearing hydrocarbon based fuels like fuel oil, crude oil or residual fuel oil can also be fired in the gas turbines, but with some inherent problems like frequent cleaning of gas turbine, more maintenance and spares, etc.

Another major drawback is that when the demand of power drops below 80% of gas turbine capacity, the specific fuel consumption increases and the steam output from WHRB also drops. The steam output can be maintained by resorting to a supplementary fuel firing in WHRB. The burners for supplementary firing are generally installed in the exhaust flue duct provided between the gas turbine and WHRB, and are designed to enable WHRB to maintain full steam output even when the gas turbine is partly loaded. This system ensures a high flexibility in design and operation of the plant, as it is possible to widely vary ratio of steam to power loads without very much affecting the overall plant efficiency. In case of exhaust duct based supplementary firing, the fuel requirement is substantially reduced proportionate to additional steam generated due to presence of about 15% hot unburned Oxygen in exhaust flue gases.

The gas turbine based cogeneration scheme with the supplementary-fired WHRB, with firing in duct between gas turbine and WHRB, is shown in Fig. 3.3. If supplementary firing is not provided, it is becomes a simple cogeneration system consisting of gas turbine generator and WHRB.

3.3.3 Combined steam/gas turbine based cogeneration system

It is clear from the title of system itself that it works on the basis of combination of both Rankine and Bryton cycles, and hence it is called combined steam/gas turbine based cogeneration system. In this system, fuel energy is first utilised in operating the gas turbine as described in Gas turbine based cogeneration system. Waste heat of high temperature exhaust flue gases from the gas turbine is recovered in WHRB to generate a high-pressure steam. This high-pressure steam is expanded through a back-pressure steam turbine, or an extraction-cum-back pressure steam turbine, or an extraction-cum-condensing steam turbine to generate some additional electric power. The low-pressure steam available either from the exhaust of back-pressure steam turbine or from extraction is supplied to the process consumer. Such combination of two cycles gives a definite thermodynamic advantage with very high fuel utilisation factor under various operating conditions.

When the ratio of electrical power to thermal load is high, the cogeneration plant based on combined cycle principle provides better results than the plant based on only back pressure steam turbine due to availability of additional power from steam turbine, besides low pressure steam, without firing of any extra fuel. If supplementary firing is resorted to in WHRB, as mentioned in case of Gas Turbine based system, to maintain steam supply during low loads on gas turbine, the operational flexibility of such plants can be brought nearer to extraction-cum-condensing steam turbine.

The process in which the demand of electricity remains very high even when the demand of steam is very low, then extraction-cum-condensing steam turbine can be used instead of back pressure steam turbine. The control concept is similar to that as mentioned above, except that the steam turbine generator also participates in control of electrical output. The process steam is controlled by steam turbine bypass valve. In case of zero process steam output, the control range of electrical power output is extended by allowing almost total steam exhaust from steam turbine to go to the condenser for that particular duration.

Process steam requirements at different parameters can also be satisfied in combined cycle system by installing either a condensing steam turbine with double extraction, or a back pressure turbine with one or two extraction.

Combined gas-cum-steam turbine system based cogeneration achieves overall plant efficiency of around 90% with optional fuel utilisation. In addition to this, the combined cycle plants are most economical in many cases due to very low heat rates, low specific capital cost of gas turbine plants and availability of power from open cycle operation of gas turbine plant, as it requires lesser time for erection. Major drawback of this system is less fuel flexibility as in case of gas turbine based cogeneration system.

3.3.4 Reciprocating engine based cogeneration system

In this system, the reciprocating engine is fired with fuel to drive the generator to produce electrical power. The process steam is then generated by recovery of waste heat available in engine exhaust in WHRB. The engine jacket cooling water heat exchanger and lube-oil cooler are other sources of waste heat recovery to produce hot water or hot air. The reciprocating engines are available with low, medium or high-speed versions with efficiencies in the range of 35 - 42 %.

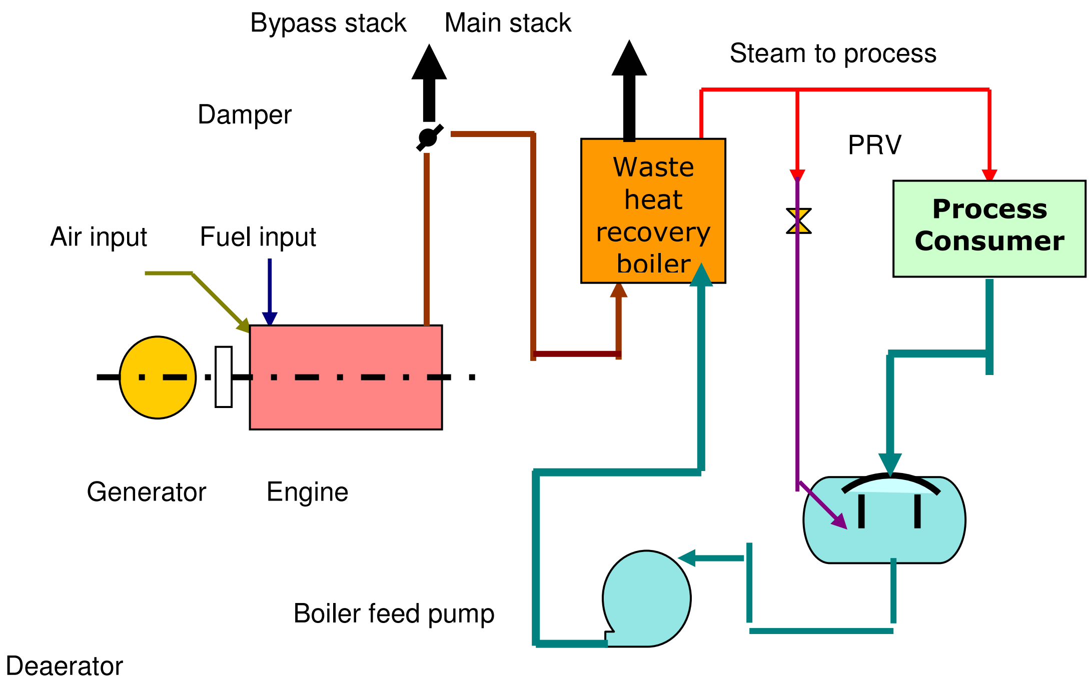


Figure 3-4: Reciprocating engine based cogeneration system with unfired WHRB

Generally, low speed reciprocating engines are available with high efficiencies. The engines having medium and high speeds are widely used for cogeneration applications due to higher exhaust flue gas temperature and quantity. When diesel engines are operated alone for power generation, a large portion of fuel energy is rejected via exhaust flue gases. In cogeneration cycle, practically all the heat energy in engine jacket cooling water and lube-oil cooler, and substantial portion of heat in exhaust gases is recovered to produce steam or hot water. With this, the overall system efficiency of around 65-75% is achieved. The system configuration is shown in Fig. 3.4.

The heat rates of reciprocating engine cycles are high in comparison to that of steam turbine and gas turbine based cogeneration systems. This system is particularly suitable for application requiring a high ratio of electric power to steam.

Reciprocating engines can be fired only with hydrocarbon based fuels such as High speed diesel, Light diesel oil, residual fuel oils, Natural gas, etc. The engines are developed in which natural gas is also directly fired. In view of lower overall fuel efficiency as mentioned above, the system is not economically better placed compared to steam turbine or gas turbine based cogeneration systems, particularly where power and steam are continuously in demand. Further to above, diesel engines are more maintenance oriented and hence generally preferred for operating intermittently, or as stand by emergency power source. These are major drawbacks preventing widespread use of diesel engine based cogeneration system.

3.4 Factors for selection of cogeneration system

Following factors should be given a due consideration in selecting the most appropriate cogeneration system for a particular industry.

- 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.

3.4.1 Typical Heat-to-Power ratio in various industries

As discussed, energy in forms of electricity and usable heat or cooling is generated in cogeneration plant using a single process. Proportionate requirement of heat and power varies from site to site. Hence, cogeneration system must be selected with due care and appropriate operating schemes must be installed to match the demands as per requirement. Typical Heat-to-Power ratios for certain energy intensive industries are provided in Table 3.1 below.

Table 3-1: Typical Heat-to-Power Ratios for Energy Intensive Industries

Industry	Minimum	Maximum	Average
Breweries	1.1	4.5	3.1
Pharmaceuticals	1.5	2.5	2.0
Fertilizer	0.8	3.0	2.0
Food	0.8	2.5	1.2
Paper	1.5	2.5	1.9

Concept of cogeneration would be generally found most attractive with existence of following circumstances in the industries.

- The demand of steam and power both is more or less equal, i.e. consistent with the range of power-to-steam output ratios that can be obtained from a suitable cogeneration plant.

- A single industry or group of industries requires steam and power in sufficient quantum to permit economies of scale to be achieved.

- Peak and troughs in demand of power and steam can be managed or, in case of power, adequate back-up capacity can be obtained from the utility company.

It may be required to make certain assumptions while assessing various system alternatives with reference to above aspects, as most of these specific factors may be unknown for general considerations.

3.4.2 Operating strategies for cogeneration plant

The cogeneration plant may be operated within three main operating regimes as follows to take optimum techno-economic benefits.

- The cogeneration plant is operated as base load station to supply electric power and thermal energy and short fall in power is drawn from the utility company and heat from standby boilers or thermic fluid heaters.

- The cogeneration plant is operated to supply electric power in excess of the industry's requirements, which may be exported, whilst total thermal energy available is utilised in the industry.

- The cogeneration plant is operated to supply electric power , with or without export, and thermal energy produced is utilised in the industry with export of surplus heat energy, if feasible, to nearby consumers.

3.5 Techno-economic advantages of cogeneration technology

Following techno-economical advantages are derived by making application of cogeneration technology to meet the energy requirements of the industries.

- First and foremost is the cogeneration technology's conformance to vital and widely discussed concept of energy conservation due to highly efficient use of fuel energy through system optimisation studies prior to project execution.

- With relatively lower capital cost and low operating cost, due to high overall plant efficiency, the cost of power and steam becomes economically quite attractive for the industry. Recurring costs are also lesser.

- Industrial cogeneration plants supplement the efforts of the state electricity boards to bridge the ever-widening gap between supply and demand of power by very efficient power generation in-house.

- As electricity from a cogeneration system is generally not required to be transferred over a long distances, the transmission and distribution losses would be negligible.

- Reliability of cogeneration systems is very high, which also reduces dependency of industries on the state electricity board grids for power requirements to bear minimum. This would save the plant from unexpected disturbances of power system.

- Impact on environmental pollution from cogeneration system is low in comparison to large size power plants due to less consumption of fuel and efficient operation.
- If cogeneration systems are implemented in sugar mills or rice mills, totally renewable source of energy or waste fuel such as bagasse or rice husk can be used to fire the boiler to generate steam. This steam can be used to drive the steam turbine. This would save the precious national fossil fuel resources.

Table 3.2 shows a summary of relative advantages and disadvantages of present day widely accepted different variants for cogeneration systems as a reference. Each system has got its own merits and demerits, which is required to be considered on case-to-case basis while selecting cogeneration system for a particular industry.

3.6 Why cogeneration for industry

It is universally accepted fact that the primary sources of energy like fuels are fast depleting as they all are non-renewable in nature. The costs of these primary sources of energy have been showing upward trend since last twenty years or so. Hence, it has become a challenge for all developing nations to save energy to a much greater extent so as that the primary sources of energy last longer and longer.

Based on foregoing discussion, it can be authentically said that use of cogeneration system in industrial sector is one of the best viable options for energy conservation in the most effective and economical way. Depending on type of process or engineering industry, its requirement of power and steam, their essentiality, etc., an appropriate cogeneration system can be easily selected by considering all the factors described below.

Table 3-2: Advantages/Disadvantages of Cogeneration System Variants

Variant	Advantages	Disadvantages
Back Pressure Steam Turbine and Fuel firing in Conventional Boiler	- High fuel efficiency rating - Very simple Plant - Well suited to all types of fuels of high or low quality - Good part load efficiency - Moderate relative specific capital cost	- Little flexibility in design and operation - More impact on environment in case of use of low quality fuel - Higher civil construction cost due to complicated foundations
Extraction-cum-Condensing Steam Turbine and fuel firing in Conventional Boiler	- High flexibility in design and operation - Well suited to all types of fuels, high quality or low quality - Good part load efficiency - More suitable for varying steam demand	- More specific capital cost - Low fuel efficiency rating, in case of more condensing - More impact on environment in case of use of low quality fuel - Higher civil construction cost due to complicated foundations - High cooling water demand for condensing steam turbine
Gas Turbine with Waste Heat Recovery Boiler	- High fuel efficiency at full load operation - Very simple plant - Low specific capital cost - 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	- Moderate part load efficiency - Limited suitability for low quality fuels - Not economical, if constant steam load a problem
Combined Gas and Steam Turbine with Waste Heat Boiler	- Optimum fuel efficiency rating - Relatively low specific capital cost - Least gestation period - Less impact on environment - High operational flexibility - Quick start and stop	- Average to moderate part load efficiency - Limited suitability for low quality fuels - High civil construction cost due to more and complicated

	- Still better efficiency with supplementary firing in Waste heat recovery boiler	foundations/buildings - More cooling water demand with condensing steam turbine
Reciprocating Engine and Waste Heat Recovery Boiler with Heat Exchanger	- Low civil construction cost due to block type foundations and least nos. of auxiliaries - High electrical power efficiency - Better suitability as emergency standby plant - Least specific capital cost - Low cooling water demand	- Low overall plant efficiency in cogeneration mode - Suitability for low quality fuels with high cleaning cost - High maintenance cost - More impact on environment with low quality fuel - Least potential for waste heat recovery

Out of all the variants, cogeneration systems based on combined cycle configurations with cogeneration of power and heat permit the optimal utilisation of fuel energy in the true sense of Second Law of Thermodynamics. Besides highest fuel efficiency and by virtue of its low capital cost, the combined cycle based option has been found the most acceptable and economical solution.

Steam turbine based cogeneration systems are of greater interest to the industries with moderately large and stable steam demand, and further where it is necessary to use fuels of lower quality like coal, lignite, furnace oil, etc which can not be directly fired in gas turbines. Though high ash bearing dirty fuels like residual fuel oil or furnace oil can be fired in gas turbines, but only to some limited extent due to inherent problems associated with it.

4 COGENERATION WITH STEAM TURBINE CYCLE

4.1 Introduction

The steam turbine based cogeneration is the oldest and most prevalent in our country. The factors considered for choosing of steam turbine for different applications are reliability, variable speed operation and possibility of energy savings. Besides power generation, the steam turbines are used as prime-mover for many process equipment such as pumps, fans, blowers and compressors. It is generally preferred to keep steam turbine driven equipment for running critical services, where power tripping may cause serious problems.

For the continuous process plants requiring energy in the forms of power and steam in more or less same quantum (ratio of power: heat generally around 1), the steam turbine based cogeneration is an ideal solution to optimise the cogeneration system for energy saving and economy. The electrical efficiency of industrial duty steam turbine generators varies over a wide range depending on whether the steam turbine is extraction-cum-condensing type or back-pressure type. However, it is feasible to achieve significantly high level of overall system efficiency, more than 80%, through optimum use of heat energy available in extraction steam or back-pressure exhaust steam. Thus, by utilising energy available in fuel, first to generate electric power and then as steam, principle concept of cogeneration is satisfied to great extent.

For the plant having frequent power as well as steam load fluctuations, the steam turbines offer the best solution for energy saving, as the load variation on steam turbine would not significantly affect the heat rate. If fluctuation for power and steam would go hand in hand, the best performance would be available from this system. In case, there is fluctuating steam load with more or less constant power load, some steam may go to waste, which may marginally decrease overall cogeneration efficiency.

The steam turbine based cogeneration plant consists of a steam turbine generator of back-pressure, extraction-cum-back pressure or extraction-cum-condensing type in accordance with requirement of steam for the process plant and a steam generator or boiler fired with conventional fuels such as coal, lignite, fuel oil, natural gas, etc. or non-conventional fuels such as bagasse, rice husk, etc. Single stage steam turbines are used where the power requirement is low and multi-stage steam turbines are used for meeting high power requirements.

4.2 Performance of Steam turbines

Performance of steam turbines is expressed in terms of Theoretical Steam Rate (TSR) and Actual Steam Rate (ASR), which is the quantity of heat in kJ required to generate one kWh of electric power.

TSR and ASR can be determined from the power generation and the steam input log data. Efficiency of steam turbine is directly proportional to the steam pressure drop through the turbine, i.e. greater the steam pressure drop, greater will be the power output. A reduction in steam turbine exhaust steam pressure results into more power generation than an increase in pressure of steam at turbine inlet. Following technical factors may be noted in this regard.

- Specific steam consumption depends on the absolute pressure ratio of the turbine.

- Back-pressure steam turbines are providing better thermal efficiency in the range of 70 – 85%.
- Extraction-cum-condensing/back-pressure steam turbines are commonly installed for total generation schemes due to their excellent flexibility to meet power requirement coupled with the steam requirement at different levels. Such systems achieve thermal efficiency in the range of 50 – 75%.
- Condensing steam turbines works at low thermal efficiency between 15 – 35% due to wastage of substantial useful heat in condensing of the steam.

4.3 Practices for optimising steam turbine performance

The steam turbines operated in following mode would provide the optimum performance.

4.3.1 Design stage

In the continuous process industry, the demands of steam are generally very specific for a given process and the capacity of the plant envisaged. The steam flow, pressure and temperature levels are dictated by the equipment at the consumption point. Hence, the pressure levels required from the steam turbine are fixed for extraction or extraction/back-pressure. At the design stage of the system, the process steam demands and power demands should be integrated – either electrical power or power for mechanical drive applications I in the best possible manner, in a steam turbine, keeping in view the consideration for high basic efficiency. Ideal solution is a back-pressure steam turbine. If the steam demand is such that, less power is produced than the plant requirement, a condensing portion will have to be considered along with extraction. This would result in lower efficiency, but would attain desired balance of power and steam requirements.

4.3.2 Plant operating stage

i. **Best operational mode**

Power or heat operated - Depending on the total power load of the industry, number of steam turbines are arranged on one line so that one or more steam turbines can be operated according to demand of power. With such philosophy of operation, it is possible to run the turbines close to the optimal operating range.

ii. **Steam conditions**

Decentralised cogeneration power plants of low and medium output in the range of 1 to 10 MW can be considered. Input steam conditions may be fixed between 30 - 70 bar and live steam temperature may be fixed between 400 – 500 ^{0}C to obtain desired steam turbine performance.

iii. **Steam quality**

Maintaining of steam quality injected into a steam turbine as per specified parameters is one of the vital factors for performance of equipment. Steam quality depends on the quality of DM water and boiler feed water sent to the boiler. On-line monitoring of steam conductivity is must as a part of instrumentation, which provides the data whether any impurity is going to the turbine. Normally steam and water samples are collected at least once in eight hours and analysed to ascertain the quality.

iv. **Control for steam turbines**

Control of the steam turbines can be achieved through the following optional facilities.

- A throttle valve in front of the steam turbine may be installed through which steam pressure of flow leading from the steam line to the individual turbines as well as their output would be controlled.

- A nozzle group control may be provided in the individual turbine, which would permit individual nozzles before the first blade wheel (control wheel) to switch in or off to control the mass flow rate of the other stages as well as to regulate the output.

v. **Monitoring for steam turbines**

Continuous or on-line monitoring of following parameters would be vital to avoid fall in the steam turbine performance.

- Monitoring of conductivity of steam to ensure silica content in steam, as silica would deposit on the blades to adversely affect the output.
- Monitoring of axial differential expansion, vibrations, etc. must be carried out using suitable microprocessor based instrumentation.
- Monitoring of lube-oil circulation in bearings along with continuous cleaning of lube-oil through centrifuge is very important.

4.3.3 Plant maintenance stage

Generally, the periodic preventive maintenance of steam turbine is carried out as follows.

- Inspection of steam turbines and steam pipelines may be carried out at least once a week for observing irregularities.
- Thorough inspection and overhauling may be resorted to every 5 years.

5 COGENERATION WITH GAS TURBINE CYCLE

5.1 Introduction

The gas turbine based cogeneration is relatively new entrant in our country existing since last 20 years or so. The factors considered for choosing of gas turbine for different applications are reliability, quick start/stop, less maintenance, quick maintenance time, availability of useful heat for direct heating or steam generation and possibility of energy savings. Besides power generation, the gas turbines are used as prime-mover for process equipment such as pumps and compressors.

The continuous process plants in need of more energy in the form of heat (or specifically as steam), along with a need of energy in the form of electric power (power: heat ratio generally less than 1), the gas turbine based cogeneration is an ideal solution to optimise the cogeneration system for energy saving, as the electrical efficiency of industrial heavy duty gas turbine generators is around 24 – 30% (depending on rating of gas turbine), more heat energy would goes to waste as exhaust flue gases from the gas turbine generator. Recovery of heat from the exhaust flue gases, if optimised, through technically feasible means, overall plant efficiency achieved could be more than 80%.

However, the gas turbine is not the best choice for the plant having frequent process load fluctuations, as the heat rate of gas turbine increases substantially when it is operated at less than 80% of its rated capacity. Ideal situation for this system is constant power as well as heat load to achieve the best performance.

The gas turbine based cogeneration plant consists of gas turbine generator and waste heat recovery boiler (WHRB) of unfired, supplementary fired or fully fired type attached to it. It is also feasible to set up cogeneration system consisting of gas turbine generator and absorption chiller in which waste heat is used to generate chilled water.

The gas turbine is fired with conventional fuels such as natural gas, high speed diesel, light diesel oil, naphtha, etc. Fuel like furnace oil can be fired in the gas turbine, but the performance would not be at par when it is fired with other fuels. Coal gas is being tried out as fuel adopting integrated gasification combined cycle technology, but its viability as fuel for normal operation of the gas turbine is yet to be established. The steam is generated in WHRB through recovery of waste heat available in exhaust flue gases emanating from the gas turbine. The steam is utilised in the process or for running the steam turbine to generate power.

The efficiency of industrial heavy duty gas turbines is found in the range of 25 – 35% depending on rating of gas turbine. Thus, if it would not be possible to recover substantial amount heat available in the exhaust flue gases, the cogeneration plant would not achieve optimum efficiency.

5.2 Performance of Gas turbines

Performance of gas turbines is expressed in terms of Heat rate, which is the quantity of heat in kJ required to generate one kWh of electric power.

The performance of gas turbine would greatly depend on the ambient air conditions, fuel quality, cooling water supply, water injection, site altitude.

- Heat rate (fuel input in kJ/kWh) of the gas turbine increases as the ambient temperature increases. At higher temperature, the air density would reduce, which would reduce mass of air entering into compressor. Due to reduction in overall mass of flue gases, the gas turbine output would also decrease. The curves are provided by the manufacturers indicting increase in heat rate vis-à-vis rise in ambient temperature.

- Similarly, at high altitudes, heat rate of the gas turbine increases due to consequent reduction in density of air at higher altitudes.
- Quality of fuel and quality of air also adversely affect the performance of the gas turbine.

- When steam or water injection is done in the gas turbine to reduce NOx emission, the power output increases with consequent reduction in availability of waste heat from the exhaust flue gases.

5.3 Practices for optimal gas turbine performance

The performance evaluation of the new generation of gas turbines in cogeneration mode of operations is complex and presents problems, which have to be addressed. The trend is being slowly established in the industries to improve maintenance strategy and optimise performance. This calls for total performance based planned maintenance philosophy of on-line condition monitoring and management of main plant equipment.

Maintenance practices may be integrated with operational practices to ensure that the plants have the highest reliability with optimum efficiency.

5.3.1 At designing stage

- Gas turbines of small capacity (50 kW) to large capacity (500 MW) are available. It would be better to avoid small capacity gas turbines, as they work with least electrical efficiency, unless it is possible to recover all the heat from the exhaust flue gases so that the plant could achieve optimum overall performance.

- Thorough knowledge of fuel characteristics is intended to provide a background to fuel suitability considerations. The gas turbine manufacturers may generally regard conformance to the fuel specification mandatory, but as many characteristics are relevant to each other, it is necessary for each fuel to be considered individually, for whether or not it meets the specification requirements. Hence, the fuel specification may be provided to the manufacturer after checking number of samples.

- If fuel not meeting the specification requirements in many respects is fired in the gas turbine, certain limitation for performance may have to be observed. Hence, it is vital sort out this issue at the design and pre-ordering stage so as to get optimum and consistent performance.

- Knowledge of surroundings, air quality, humidity, etc. is a must so as to take necessary actions to avoid effects on performance.

5.3.2 At operating stage

The gas turbines operated in following mode would provide the optimum performance.

Best operational mode

Power or heat operated - Depending on the total power load of the industry, number of gas turbines are arranged on one line so that one or more gas turbines can be operated according to demand of power. With such philosophy of operation, it is possible to run the gas turbines close to the rated capacity so as to achieve optimum heat rate. Such method of operation would avoid running of the gas turbine at less than 80% of its rated capacity, which otherwise would result into higher heat rate.

Control for gas turbines

Control of the gas turbines can be achieved through amount of fuel injected into the combustion chamber of the gas turbine. The governing system for the gas turbine should be very precise and extremely reliable, and hence it is always computerised.

Monitoring for gas turbines

An on-line condition monitoring system shall be designed to provide extensive database to ensure that it can achieve some or all of following goals depending on complexity of system; high equipment availability, maintaining optimum efficiency level and minimising performance degradation of equipment, extending time between inspections and overhauls, estimating availability, etc. The system needs to be carefully tailored to individual plant and equipment requirements and be able to obtain real time data.

Following parameters are vital for on-line monitoring.

- Monitoring of accurate fuel flow, pressure and temperature.
- Monitoring of flue gas temperature at turbine inlet, temperature spread around exhaust manifold at turbine outlet, exhaust gas temperature is must in order to monitor the performance. General relationship between load and exhaust temperature should be observed and compared to data generated so far. High exhaust temperature can be an indicator of deterioration of internal parts, gas leaks.
- Monitoring of bearing vibrations must be carried out using suitable microprocessor based instrumentation, if possible with analytical back-up. If gearbox is installed between turbine and generator, a separate monitoring of vibrations on gearbox is required.
- Monitoring of bearing temperatures and analysis, pressure and temperature of lube-oil circulated in bearings is very important. Generally, lube-oil is replaced after 8000 hours of working.
- Monitoring of inlet air temperature is important, as higher the ambient air temperature, lower would be the power output from the gas turbine or vice-versa.

5.3.3 At maintenance stage

Generally, the periodic preventive maintenance of gas turbine is carried out as follows.

- Washing of compressor, generally at an interval of one month or as specified by the manufacturer, is a must to maintain the output, as washing removes dust deposition on compressor blades occurred from ambient air drawn. Axial flow compressor performance deterioration is major cause of loss in gas turbine output and efficiency, typically 75-80% performance loss due to contaminant deposition on blades working as fouling to reduce air flow through compressor and power output. The gas turbine manufacturer specifies the type of compressor cleaning agent to be used along with period for washing and cleaning. A specific discussion is also provided elsewhere for inlet air system management.
- Thorough boroscopic inspection of turbine and compressor blades, hot-gas-path components, bearings and overhauling may be resorted to every 9000-10000 running hours, and annual thorough maintenance program may be decided accordingly.
- If fired with clean fuel natural gas, it may be necessary in industrial heavy duty gas turbines to replace the turbine blades after 25000 running hours, i.e. the life of heat resistant coating provided on the blades. Blade replacement interval may be around 20000 hours for the gas turbine fired with liquid fuels high speed diesel, kerosene oil. High ash bearing fuels like fuel oil reduces the blade life to just 10000 running hours.

5.4 Specific practices for optimizing gas turbine performance

Few specific practices discussed below are essential for the optimum gas turbine performance.

5.4.1 Evaporative cooling of inlet ambient air

Higher ambient air temperature reduces the power output from the gas turbine. The mechanical work done by the gas turbine is proportional to the mass of flue gases entering the gas turbine, and mass depends on quantity of ambient air supplied to the combustion chamber through compressor. High temperature reduces the density of air, i.e. mass (weight of air). Thus, at same compressor speed, less mass of air goes to the combustion chamber when the ambient air temperature is high. This results into reduction of power output due to less mechanical work done by the gas turbine. In order to improve or maintain the performance, ambient air is passed through inlet cooling system to reduce the temperature, which makes it denser. This results into either generation of additional power or maintaining of output as near as possible to capacity.

There are two basic systems currently available for inlet cooling. First, and perhaps the most widely accepted system is the evaporative cooler. Evaporative coolers make use of the evaporation of water to affect a reduction in inlet air temperature. Another system currently being studied is the inlet chiller. This system is basically a heat exchanger through which the cooling medium (usually chilled water) flows and removes heat from the inlet air thereby reducing the inlet temperature and increasing gas turbine output. In addition to the obvious advantage of achieving extra power, the use of an evaporative cooler improves the environmental impact of the machine. Increasing water vapor in the inlet air tends to lower the amount of oxides of nitrogen produced in the combustion process and, therefore, lowers the emissions of the machine.

A comparison of various inlet air cooling methods are summarised below.

Table 5-1: Gas Turbine Inlet cooling system-Choices

Gas Turbine Inlet Air Chilling Systems Comparative Matrix					
System Type	*Media Based Evaporative Cooling*	*Fogging*	*Mechanical Chilling, Water Cooled*	*Mechanical Chilling, Air Cooled*	*Absorption Chilling, Water Cooled*
System description	Evaporative cooling is provided through use of a fluted cellulose base media pads. The pads are located within the filter house air stream and wetted from an acceptable site source. Heat from the air stream is given up to the water in the evaporative media	Inlet air stream is cooled through the direct infusion and evaporation of minute water particles into the air stream. Heat from the air stream is given up to the water droplets evaporation thereby reducing inlet air temperature.	Inlet air stream cooling is accomplished through the use of an electric packaged chiller system (water cooled, cooling water source or tower) in conjunction with inlet air heat exchange coil (Chilled Water or Glycol).	Inlet air cooling is accomplished through the use of an electric packaged chiller system (air cooled, typically fin fin type cooler) In conjunction with inlet air heat exchange coil (Chilled Water or Glycol).	Inlet air stream cooling is accomplished through the use of a lithium-bromide absorption chiller system (water cooled, cooling tower) In conjunction with inlet air heat exchange coil (Chilled Water or Glycol).
Installed cost ($/KW added)	25-50	45-70	200-500	250-550	300-700
Operating/main cost	Low	Low	High	High	High
Heat rate change	-1.5 to –3%	-1.5 to –2.5%	-1 to –2%	-1 to –2%	-1 to –2%*
Power output increase (varies w/ambient)	5 to 10%	5 to 10%	Up to 15%	Up to 15%	Up to 20%

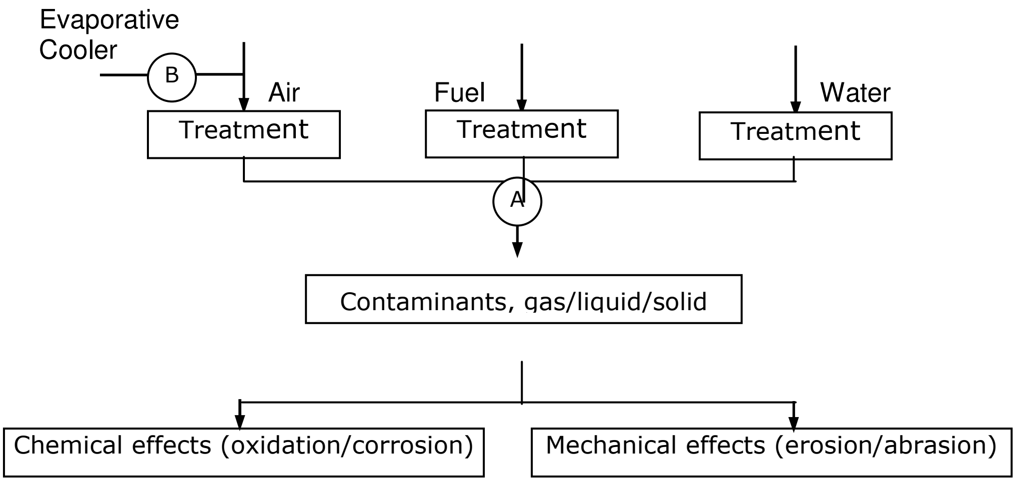
In Selecting Inlet Air cooling As a Retrofit to an Existing Plant, Points to watch:

- Check the generator capacity in order not to overload the generator.
- Quality of raw water for the evaporative cooler
- When using an existing demineralised water treatment plant, be careful about the capacity and quality of available demineralised water
- With an existing heat recovery steam generator, inlet air cooling will change the behavior of the existing HRSG, leading to a drop in steam production at high pressure and increase in intermediate and low pressure steam

5.4.2 Air/fuel/water management

The longevity of a gas turbine at site is determined by the extent of its operation within design limits under mechanical and thermal loads as well as the effect of air, fuel and injected steam/water on gas path surfaces in undermining component material properties. The constituents entrained in air, fuel, etc. may affect the gas path components.

The concept of air/fuel/water management is represented schematically in Fig. 5.1, which shows that instead of prescribing separate limits for air/fuel/water quality, limits for combined concentrations of harmful contaminants comprising the total gas turbine environment are specified. This allows to arrive at more realistic effect of critical contaminants and to decide about greater flexibility to set up system for control.



Note: A in circle – Control of total contaminants
B in circle – Secondary control of evaporator cooling water

Figure 5-1: Schematic of air/fuel/water management

- Because of the wide range of environments that prevail all around country and difficulty to have reliable data on airborne constituents, generally, concentrations of airborne contaminants are estimated values. Contaminants entering the gas turbine can be in the form of gas, liquid or solid particles.

- Airborne contaminants such as dust, salt, corrosive vapours, oil, etc. can cause erosion of compressor blades, corrosion, fouling of components in hot section path, thereby reducing their life. A careful attention should be paid to inlet arrangement and application of correct materials and protective coatings.

- The air contaminants are removed by installation of good quality air filters at air inlet. Detailed study of air quality at particular site may be made at design stage so as to install air filter to get the best possible result. Regular cleaning of air filters and periodic replacement would be essential to maintain the power output at desired level. Monitoring of differential pressure across the filter bank provides good idea for condition of the air filters.

- In case of gas fuel, removal of condensate carry over is achieved by installing knock-out drum at gas pipeline inlet point. Solid particles are trapped in on-line scrubber and filters through which gas is passed after passing through knock-out drum. Finally, gas fuel is passed through micro-fine filter place just before inlet to the gas turbine. Supply of clean gas is a must in order to maintain the performance of the gas turbines.

- Liquid fuels such as HSD are filled in the day tank from bulk storage tank, in which it remains for 24 hours to permit the sludge, mud, water, etc. to settle in the bottom. Then, the liquid fuel is passed through centrifuge to remove remaining dirt, sludge, water particles, etc. and filled in cleaned fuel tank. Thereafter, the liquid fuel is sent to the gas turbine at required pressure through pump having the primary filter (20 microns) on suction side and the secondary filter (5 microns) on discharge side to remove remaining solid particles, whatever possible.

- In case of fuels such as naphtha, which are less viscous, the fuel additives are added to increase its lubricity for achieving desired atomization and better mixing of air and fuel.

- The liquid fuels also contain corrosive trace metal contaminants like sulphur, vanadium, lead, sodium, potassium, etc. in varying proportion. Extremely high temperature upon combustion produces salts of these trace metals, which hit the heat resistant coating provided on the turbine blades and corrodes it. The special additives are injected along with fuel, which combines with trace metals to form ash. The ash gets deposited on turbine blades without causing any degradation of coating. The ash is removed through periodic washing as mentioned elsewhere in the manual.

- Water is injected into the gas turbine in order to control formation of oxides of nitrogen. Water chemistry and treatment, a technology in itself, plays a critical role in maintaining the gas turbine performance. Contaminants in water injected into the combustor for emissions control can be considered as being equivalent to contaminants in fuel due to more or less same quantity of both being used. As with air and fuel, two low-key concerns are corrosion and deposition/fouling. Sodium and potassium, actively involved in hot corrosion, are dissolved in water. Only DM water should be used for injection to overcome these problems and to maintain the gas turbine performance.

- The purpose of this discussion is to provide general information relating to combustion/cooling air, wide range of fuels and water, which may be sent to the gas turbine. Because of importance of these inputs in determining the optimum performance of the gas turbine, it is though fit to provide discussion as a part of good practice manual.

5.5 Waste heat recovery for steam generation/HVAC/heating

The technology employed for waste heat recovery from the gas turbine exhaust gases consists of waste heat recovery boiler (WHRB) for production of steam, use of heat in absorption chiller for generating refrigeration effect, or use of heat for direct heating process.

Mostly, water tube WHRB having configuration like unfired, supplementary fired or fully fired, is used to generate the steam by utilising waste heat available in exhaust gases. Potential of steam generation is the best practice to achieve the optimum cogeneration efficiency. Selection of unfired, supplementary fired or fully fired WHRB is made based on the steam requirements projected by the process. In order to make the operation of WHRB plant efficient, lot of all round development has taken place in case of components, materials, control system, etc. The control system has played significant role in vastly improving the WHRB performance.

Another aspect of consideration, like that in the fired boilers, is deployment of reliable control system into WHRB and its integration with the gas turbine as to optimise the overall cogeneration performance. Moreover, after achievement of such integration, it is also important to make the operators conversant to the operating practices after deployment of controls; otherwise there would be no meaning of going for sophisticated control system.

Many a times, the people ignore potential of waste heat recovery due to availability of less quantum of heat. However, it is very vital not to ignore even this smallest of potential of heat recovery to utilize it in whatever feasible manner, for example to heat up something. All possibilities of waste heat recovery offer good opportunity to optimise the cogeneration system performance. Following few causes greatly attribute to affect WHRB performance adversely, as seen in case of fired boilers.

- Lack of awareness of developments in boiler technology.
- Inadequate evaluation of overall techno-commercial benefits.
- The fact that good practice projects often given second priority.

One should study and analyse various technological options available for waste heat recovery irrespective of its potential. Few lines mentioned in the portion relevant to the fired boilers is also applicable to WHRB. The unfired version of WHRB may not be found similar to the fired boiler, but supplementary fired or fully fired versions of WHRB are more or less similar to the independent fired boilers.

5.6 Steam Generation/Combustion Efficiency

i. To convert water into steam, the temperature must be raised to its boiling point (saturation temperature) by adding sensible heat. Then the latent heat is added to turn water into steam. For example, increase of temperature of 1 kg of water from 0^0C to 100^0C requires 419 kJ/kg of sensible heat. To convert 1 kg of water into steam requires 2258 kJ/kg of latent heat. When this large quantity of heat supplied to water can be recovered by process at the point of use to its optimum, which is called system performance optimisation.

ii. Total efficiency is defined as the effectiveness of any combustion apparatus to convert the internal energy contained in the fuel into heat energy for utilisation by the process. Any heat losses lower the efficiency of the process. Radiation losses from heat escaping through the surface of WHRB walls are one example of losses.

iii. WHRB efficiency is the total heat contained per unit in the flue gases minus the energy losses through radiation, convection, etc. as well as final loss in the form of energy carried away by the flue gases finally leaving WHRB.

iv. In case of supplementary fired or fully fired WHRB, energy input would be sum of heat contained per unit in flue gases and heat contained per unit in the fuel fired. Thus overall efficiency also takes into consideration combustion efficiency. WHRB efficiency in such case is the total energy input minus the energy losses through radiation, convection, etc. as well as final loss in the form of energy carried away by the flue gases finally leaving WHRB.

5.7 Points requiring attention for optimisation

Following points are required due attention in order to optimise, maintain or improve the performance of WHRB. These are the factors relevant to the design, operation and maintenance of boilers, if considered at various stages as required, they play instrumental role in enhancement of performance.

5.7.1 At designing stage

i Generally, the WHRB installed in cogeneration system is water tube type, as it is most suitable for this specific application. Configurations for the water tube WHRB are horizontal/vertical, single/double/triple pressure, supplementary fired/fully fired, etc. is available. Hence, it is essential to go for very close scrutiny of steam requirements and parameters for the plant and then to select type of boiler.

ii. The most vital factor to be taken into account during design stage is the fuel quality in case of supplementary/fully fired WHRB, as it has to encounter fuel throughout its life. Hence, all aspects of fuel composition should be invariably considered while designing the combustion system components such as ducts, duct burners/burners, furnace, drum selection, water circulation – natural or assisted, wall design, etc. Chemical and physical composition of fuel greatly affects furnace and heat transfer area requirement. In case the WHRB is to be fired with high ash bearing fuel such as fuel oil, it is vital to consider presence of hydrogen, sulphur, trace metals, carbon, ash, calorific value, moisture, etc. at the design stage. Physical properties such as viscosity, flash point, etc. also play an important role. In order to arrive at the best average data of fuel composition for design consideration, it may be necessary to test number of fuel samples.

iii. Once, fuel composition is established, next important stage is the selection of material for tubes water wall, lining, etc. Surface area required for the optimum heat transfer from burnt flue gases at different stages in the WHRB should be carefully considered to optimize the combustion efficiency.

iv. Radiation losses depend on the temperature of the WHRB's external surfaces. The WHRB provided with inferior and poor quality of insulation and poor design characteristics tend to have higher radiation losses. Now a day, insulating materials of extremely high-class quality and characteristics are available, use of which has been found highly cost effective due to reduction of radiation losses. Slight more capital investment repays in no time.

5.7.2 At operating stage

i The best way to optimise the efficiency is to send all the flue gases total flue gases to WHRB, i.e. not to divert flue gases to atmosphere by keeping a bypass stack damper closed. This is the best way to ensure maximum recovery of waste heat from the flue gases.

ii. Another important point is to maintain the quality of boiler feed water strictly as specified by the WHRB manufacturer in order to minimise the scaling of tubes, deposition in drums. Necessary chemical treatment should be provided to boiler feed water.

iii The best way to maximise combustion efficiency in supplementary/fully fired WHRB is to measure oxygen and combustibles in the flue gas on a continuous basis. This requires deployment of instrumentation for on-line continuous monitoring of flue gas composition along with other relevant parameters. On observance of change in desired level of any component, it would be possible to initiate corrective measure immediately, either automatically or manually, to bring back that component to its desired level.

iv. Three essential components of combustion are fuel, oxygen and heat. Stoichiometric combustion is defined as having just the right proportion of oxygen and fuel mixture so the most heat is released from fuel. In most fossil fuels, the chemical elements that react with oxygen to release heat are carbon and hydrogen contained by the fuel.

v. Oxygen requirement for combustion is obtained from air supplied to the boiler along with fuel. Air contains about 21% oxygen and 79% nitrogen by volume (neglecting carbon dioxide, etc.). Hence, ideally, it is necessary to provide just the right amount of air to completely burn all the fuel. The ratio of required volume of air for complete burning of one cubic metre of fuel is known as stoichiometric air/fuel ratio.

One cubic meter of methane (at standard pressure and temperature) requires 9.53 cubic meter of air for complete burning. Hence, stoichiometric air to fuel ratio for methane is 9.53/1.0, i.e. 9.53.

List of stoichiometric air/fuel ratios and heats of combustion for few common fuels is provided in Table 5.1 and 5.2 for reference.

Table 5-2: Combustion ranges for gaseous fuels

Fuel	Stoichiometric Air/fuel ratio (m^3 air/m^3 fuel)	Heat of combustion (kJ/ft^3)
Hydrogen (H_2)	2.38	328
Carbon Monoxide (CO)	2.38	322
Methane (CH_4)	9.53	1013
Propane (C_3H_8)	23.82	2590
Natural gas	9.4 – 11.0	950 – 1150
Coke Oven Gas	3.5 – 5.5	400 – 600

Table 5-3: Combustion ranges for liquid fuels

Fuel	Stoichiometric Air/fuel ratio (m^3 air/m^3 fuel)	Heat of combustion (kJ/ft^3)
Carbon (C)	150	14.093
Sulphur (S)	56	3.983
High speed diesel	180 - 195	18500 – 19800
Furnace oil	170 - 185	17500 - 19000

However for all practical purposes, this proves elusive for a number of reasons, including inadequate mixing of air and fuel, burner performance, fluctuating operating and ambient conditions, burner wear and tear. Hence, to ensure that the fuel is burned with little or no combustibles, some amount of excess air than actually required is supplied. For ensuring supply of excess air in required amount, excess oxygen in flue gas is continuously measured and necessary adjustments are made through boiler control system. Similarly, to ensure the amount of hydrogen and carbon monoxide in the flue gas is minimised, combustibles are also measured.

Heat losses through flue gases are the single largest energy loss in a combustion process. It is impossible to eliminate total flue gas loss the products of combustion are heated by the combustion process itself. But flue gas loss can be minimised by reducing the amount of excess air supplied to the burner, as flue gas heat losses increase with both increasing excess air and temperatures.

Measuring oxygen alone may be sufficient to determine combustion efficiency because of more or less constant operating conditions not affecting quantum of combustibles in the flue gases. If possible, other components may also be measured for better picture. Similarly, measuring combustibles alone does not provide sufficient data to make continuous adjustments to combustion process. To maintain the combustion efficiency to its optimum level, it is essential to measure both oxygen and combustibles in flue gas on continuous basis and integrate it with control system.

Another area of losses is through blow down given to boiler water. Dissolved salts enter the boiler through the make-up water supplied from water treatment system. Continuous evaporation of water in boiler leaves behind the salts in the boiler leading to continuous increase

It can be concluded based on above discussion that fired WHRB monitoring and control system should have a flue gas analyzer, which would effectively measure oxygen and control the amount of excess air in flue gas and measure hydrogen, carbon dioxide and carbon monoxide, the components adversely affecting the combustion efficiency.

Fuel preparation for supplementary/fully fired WHRB plays significant role to supplement efforts towards optimising the performance.

Fuel oil/LSHS – preparation

- Carbon and hydrogen in FO, which are converted into carbon dioxide and water vapour on combustion releasing large amount of heat. In the event of incomplete combustion, carbon may be converted into carbon monoxide, which results into liberation of lesser quantum of heat. Proper filtration and preparation, i.e. heating to 50 – 60^0C reduce viscosity, helps in better atomisation on firing and mixing with air. This improves the combustion process and performance.
- Spillages and leakages through negligence of faulty fittings in fuel pipeline should be avoided in totality. Apart from being wastage, they can cause accidents, pollution and fire-risk.
- The oil level indicator provided on the storage tank must be accurate.
- Redundant fuel lines in the storage area should be removed to avoid unnecessary chances of spillages.
- The oil should be sent to the boilers through duplex oil filters, which should be maintained regularly.

5.7.3 Reduction of losses

Elimination of losses is impossible, but reduction is possible to great extent. Various ways and means to reduce the losses are briefly mentioned below.

i. Radiation losses depend on the temperature of the boiler's external surfaces and are independent of the load at which the boiler operates. Thus at low load, radiation losses may account for a significantly high proportion of the total boiler losses. Hence, operation of boiler at low load may be avoided to the extent possible to minimise undue losses.

ii. Radiation losses depend on the temperature of the boiler's external surfaces and are independent of the load at which the boiler operates. Thus at low load, radiation losses may account for a significantly high proportion of the total boiler losses. Hence, operation of boiler at low load may be avoided to the extent possible to minimise undue losses.

iii. Radiation losses depend on the temperature of the boiler's external surfaces and are independent of the load at which the boiler operates. Thus at low load, radiation losses may account for a significantly high proportion of the total boiler losses. Hence, operation of boiler at low load may be avoided to the extent possible to minimise undue losses.

iv. Proper provision of insulation on the steam and feed water pipelines and valves contributes a lot towards WHRB performance optimisation by minimising radiation losses. If insulation is removed for repairing, it should be immediately made good as soon as repairing work is over. This is seldom done in most of the industries.

v. Similarly, it is essential to immediately attend to stop leakage of feed water and steam from respective pipelines joints and valves to minimise the losses.

5.7.4 Inspection prior to outage for maintenance

A critical part of WHRB maintenance is the annual inspection. The team consisting of maintenance engineer, water chemistry specialist and manufacturer's engineer may be formed for such inspection, as the representatives from different areas trained in different disciplines look at different things from varied angles to provide far better assessment of parts. Such inspections not only help to identify existing problems, they are also the best planning tools for the next outage. The inspection may be planned well in advance of date of outage so that adequate time is available to get the spare parts and engage a good contactor for maintenance. Areas of inspection are briefly brought out below.

- Areas that commonly need to be repaired are holes in expansion joints, casing penetrations, piping supports, leaking joints/valves, etc.
- Tubes in superheater, evaporator section, economizer, etc. for leaks, corrosion, deposits, bending, etc.
- Steam drums for deposition, signs of consistent stable water levels, evidence of steam leakage around baffles, drum penetrations, etc.
- Overhauling, certification and setting of all safety valves.
- Chemical cleaning of WHRB.
- Overhauling of all the pumps.
- Repairing of damaged insulation, cladding, etc.
- Inlet duct and the gas turbine expansion joint for hot spots and damage.
- Duct burners, bent runners, igniter condition, etc.

6 COGENERATION WITH RECIPROCATING ENGINE CYCLE

6.1 Introduction

The reciprocating engine based cogeneration has made in roads in our country with introduction of large size engines fired with fuel oil, light diesel oil or natural gas as well. The factors considered for choosing of reciprocating engine for different applications are reliability, quick start and stop, low environmental impact and possibility of energy savings through utilisation of waste heat. Duration of preventive maintenance would be comparatively less than that in case of gas turbines and steam turbines. Besides power generation, the reciprocating engines are used, generally to meet emergency needs, as prime-mover for process equipment such as pumps, fans, blowers, etc. Still, the reciprocating engines have been considered as standby emergency power supply equipment in most of the industries, however, the trend is slowly changing to install and operate such plant as base load stations.

The plants in need of more energy in the form of electric power along with a moderate need of energy in the form of heat (power: heat ratio more than 1), the reciprocating engine based cogeneration is an ideal solution to optimize the cogeneration system for energy saving, as the electrical efficiency of reciprocating engine generator is more than that of gas turbine generator. Besides this, the plant having frequent process load fluctuations, the reciprocating engine offers a good performance, as the drop in efficiency at reduced load running is not significant.

The reciprocating engine is also good choice for the plant having frequent process load fluctuations, as the heat rate of reciprocating engines is not significantly affected on lower side, when it is operated at lesser load than its rated capacity. Though, an ideal situation for this system is constant power as well as heat load to achieve the best performance, as reduction in availability of waste heat would be more in proportion to the reduction of power load.

Reciprocating engines embody mature technologies and have proven themselves for varied applications; standby power, base load power, peaking power. They readily tolerate intermittent start-stop duty and maintain good performance under variable cyclic loads. Additionally, the engines remain compliant with air-quality regulations at a wide variety of altitudes and ambient temperatures.

The reciprocating engine based cogeneration plant consists of reciprocating engine generator and hot water generator, or waste heat recovery boiler (WHRB) of unfired, supplementary fired or fully fired type, or absorption chiller attached to it.

The reciprocating engine is fired with conventional fuels such as natural gas, high speed diesel, light diesel oil, fuel oil, etc. The waste heat available in exhaust flue gases is recovered in WHRB to generate steam, or in hot water generator, or in absorption chiller to get refrigeration effect.

6.2 Reciprocating engines

Performance of reciprocating engine is expressed in terms of Heat rate, which is the quantity of heat in Btu, kJ or kcal required to generate one kWh of electric power. It is also expressed in terms of Specific Fuel Consumption, which is quantity of fuel consumed in grams per BHP per hour, or lbs per BHP per hour.
Performance of reciprocating engine would greatly depend on the ambient air conditions, fuel quality, cooling water supply, site altitude, quality of lubricating oil and super-turbo-charger.

Reciprocating engines in industry operate under a variety of conditions. These range from low speed at low steady outputs, through the more highly rated engines with variable outputs.

6.3 Practices for optimising reciprocating engine performance

The reciprocating engine based cogeneration operated and maintained in following mode would provide the optimum performance.

6.3.1 At operating stage

i. **Best operating mode**
Power or heat operated - Depending on the total power load of the industry, number of reciprocating engines are arranged on one line so that one or more engines can be operated according to demand of power. With such philosophy of operation, it is possible to run the reciprocating engines close to the rated capacity so as to achieve optimum specific fuel consumption or heat rate. Such method of operation would avoid running of the engine under capacity to the extent feasible, which otherwise would result into higher heat rate.

ii. **Normal operating state**
The reciprocating engines of small capacity to large capacity are available. It would be better to avoid small capacity engines except for emergency standby source of power, as they offer almost no potential for heat recovery so as to operate in real cogeneration mode. However, the principle factor for selection of size would be power: heat ratio as explained elsewhere in the manual. Following points are worth noting for efficient and trouble free operation of the engines.

- The operating temperature of the engine should be maintained within the normal limits specified by the manufacturer. The oil temperature is normally maintained between 65 and 70^0C.
- Prolonged overload condition on the engine should always be avoided. Unbalance load condition should be limited so that rated current is not exceeded in any phase of the generator.
- It is desirable to provide suitable flywheel inertia to limit the cyclic irregularity.
- It is desirable to maintain the engine speed at normal level. Sudden load imposition or shedding may abruptly change the speed and may damage some moving part.
- Do not allow the exhaust temperature to go above 430^0C by preventing overloading and restricting air supply to improve the fuel efficiency.
- Cooling water pH should be maintained between 7 to 8 to avoid corrosion and scaling.
- Try to run the large rated engines at more than 50% and small rated engines at 60% of their rating to have better performance.

iii. **Control for reciprocating engines**
Control of the reciprocating engines can be achieved through amount of fuel injected into the combustion chamber of the engine. The governing system for the reciprocating engine should be very precise and extremely reliable, and hence it is always microprocessor based computerised version.

iv. **Monitoring for reciprocating engines**
Continuous or on-line monitoring of following parameters would be vital to avoid fall in the reciprocating engine performance.

- Monitoring of fuel flow, pressure and temperature.

- Monitoring of exhaust flue gas temperature is must in order to monitor the performance of waste heat recovery system.
- Monitoring of bearing vibrations on engine and generator must be carried out using suitable microprocessor based instrumentation.
- Monitoring of pressure and temperature of lube-oil sent to engine cylinders, crank shaft, bearings lubrication is very important. Generally, lube-oil is replaced between 250-500 hours of working, or as specified by the manufacturer in accordance with the specific engine requirement.
- Monitoring of inlet air temperature and pressure is important, as higher the ambient air temperature, lower would be the power output from the reciprocating engine or vice-versa.

6.3.2 At maintenance stage

Generally, the periodic preventive maintenance of reciprocating engines is carried out as follows.

i. Major point of maintenance to be attended is replacement of lubricating oil on condition basis, and not only on basis of norms of running hours prescribed by the manufacturer. Field oil testing kits may be used for testing to support the decision whether to change the oil. Specific discussion is provided in succeeding paragraphs in view of importance of lubrication system for consistent performance of engine, which may be considered to correctly understand the importance of this point.

ii. Avoid over lubrication to prevent deposits in the engine and on the turbo-charger blades.

iii. Thorough inspection of reciprocating engine components like cylinders, pistons, piston rings, injectors, valves, bearings, etc. for clogged parts, excessive wear, pitting marks may be carried out and overhauling may be resorted to after running hours prescribed by the manufacturer.

iv. Check compression pressure regularly where such provisions are made.
v. Periodic cleaning/replacement of air filers, fuel filters, etc. is very important for desired performance of the engine.

vi. Leakages of fuel and lube-oil, minor or major, are to be avoided at all costs, as they are largely a major factor for higher fuel and lube-oil consumption.

vii. The heat exchangers for lube-oil and engine jacket cooling water may be cleaned at an interval of around 500 hours depending on the water quality.

6.4 Specific practices for reciprocating engine performance

Following specific points are required due attention in order to optimise, maintain or improve the performance of the reciprocating engine generator. These are the factors relevant to the design, operation and maintenance of engines, if considered at various stages as required, they play instrumental role in enhancement of performance.

i. **At designing and installation stage**

- Specific fuel consumption of engine varies with the change in ambient air (intake) temperature and pressure. Ambient air pressure changes are related to the site altitude. Hence, it is important to consider highly reliable site data as design basis to decide engine rating correctly. The data for various correction factors is available for super-charged and non-super-charged engines from engine manufacturers.
- Two stroke engines may be provided with extra long stroke for fuel economy.

- It is preferable to get the engine with advance digital electronic control for air: fuel ratio, which marked improves the gas fired engine performance.
- The reciprocating engines, provided with radiators and engine driven cooling fan, about 7 – 10% loss of engine bhp is found. Hence, such designs may be selected where there is a shortage of cooling water supply.
- The engine exhaust system should be designed for proper fuel and engine efficiency so that exhaust back-pressure is within permissible limits and is not exceeded. The exhaust pipeline should have minimum nos. of smooth bends (bend radius 4 times diameter of pipe). Higher than permitted back-pressure results into adverse effect on the scavenging of engine and there would be less oxygen in the cylinder during the subsequent compression stroke. The mechanical efficiency will reduce due to higher exhaust pumping losses and will increase the specific fuel consumption.
- The engine rooms heat up during running of generator sets due to heat radiation from the engine, generator, exhaust pipeline, and hot air from the radiator fans. Increase in ambient temperature results in hot air inside the room, which increases the fuel consumption due to decrease in the air: fuel ratio, as the mixture becomes richer, there is drop in the fuel efficiency. It is therefore, very essential that the engine room is provided with effective ventilation so that hot air is continuously removed by circulation with cool air. Provision of roof ventilators or wall mounted exhaust fans on upper side can be considered.
- As much of the radiated heat is from the exhaust pipelines and manifolds, use of some type of insulation lagging on these components reduces the heat radiated into the room ambient.
- Please remember that the increase in intake air temperature from 25^0C to 40^0C results in decrease in air: fuel ratio by about 5% and the specific fuel consumption may increase in the range of 0.5 to 2% depending on the engine design.

ii. **Engine lubrication practices**

a. Principle function of engine oil or lubricant is to lubricate various moving parts of the engine to reduce friction and wear and to provide smooth and trouble free performance for increased length of time at site conditions. Besides reducing friction, the engine oil has other functions –

   - to keep the engine clean by sweeping away metal wear particles from fine clearances and between surfaces in relative motion
   - to supplement engine cooling by absorption of the frictional heat
   - to prevent corrosion of parts
   - to act as cooling media

b. Total lube-oil consumption in the engine is sum of -

   - engine lube-oil consumption
   - possible oil leakage in the system
   - losses in centrifuging
   - losses during change of oil

c. A series of different viscosity engine lubricating oils have to be available to cope with the varying design requirements on many types of engines available. Following properties of oil may be considered when making selection.

- The lubricating oil must possess good oxidation and thermal stabilities to reduce formation of sludge and carbon deposits. This gives a long trouble free service life to oil before it becomes necessary to have an engine oil change.
- In order to achieve functionally important properties, certain chemicals, known as lubricant additives are used in small but appropriate quantities, since plain mineral oils cannot perform all desired functions. The additives improve lubrication and protect equipment from deposits, rust, corrosion, wears and ill-effects of temperature extremes.
- The engines performing more arduous and heavy duty, it may be necessary to have the oil with a detergent dispersant additive. High rated engines tend to accelerate oil breakdown and formation of deposits. The oil with a high level of detergent keeps the pistons clean and reduces the wear and tear rates of piston rings and cylinder liners, thereby maintaining their performance besides extending their service life. In particular, such additive prevents decomposed products from being deposited on piston ring groves, oil paths and other engine parts.

d. In order to improve effect of lubrication, the engine should be invariably equipped with following accessories.

- Provision of good oil filtration in the engine is closely associated with long life and maintaining of oil properties.
- The wear particles taken away by oil must be kept in suspension in the oil together with dispersed decomposition and fuel combustion products until they can be removed by the engine oil filtration system.
- Prior to engine start up, main difficulty is encountered with engine lubrication, as fully stable oil circulation has not been established. As a good practice, primary pumps are used, essentially on large engines, to ensure adequate flow of lubricant established at start up.
- Arrangement for preheating of lubricating oil up to 60-70^{0}C before start up can reduce warm up period for engine. This would also provide a reduction of about 2 – 4% in Brake Specific Fuel Consumption (BSFC). Specifically for engines with large sump capacities, top up oil should also be preheated. Use of thermostatically controlled oil heaters is recommended for oil heating.
- Periodic testing of oil in the field is essential to know about deterioration of oil properties.
- Provision of good oil filtration in the engine is closely associated with long life and maintaining of oil properties.

e. It is absolutely necessary to change lube-oil as per the period specified by the manufacturer. When the oil is used for prolonged duration, there is a risk that the lube-oil starts to degrade and the additives are consumed. The limits are set for various chemical and physical properties of the lube-oil to ensure its good quality. Hence, the lube-oil should be changed when the condemning limit is reached. Limits for various properties are mentioned below as information.

Table 6-1: Lube-oil properties

Property	Implication	Unit	Condemning limit
Base number	Prevent corrosion	mg KOH/gm	Min 15-20 (HFO operation)
Insolubles	"Dirt in oil"	% mass	Max 2.0
Viscosity	Increase fuel input	cSt/100^{0}C	Max 25% increase
Water	Damages bearings	% vol	Max 0.3
Flash point	Explosion risk	^{0}C	Min 170 (open cup)

iii. **Fuel Management practices**

The fuels used in the reciprocating engines are all hydrocarbon based, as they are extracted as byproducts of crude oil. The engines fired with natural gas experience least problems due to gas being the cleanest fuel. The liquid fuels fired in the engines are classified according to their evaporation rate or volatility. The engines are fired with less volatile fuels high speed diesel (HSD), light diesel oil (LDO), etc., and residual oils furnace oil, LSHS, etc. of varying viscosities. Following points relevant to fuels may be paid due attention to get optimum performance from the engine.

- The diesel fuel quality is controlled in India in accordance with IS: 1460 – 1974, which covers two grades HSD and LDO. The quality of heavy or residual fuel oils is covered under IS: 1593 – 1983.
- Fuel oils are generally very difficult to vaporise and must be atomized or broken into fine minute droplets in order to achieve desired mixture of air and fuel prior to firing takes place.
- It is also necessary to control coking properties and sulphur content in heavy fuel oils to avoid excessive sulphur deposits and corrosion due to sulphur compounds under adverse conditions. If the fuel oil contains compounds of sodium, iron, nickel or vanadium, the adverse effects of these trace metals may be taken into account.
- Viscosity of fuel plays a major role in optimising the performance of the engine. If the viscosity is too low, or too high, the droplet size, spray pattern and so the consumption and fuel efficiency would vary Too low viscosity introduces an element of excessive wear, whereas too high viscosity results in incomplete combustion besides frictional losses and increased load on fuel pumping system. With viscous oils, it is necessary to reduce the viscosity before they can be atomized. This is achieved by preheating of fuel to appropriate temperature to obtain appropriate viscosity at the injector tips.
- It is necessary to ensure proper storage and handling for liquid fuels. Dirt and contamination will adversely affect fuel quality. HSD or LDO may be passed through the centrifuge before sending to day tank.
- The day tank should have conical bottom with a drain valve on drain pipeline, so that sludge deposited at the bottom could be easily removed from time to time. The engine supply line should be taken from the point above the conical portion.

iv. **Cooling system practices**

The engine cooling system also plays an important role in maintaining the performance. Following tips are provided to supplement the tips provided for other systems.

- Water cooled engines would work at lower specific fuel consumption with provision of separate and independent cooling water circulation system consisting of cooling towers, cooling water circulating pumps and heat exchangers.
- The cooling water system should be designed to achieve and maintain difference of 6 - 10^0C in the cooling tower inlet water and outlet water temperature, which results better fuel efficiency.
- The raw water should never be used in the engine cooling water system. It is essential to circulate only soft water so as to avoid corrosion and scaling in the pipelines.

7 CASE STUDIES

7.1 Back-pressure steam turbine and Bagasse fired boiler-Sugar Mill

Generally, in all sugar mills, the cogeneration systems having configuration of steam turbine generator (back-pressure or extraction-cum-back-pressure type) and fired boiler are found working, providing the best performance results. Moreover, such type of cogeneration system fires non-conventional fuel bagasse (sugar cane waste) in the boiler and then also works at optimum efficiency.

The case study is provided below is based on the system working in one of the largest sugar mills in Gujarat state.

7.1.1 Equipments

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

a. 6 nos. of Back-pressure type, single stage steam turbine generator sets as per ratings provided below.

i. 1 x 1500 kVA (1 x 1200 kW)
ii. 1 x 1875 kVA (1 x 1500 kW)
iii. 1 x 3125 kVA (1 x 2500 kW)
iv. 1 x 3750 kVA (1 x 3000 kW)
v. 2 x 3750 kVA (2 x 3000 kW)

b. 8 nos. of Bagasse fired steam generators as per ratings provided below.

i. 1 x 60 TPH, 30 Kg/cm^2, 375^{0}C
ii. 1 x 50 TPH, 20 Kg/cm^2, 375^{0}C
iii. 5 x 30 TPH, 20 Kg/cm^2, 375^{0}C
iv. 1 x 25 TPH, 20 Kg/cm^2, 375^{0}C

Cogeneration equipment data is mentioned below.

Table 7-1: Cogeneration equipment Data

Steam turbine generator data					
Parameter	**Unit**	**Quantity - unit rating wise data**			
Steam turbine data					
Type		Back-pressure, single stage	Back-pressure, single stage	Back-pressure, single stage	Back-pressure, single stage
Nos. installed		2 nos. (New)	1 no.	1 no.	1 no.
Rating	kW	3000	3000	2500	1500
Speed of turbine	RPM	8250	6000	9100	10016
Reduction gearbox data					
Speed ratio	RPM	8250/1500	6000/1500	9100/1500	10016/1500
Type of gearbox		Oil filled	GL-45 Oil filled	Triveni Maag Oil filled	Triveni Maag Oil filled
Steam parameters					
Inlet live steam pressure	Kg/cm^2	30	20	20	20
Inlet live steam temp	^{0}C	370	370	370	370
Inlet live steam flow	TPH				
Parameter	**Unit**	**Quantity - unit rating wise data**			

Steam parameters.....contd.					
Exhaust steam pressure	Kg/cm^2	1	1	1	1
Exhaust steam temp	^0C	120	120	120	120
Specific steam consumption	Kg/ kWhr	11.5	14.75	10.65	8.35
Generator data					
Rating for apparent power	kVA	3750	3750	3125	1875
Power output at rated power factor	kW	3000	3000	2500	3000
Generation voltage	Volts	420	440	440	440
Full load current (at rated power factor)	Amp	5155	4900	4100	2580
Rated power factor (lag)		0.8	0.8	0.8	0.8
Frequency	Hz	50	50	50	50
Generator shaft speed	RPM	1500	1500	1500	1500
Steam generator data					
Parameter	**Unit**	**Quantity - unit rating wise data**			
Nos. installed		1 No.	1 No.	5 Nos.	1 No.
Type of furnace		Damping grate type	Spreader stoker type	Horse shoe, rotary feeders	Spreader stoker type
Heating surface area	sq. metre.	1636	1799	1065	960
MCR steam flow	TPH	60	50	30	25
pressure (g)	Kg/cm^2	32	20	20	20
temperature	^0C	375	375	375	375
Boiler accessories		Superheater, economizer, air pre-heater	Coil type integral superheater, air pre-heater	Coil type integral superheater, air pre-heater	Coil type integral superheater, air pre-heater
Soot blowers		provided	provided	provided	provided
Boiler draft system		Balanced draft with FD & ID fans	Balanced draft with FD & ID fans	Balanced draft with FD & ID fans	Balanced draft with FD & ID fans

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

Table 7-2: Fuel data

Fuel composition data			
Main fuel - Bagasse			
Fuel flow		MT/hour	27
Higher heating value (Gross cal value)		kCal/kg	2288
Lower heating value		kCal/kg	
Moisture	*M*	% w/w	50.27
Carbon	*C*	% w/w	21.71
Hydrogen	*H*	% w/w	3.09
Nitrogen	N_2	% w/w	0.20
Oxygen		% w/w	23.23
Sulphur		% w/w	0.00
Ash	*A*	% w/w	1.5
Auxiliary fuel – Furnace oil			
Fuel flow		Kg/hour	Not fired usually
Higher heating value		kCal/kg	9500
Lower heating value		kCal/kg	9350

7.1.2 Normal operating philosophy

- The sugar manufacturing plant works on seasonal basis, i.e. generally for a period of 8 months from September to April every year, when the sugarcane crop would be available for crushing. In remaining 4 months, rigorous preventive maintenance of all the equipment is carried out so that the plant works without any problem during ensuing season.

- In the case study provided, generally, 2 x 3000 kW (new) Triveni steam turbine generators with 60 TPH WIL boilers, and 1 x 3000 kW (old) Belliss steam turbine generator and 1 x 2500 kW Triveni steam turbine generator with 50 TPH and 30 TPH boilers in required numbers are operated at full load. As 2 x 3000 kW steam turbine generators and 60 TPH boilers are matching with each other so far steam parameters is concerned, i.e. it becomes one island. Second island is formed by remaining steam turbine generators and boilers due to matching of steam parameters.

- Remaining equipment is operated either in the event of breakdown or shutdown of any of the above units, or according to the power and steam load requirements by the production. The CPP meets the total electric power and steam requirements of the manufacturing plant as soon as the production is commenced consequent to availability of sugarcane for crushing. The plant is working conforming to the concept of total co-generation power plant technology, which is encouraged all around the world in a big way due to conformance to very vital concept of energy conservation.

- The electric power generated in CPP is totally utilised to operate the process equipment, utilities and plant/office/area illumination. During normal plant operations, the power generation is maintained at more than 90% of machine rating and around 0.85 power factor so as to get optimum efficiency.

7.1.3 Power Plant Performance Analysis

Based on the plant operating data for last 12 months available for two co-generation islands, the CPP performance has been arrived at as follows.

Electrical generation output = 2949 kW X 2 = 5898 kW
= 5898 x 860 x 4.18 kJ/h
= 2,12,02,130 kJ/h

29 TPH x 2 = 58 TPH at 1.0 bar.
Enthalpy of steam at 1.0 bar = 642 kcal/kg
Energy in steam out put = 58 x 1000 x 642 x 4.18 kJ/h
= 15,56,46,480 kJ/h

Total energy output = 17,68,48,610 kJ/h

Total fuel input = 27 TPH bagasse
GCV of Bagasse = 2288 kCal/kg
Total energy input = 27 x 1000 x 2288 x 4.18 kJ/h
= 25,82,23,680 kJ/h

Overall efficiency = Total energy output/Total energy input
= 68.5%

	Plant Load Factor	Overall Efficiency
Island#1		
3000 kW Steam turbine generator #1 & 2	82.63%	68.5%
60 TPH Boiler		
Island#2		
2500 kW Steam turbine generator # 1	64.70%	66.74%
3000 kW Steam turbine generator # 1		
50 TPH and 30 TPH Boilers		

ii. The power load on new steam turbine generators is maintained almost constant due to their better performance, the steam load is also maintained on the connected boiler, and as such the plant load factor and efficiency are observed better in this system. The power load variations are generally taken care off by the system consisting of older steam turbines and boilers, as such the plant load factor and efficiency have been observed marginally in comparison to Island#1 mentioned above.

iii. The average age of the steam turbines and boilers is around 8 years. The specific steam consumption derived based on the enthalpy difference method is found only marginally offset from the data provided by the manufacturer, which could also be due to some disparity between required and actual inlet steam parameters.

iv. There is no provision for measurement of actual quantity of Bagasse being fired in the boilers. Hence, actual data for steam generation vis-à-vis fuel is not generated for the CPP. Based on derivation of specific steam consumption, noted steam parameters such as pressure and temperature, power load maintained and analysis of Bagasse, the fuel consumption can be derived, which would provide reasonably accurate data. The calibrated energy meters are provided for measurement of electricity.

iv. Heat balance diagram for Island#1 is provided on next page in Fig.7.1.

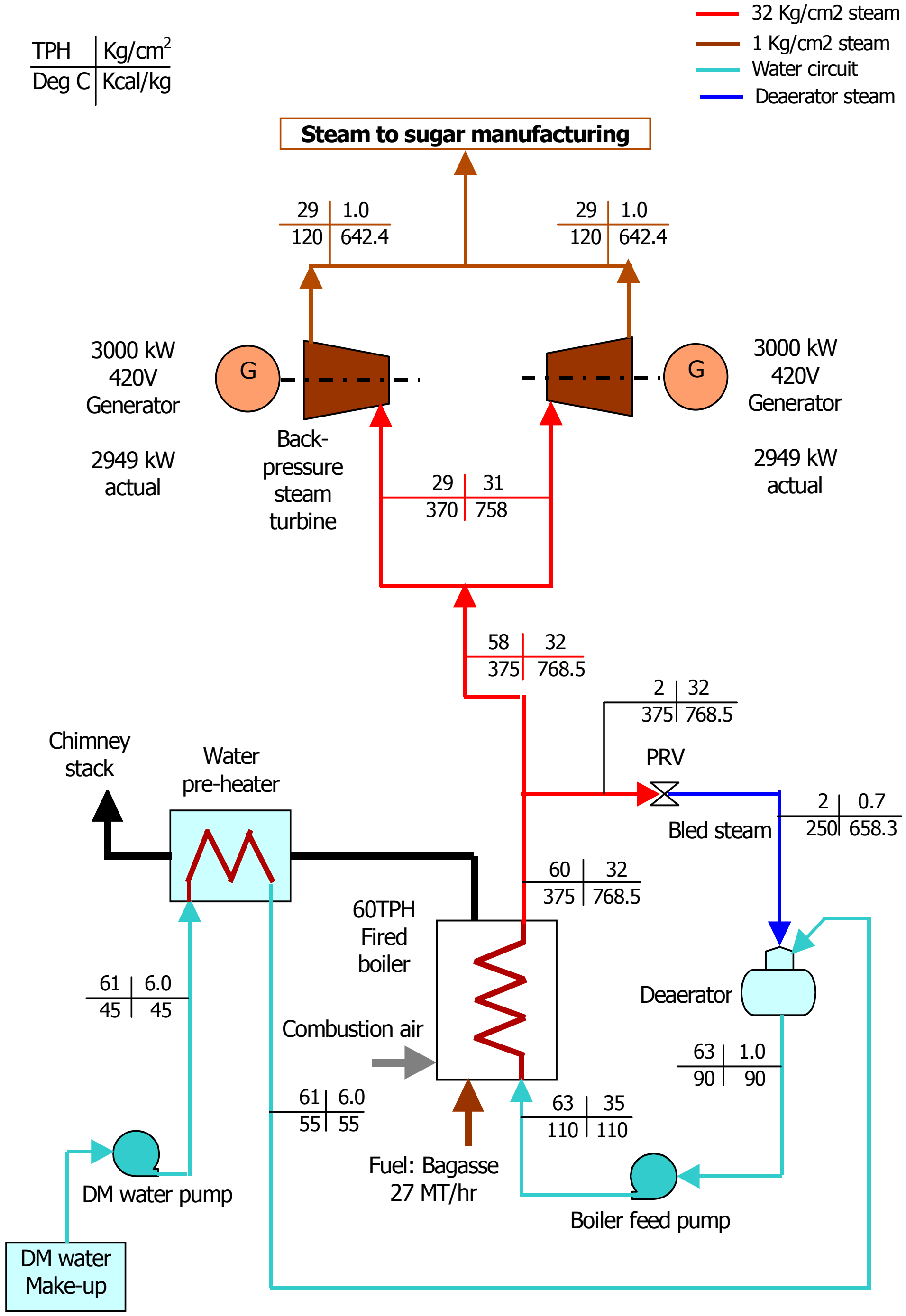


Figure 7-1: Cogeneration system-Sugar Mill

7.2 Extraction-cum-Back pressure steam turbine-Caustic Soda Industry

Another case study for steam turbine cogeneration plant is based on the cogeneration system in the soda ash manufacturing continuous process chemical plant. The soda ash process is one of the highly energy intensive chemical processes requiring power as well as steam almost in same proportions, i.e. ratio of power to heat would be nearly one. Generally, in soda ash plants, the extraction-cum-back pressure type steam turbine based cogeneration systems and fired boilers are found working, providing the best performance results due to achievement of extremely good heat balance due to excellent utilisation of energy in two different forms. The high pressure boilers are generally fired with coal or lignite or fuel oil.

The case study is provided below is based on the system working in one of the largest soda ash plants existing in Gujarat state.

7.2.1 Equipments

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

a. 3 nos. of Extraction-cum-backpressure type, single stage steam turbine generator sets as per ratings provided below.

   i. 2 x 13750 kVA (1 x 11000 kW), Single extraction-cum-back pressure
   ii. 1 x 5250 kVA (1 x 4200 kW), Double extraction-cum-back pressure

b. 4 nos. of Lignite-cum-coal fired steam generators as per ratings provided below.

   i. 3 x 70 TPH, 105 Kg/cm^2, 405^{0}C
   ii. 1 x 50 TPH, 105 Kg/cm^2, 405^{0}C

Cogeneration equipment data is mentioned below.

Table 7-3: Cogeneration equipment Data

Steam turbine generator data			
Parameter	**Unit**	**Quantity - unit rating wise data**	
Steam turbine data			
		STG # 1 and 2	STG # 3
Type		Extraction-cum-Back-pressure	Extraction-cum-Back-pressure
Nos. installed	Nos.	2 nos.	1 no.
Rating	kW	11000	4200
Speed of turbine	RPM	8250	11500
Reduction gearbox data			
Speed ratio		8250/3000	11500/1500
Type of gearbox			
Inlet steam parameters			
Inlet live steam pressure	Kg/cm^2	105	105
Inlet live steam temp	^{0}C	500	500
Inlet live steam flow	TPH	135	28.5
Specific steam consumption	Kg/kWhr	NA	NA

Parameter	**Unit**	**Quantity – unit rating wise data**	
1st Extraction steam parameters			
Steam pressure	Kg/cm^2	40	40
Steam temperature	^{0}C	380	380
Steam flow	TPH	50	2
2nd Extraction steam parameters			
Steam pressure	Kg/cm^2	Not applicable	22
Steam temperature	^{0}C	Not applicable	325
Steam flow	TPH	Not applicable	12.8

Back pressure (exhaust) steam parameters			
Steam pressure	Kg/cm^2	22	2.2
Steam temperature	^0C	280	161
Steam flow	TPH	85	13.7
Generator data			
Rating for apparent power	kVA	13750	5250
Power output at rated power factor	kW	11000	4200
Generation voltage	Volts	6600	6600
Rated power factor (lag)		0.8	0.8
Frequency	Hz	50	50
Generator shaft speed	RPM	3000	1500
Steam generator data			
Parameter	**Unit**	**Quantity - unit rating wise data**	
		Boiler # 1, 2, 3	Boiler # 4
Nos. installed	Nos.	3	1
Type of furnace		Stocker	Stocker
Heating surface area	sq. metre.		
MCR steam flow	TPH	70	70
pressure (g)	Kg/cm^2	105	105
temperature	^0C	505	505
Flue gas temperature entering the chimney	^0C	150 max.	150 max.
Feed water temperature entering economizer	^0C	150	150
Soot blowers		provided	provided

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

Table 7-4: Fuel Data

Fuel composition data				
Component		**Unit**	**Lignite**	**Coal**
Fuel flow		MT/hour	9.34	4.0
Higher heating value (Gross cal value)		kCal/kg	3894	5832
Lower heating value		kCal/kg	NA	NA
Moisture	*M*	% w/w	32.16	5.58
Carbon	*C*	% w/w	31.78	64.07
Hydrogen	*H*	% w/w	3.48	5.17
Nitrogen	N_2	% w/w	2.82	1.08
Oxygen		% w/w	14.43	11.93
Sulphur		% w/w	2.53	0.95
Ash	*A*	% w/w	12.8	11.22
Ratio of fuel maintained for firing		%	70	30
Fuel GCV based on 70:30 ratio considered for performance				4200

7.2.2 Normal operating philosophy

⇒ The soda ash plant is working round the clock having very critical continuous chemical process. Interruption of more than half an hour in availability of energy either in the form of electric power or steam creates enormous problems in the ongoing process resulting into substantial production losses. One of the major process areas requiring power is Lime Kiln, which must be kept burning under adverse circumstances, otherwise it proves disastrous if the kiln dies down. In the stream of soda ash as final product, the screw conveyers get jammed due to hygroscopic nature of the chemical. 2 nos. of continuously rotating calciners are another drive requiring uninterrupted power and steam.

⇒ In the case study provided, one no. 11000 kW steam turbine generator and 4200 kW steam turbine generator along with three nos. of 70 TPH boilers are operated at around 80-85% of rated capacity.

⇒ One no. 11000 kW steam turbine and one of the boilers are kept as standby to take into service either in the event of breakdown or maintenance shutdown of any of the running units. The standby is considered essential in view of criticality of chemical process and to avoid production losses on this account.

⇒ The CPP starts meeting requirement of electric power and steam of the plant as soon as the production process is commenced. With starting of process equipment in sequence, the power load increases, which provides more and more steam to process. Entire scheme is so designed that power and steam requirements increase hand in hand maintaining good efficiency of the CPP. The heat balance achieved is excellent. The plant is working conforming to the concept of total co-generation power plant technology, which is encouraged all around the world in a big way due to conformance to very vital concept of energy conservation.

7.2.3 Utilisation of energy available in the extraction/back-pressure steam

Steam injection to steam turbine at 105 Kg/cm^2, 505 ^{0}C

High pressure steam at 105 Kg/cm^2, 505 ^{0}C temperature available from the boilers is sent to a common header and from header to the steam turbines as follows. 3 boilers are operated out of 4 nos. installed.

- 11000 kW steam turbine generator – 135 TPH
- normally operated at 9000 kW load
- 4200 kW steam turbine generator – 28.5 TPH
- normally operated at 3000 kW load

The steam turbines generate around 12000 kW electric power, which is utilised in the plant production activities, offices, area illumination and also in the housing colony. This is the primary utilisation of heat energy available in the steam.

- Steam at 40 Kg/cm^2

From both, 11000 kW steam turbine and 4200 kW steam turbine, the steam at 40 bar pressure is taken out via extraction as follows.

- From 11000 kW steam turbine generator extraction steam
- 50 TPH, 40 Kg/cm^2, 380 ^{0}C
- From 4200 kW steam turbine generator 1st extraction steam
- bear minimum 2 TPH, 40 Kg/cm^2, 380 ^{0}C

The extraction steam is utilised as follows.

⇒ This extraction steam is injected into 3 nos. of back-pressure steam turbines, which drive the screw compressors used to compress CO_2 for sent to the process. The back-pressure steam turbines provide the low pressure steam at 2.2 Kg/cm^2, 161 ^{0}C temperature, which is taken to 2.2 bar steam header.

⇒ To further optimise the utilisation of 40 Kg/cm^2bar steam, around 4 TPH steam is injected into a back-pressure steam turbine, which drives a large capacity boiler feed water pump, common for all the boilers, under normal plant running conditions. HT motor driven BF pump is utilised only during start-up of first boiler or during maintenance/breakdown of turbine driven feed pump. Again back-pressure steam turbine provides the low pressure steam at 2.2 Kg/cm^2, 150 ^0C temperature, which is diverted to 2.2 Kg/cm^2 header for further utilisation of heat in the process.

⇒ The utilisation of steam to drive the plant auxiliaries has resulted into substantial saving of electrical energy, which would have been otherwise required to drive very high capacity compressors and large capacity BF pump using electric motor as prime-mover.

Steam at 22 Kg/cm^2 and 8 Kg/cm^2 (Deaerator steam)

The steam at 22 Kg/cm^2 is available in the system as follows from both the steam turbines in operation.

i. From 11000 kW steam turbine generator back-pressure or exhaust steam, 85 TPH, 22 Kg/cm^2, 280 ^0C
ii. From 4200 kW steam turbine generator 2nd extraction steam
iii. 12.8 TPH, 22 Kg/cm^2, 325 ^0C

The exhaust and extraction steam is utilised as follows through 22 Kg/cm^2 header.

⇒ Major part of steam is utilised in 2 nos. of calciners for calcinations process of soda ash. The steam is passed through de-superheating station to reduce the temperature to 230 ^0C, which is marginal loss of energy. Part of steam is absorbed to convert sodium bicarbonate to sodium carbonate ($2NaHCO_3 + H_2O = Na_2CO_3 + 2H_2O$) and balance comes out as condensate from Calciners. Thus, for steam used in reaction, all heat available in 22 bar steam is utilised.

⇒ 22 bar steam, condensed as mentioned in a. above, is flashed to convert to 8 Kg/cm^2, 205 ^0C steam. This steam is sent to the deaerator as pegging steam. Mostly the deaerator steam is supplied in this manner and shortfall, if any, is supplied through 22/8 Kg/cm^2 PRDS as and when required. This system saves good amount of energy, direct drawl of steam from the boiler for deaeration is totally avoided.

⇒ Some part of 22 Kg/cm^2 steam is supplied to HP feed water heater for heating of boiler feed water before it is sent to the boiler and steam condensate available in HP heater is sent to the deaerator for feeding to the boiler.

⇒ A part of 22 Kg/cm^2 steam is directly sent to the process area for direct utilisation of heat. The heat is almost utilised in the process and the condensate is recovered and sent to the deaerator.

iii. Steam at 2.2 Kg/cm^2

The steam at 2.2 Kg/cm^2 is available in the system as follows.

- From 4200 kW steam turbine generator back-pressure or exhaust steam, 13.7 TPH, 2.2 Kg/cm^2, 161 ^0C
- From 3 nos. of steam turbines driving CO_2 compressors exhaust 48 TPH, 2.2 Kg/cm^2, 161 ^0C
- From a steam turbine driving BF pump exhaust 4TPH, 2.2 Kg/cm^2, 150 ^0C

The exhaust and extraction steam is utilised as follows through 2.2 Kg/cm^2 header.

The steam available at 2.2 Kg/cm^2 from header is utilised in the process for heating purpose to its condensing temperature, as such almost all energy available is utilised and the condensate is sent back to the deaerator for onward feeding to the boilers.

iv. Steam drawn through PRDS

A number of PRDS are installed; however these are taken in service in the event of emergency, when steam at certain level may not be available due to non-availability of steam turbine generator or mechanical drive turbines. Except 22/8 Kg/cm^2 PRDS, other PRDS are not operated under normal situation to save energy. This point is also worth noting.

7.2.4 Utilisation of electric power

When the plant production is normal, 4200 kW steam turbine and one of 1100 kW steam turbines are operated maintaining the electric power load of around 12 MW out of total capacity of 15 MW available depending on number of equipment taking part in the process and the colony load. The grid power is kept as standby. 4200 kW steam turbine is utilised to the tune of nearly 80% its respective capacity, so that the steam extraction at different levels and back-pressure is available, which would provide better efficiency. The variation in plant load is absorbed by 11000 kW steam turbine generator. If 2.2 Kg/cm^2 level steam would be obtained through pressure reducing-cum-de-superheating station (PRDS), there would be loss of heat energy available in HP steam sent to PRDS.

7.2.5 Power Plant Performance Analysis

Electrical generation output = 12000 kW
= 12000 x 860 x 4.18 kJ/h
= 4,31,37,600 kJ/h

Table 7-5: Steam out put

Steam utilised at	Quantity	Energy used
	MT/h	kJ/hr
22 bar to process	15	27149100
22 bar to HP heater	5	9049700
22 bar to Calciner	14	25339160
22 bar to Calciner	76.8	139003392
2.2 bar to process	65	117646100

Total energy in steam output = 31,81,87,452 kJ/h

Total energy output (Electricity + Steam) = 42,35,44,352 kJ/h

Table 7-6: Total fuel input

Parameter	**Unit**	**Lignite**	**Coal**
Fuel flow	MT/hour	9.34	4.0
Higher heating value (Gross cal	kCal/kg	3894	5832

Total energy input = 9.34 x 1000 x 3894 x 4.18 +
4.0 x 5832 x 1000 x 4.18 kJ/h
= 74,87,20,294 kJ/h

Overall efficiency = Total energy output/Total energy input
= 56.6%

i. Based on the plant operating data available for the cogeneration plant, the performance indices are observed as follows.

	Plant Load Factor	Overall Efficiency
11000 kW Steam turbine generator #1 OR 2 4200 kW Steam turbine generator 70 TPH Boiler, 3 nos. out of 4 nos.	85-90%	around 57%

ii. The data for efficiency of the boilers is provided to supplement the overall very good efficiency levels maintained by the plant.

70 TPH, 105 Kg/cm^2, 505^{0}C Boiler # 1	75-80 %
70 TPH, 105 Kg/cm^2, 505^{0}C Boiler # 2	76-80 %
70 TPH, 105 Kg/cm^2, 505^{0}C Boiler # 3	80-82 %
70 TPH, 105 Kg/cm^2, 505^{0}C Boiler # 4	82-85 %

iii. The power load on the steam turbine generators is maintained to optimum feasible level to achieve better performance, the steam load is maintained accordingly on the operated boilers, as such the plant load factor and efficiency are observed very good for this specific system. The power load variations are generally taken care off by 11000 kW steam turbine generator maintaining almost full load on 4200 kW steam turbine generator. No parallel operation with the grid is carried out.

iii. The average age of the steam turbine # 1 and 2 and boiler # 1, 2 and 3 is around 16 years. The steam turbine # 3 and boiler # 4 are relatively new taken into service before around 8 years.

iv. There is provision of on-line weighing scales at starting point of conveyors for measurement of actual quantity of coal and lignite fired in the boiler. Moreover, the bunker levels are also monitored. The instrumentation system for measuring the steam flow and total quantity is installed dedicated to each boiler. Thus, necessary data for steam generation vis-à-vis fuel is generated for the CPP. For power measurement, usual calibrated energy meters are installed dedicated to each generator. All these measuring and monitoring systems greatly supplements efforts on the part of engineers to continuously keep a watch on the performance of the CPP.

iv. Heat balance diagram for the system is provided in Fig. 7.2 and total scheme is elaborated in Fig. 7.3 for understanding of system.

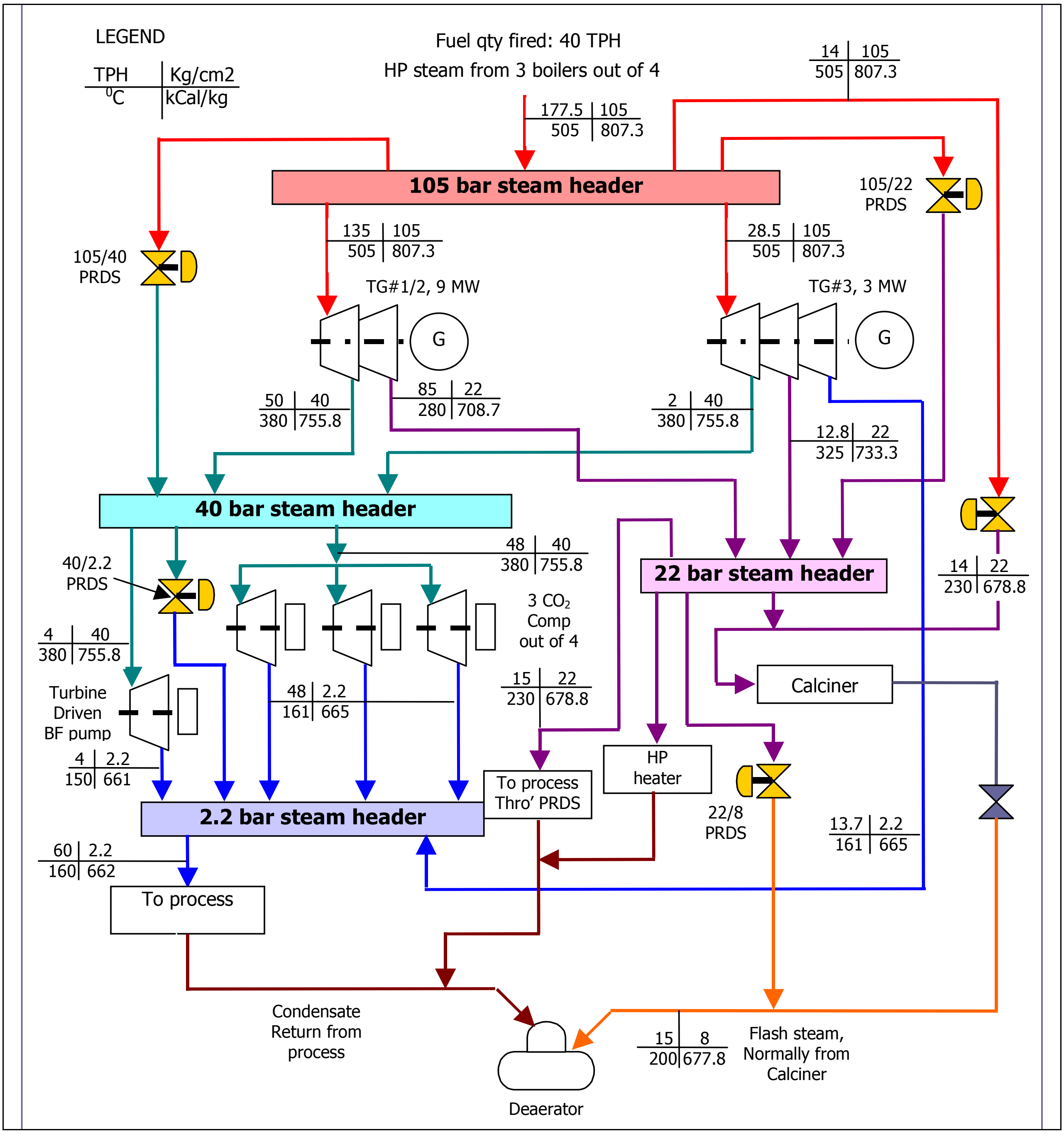


Figure 7-2: Heat balance of Cogen System- Soda Ash Plant

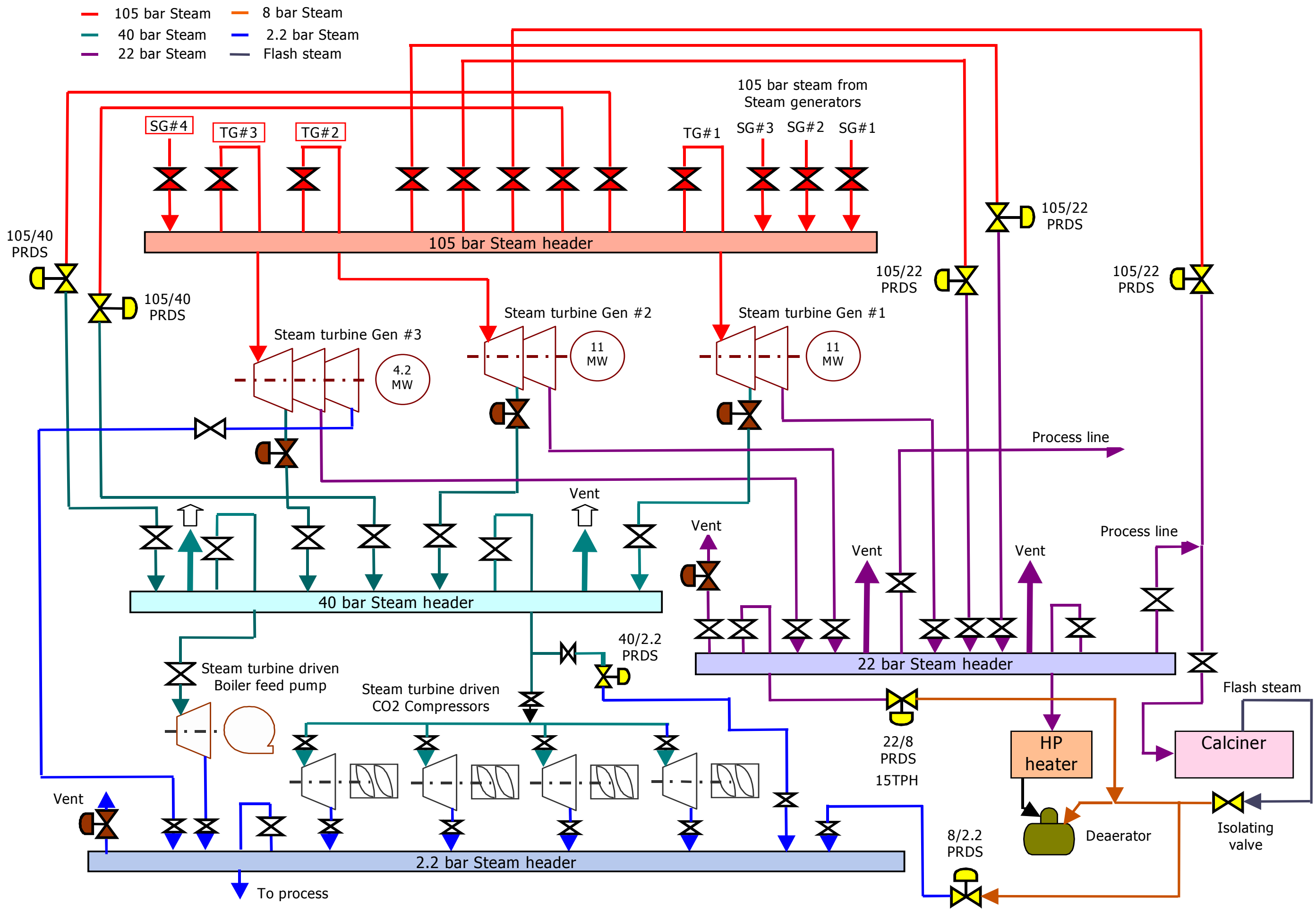


Figure 7-3: Steam Generation & Distribution System

7.3 Gas turbine generator and unfired waste heat boiler-Pharmaceutical Industry

Generally, in continuous process industries requiring more energy in the form of steam than electric power, power to heat ratio less than 1, the cogeneration systems having configuration of gas turbine 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 petrochemical plants or pharmaceutical manufacturing facilities.

The case study is provided below is based on the system working in one of the largest pharmaceutical plants in Gujarat state.

7.3.1 Equipments

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

a. 2 x 5250 kVA (2 x 4200 kW) industrial heavy duty gas turbine generator sets

b. 2 x 10.55 TPH, 9 Kg/cm^2, 200^{0}C unfired waste heat recovery boilers.

Cogeneration equipment data is mentioned below.

Table 7-7: Cogeneration equipment Data

Gas turbine generator data		
Parameter	**Unit**	**Quantity**
Gas turbine data		
Type	Industrial heavy duty	
Nos. of units installed	Nos.	2
Rating	kW	4200
Speed of turbine	RPM	17120
Gas turbine compressor inlet design conditions		
air temperature	^0C	35
pressure	Kg/cm^2	1.0332
altitude	Above MSL	36.5 metre
relative humidity	%	60
diff. pressure - inlet air filter	mbar	100
Gas turbine heat rate at designed conditions	kCal/kWh	3164.09
Cogeneration heat rate at designed conditions	kCal/kWh	969.01
Nos. of stages		
air compressor	Nos. of stages	12
gas turbine	Nos. of stages	2
Exhaust flue gas flow	Kg/sec	16.35
Exhaust flue gas temperature at turbine outlet	^0C	548
Reduction gearbox data		
Speed ratio		17120/1500

Parameter	**Unit**	**Quantity**
Generator data		
Rating for apparent power	kVA	5250
Power output at rated power factor	kW	4200
Generation voltage	kV	11
Full load current	Amp	278
Rated power factor (lag)		0.8
Frequency	Hz	50
Generator shaft speed	RPM	1500
Excitation	Self excited, brushless	

Waste heat recovery boiler data		
Type of WHRB	Water tube, horizontal, unfired, single pressure, waste heat recovery boiler	
Nos. installed	Nos.	2
Exhaust gas temp at WHRB inlet	^0C	542
Exhaust gas temp entering chimney	^0C	140
Steam parameters at boiler exit		
flow	MT/hour	10.5
temperature	^0C	200
pressure (g)	Kg/cm^2	9
Feed water parameters at boiler inlet		
MCR flow	Kg/hour	12
temperature at drum inlet	^0C	105
pressure	Kg/cm^2	12.5
temperature at boiler inlet	^0C	118

Feed water temperature entering economizer	^0C	105
Make-up water temperature at pre-heater inlet	^0C	48
Make-up water temperature at pre-heater outlet	^0C	70
Exhaust flue gas composition		
Average % CO_2	v/v %	6.0
Average % O_2	v/v %	11.0
Average stack gas temperature, T	˚C	230

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

Table 7-8: Fuel composition data

Main fuel – Natural gas			
Fuel flow		NM^3/hour	1250
Higher heating value (Gross cal value)		kCal/NM^3	9500
Moisture	*M*	% w/w	50.27
Carbon	*C*	% w/w	21.71
Hydrogen	*H*	% w/w	3.09
Nitrogen	N_2	% w/w	0.20
Oxygen	*O*	% w/w	23.23
Sulphur	*S*	% w/w	0.00
Ash	*A*	% w/w	1.5
Alternate fuel – High speed diesel			
Fuel flow		Kg/hour	1145
Higher heating value		kCal/kg	10550
Lower heating value		kCal/kg	10200

7.3.2 Normal operating philosophy

i. The pharmaceutical plant works round the clock for the medicinal products manufactured using critical chemical process as well as certain products are manufactured using the batch type process. Hence, the system is bound to experience wide variation in the demand of power and steam from time to time. Moreover, even in case of continuous process, the demand of power and steam is based on simultaneous operation of number of plant sections producing same product depending on the production level.

ii. In the case study provided, 2nos. of 4200 kW gas turbine generators along with 10 TPH unfired WHRB are operated at full load with minimum back up for electric power from the state utility. In case more steam is required than available from WHRB, existing fired boilers are utilised as per demand of steam.

iii. The gas turbine generators are run in parallel with the state utility, which provides advantage in the sense that in the event of tripping of one of the gas turbines, the plant power load to that extent gets transferred on the grid without any interruption/voltage fluctuation to critical process. For meeting short fall in the steam supply, natural gas fuel, used to run the gas turbine, is fired in the existing fired boilers to generate the steam. Whole process takes very nominal time without disturbance of any sort to the critical drug manufacturing process.

7.3.3 Utilisation of power

i. The electrical energy generated from the CPP is totally utilised in operating the process equipment such as large HT motor driven air compressor, agitators, mixers, pumps, utilities and plant/office/area illumination. The production of antibiotics is extremely critical continuous chemical process and production of formulations is carried out using batch process. Thus, the industry imposes varying power load on the system. In order to optimise the performance of CPP, the parallel operation with state grid is resorted to, so that the gas turbines would always operate at full load passing the load variations on the grid system automatically.

ii. When the gas turbines are operated at full load, they maintain optimum heat rate and thereby efficiency. Moreover, the steam availability from WHRB is also maintained to optimum requiring least occasions for operating fired boilers to meet steam requirements. This plant has been found working at excellent efficiency level maintaining attractive economics for the cost of power and steam.

7.3.4 Utilisation of steam

i. Maximum steam availability is 20 TPH from the cogeneration power plant. Major quantity of steam is utilized to run the steam fired vapour absorption chiller machines (VAM) in which the heat available in the steam is almost fully utilised. The chilled water generated VAM is circulated around the fermenters, as microbial developed in the fermentors requires temperature controlled environment for survival. Though the motor driven compression chillers are installed in the plant, they are not operated resulting into substantial saving of electrical energy.

ii. The chilled water is available in abundance, which is also sent to various plant and office building for air-conditioning. Except for few window a/c units, there is central air-conditioning plants working in the factory saving again electrical energy to great extent.

iii. The steam is also utilised for auto-clave of fermentors to make them free of any bacteria as well as some quantity in the process for heating, etc. The condensate, available from vapour absorption chillers at temperature of around 65 – 70^{0}C is recovered and sent back to the cogeneration plant for recycling. Thus the losses are minimised to great extent.

7.3.5 Power Plant Performance Analysis

i. Based on the plant operating data available for the cogeneration facility, the performance indices are observed as follows.

Table 7-9: Energy Consumption

Energy input	Qty	Unit
Natural gas	32000	Nm3/day for 1 turbines
	1333.3	m3/h
	2666.7	Nm3/hr for 2 turbines
Fuel calorific value	9500	kCal/Nm3
Energy input	253.33	laky kCal/hr
Electric power	8000	kW
Heat output	68.8	Laky kcal/h
Gas turbine Elect efficiency	27.16	%

Steam output		
Quantity	21.1	TPH
Enthalpy	676	kCal/kg
Heat output	142.64	kCal/hr
Total energy output	211.44	kCal/hr
Overall Cogen efficiency	83.46	

	Plant Load Factor	Overall Efficiency
4200 kW Gas turbine generator #1 & 2 10.55 TPH Waste heat recovery boiler # 1 & 2	90-95%	83-85%

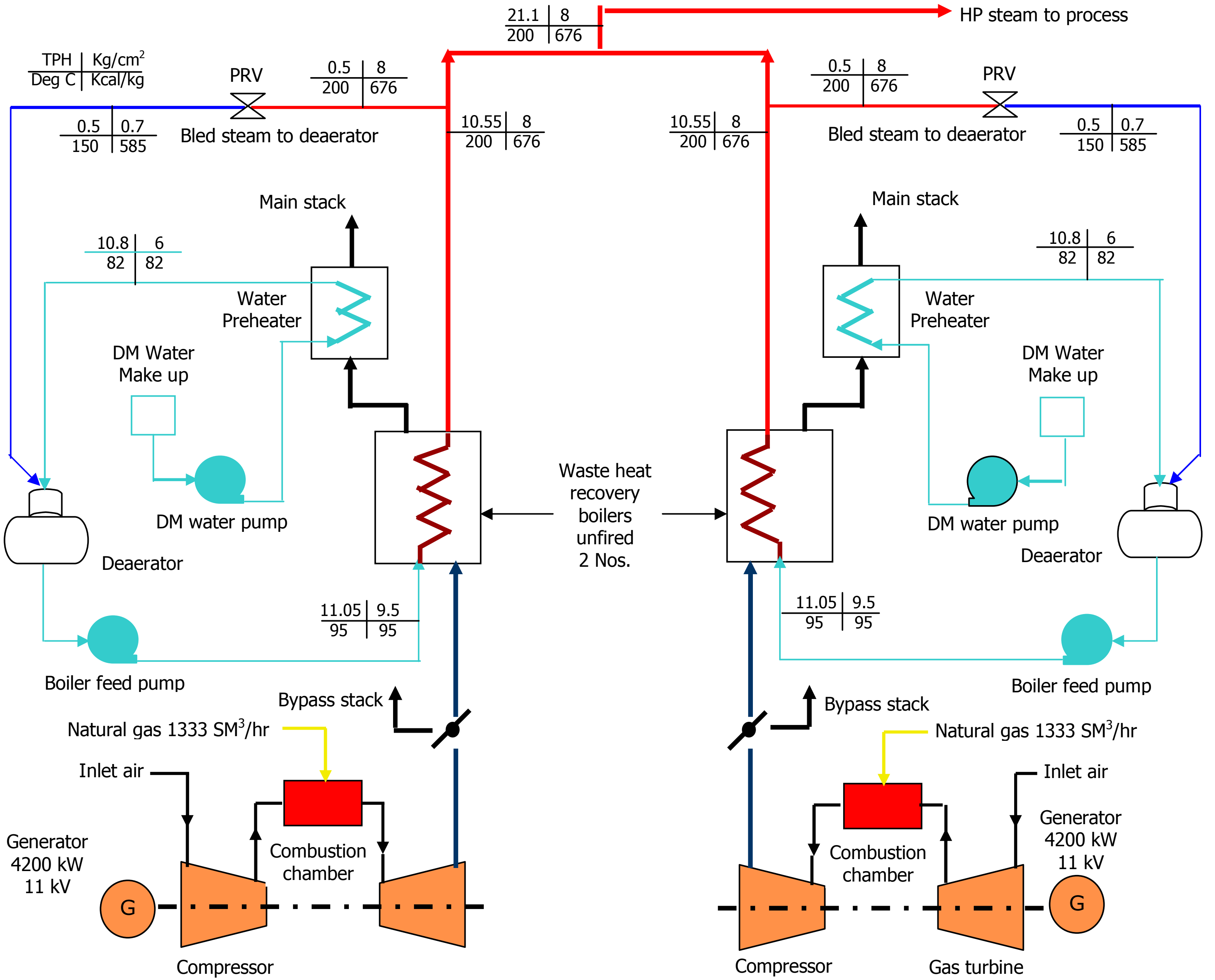
ii. The power load on new steam turbine generators is maintained almost constant due to their better performance, the steam load is also maintained on the connected boiler, and as such the plant load factor and efficiency are observed better in this system. The power load variations are generally taken care off by the system consisting of older steam turbines and boilers, as such the plant load factor and efficiency have been observed marginally in comparison to Island#1 mentioned above.

iii. The average age of the gas turbines and waste heat boilers is around 7 years. The specific steam consumption derived based on the enthalpy difference method is found only marginally offset from the data provided by the manufacturer, which could also be due to some disparity between required and actual inlet steam parameters.

iv. There is latest instrumentation system installed in individual gas turbine for the measurement of natural gas quantity as well as a separate instrument system for measurement of total quantity supplied, which is quite useful for cross checking of natural gas consumed. Actual data for steam generation vis-à-vis fuel is not generated for the CPP. Based on derivation of specific steam consumption, noted steam parameters such as pressure and temperature, power load maintained and analysis of Bagasse, the fuel consumption can be derived, which would be reasonably accurate data.

iv. Heat balance diagram for the cogeneration system is provided on next page in Fig. 7.4

Figure 7-4: Energy flow diagram



7.4 Trigeneration –Commercial Building

In downtown Chicago, M/s. Optimal Path (data center development group) and Flash Power (energy system integrator) have joined hands and set up a combined cycle-cum-cogeneration plant consisting of gas turbine generator, steam turbine generator, waste heat recovery boiler and absorption chiller, to meet 100% of the telecom energy needs. Whenever the power is surplus, it is sold to the grid.

7.4.1 Equipments

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

a. 1 x 8235 kVA (1 x 7000 kW) industrial heavy duty gas turbine generator set.

b. 1 x 3530 kVA (1 X 3000 kW) industrial extraction-cum-condensing steam turbine generator

c. 1 X 17 TPH, 24 Kg/cm^2, 350^{0}C unfired waste heat recovery boiler.

d. 1 no. Vapour absorption chiller

Cogeneration equipment data is mentioned below.

Table 7-10: Cogeneration equipment data

Gas turbine generator data		
Parameter	**Unit**	**Quantity**
Gas turbine generator data		
Type	Industrial heavy duty	
Make	Kawasaki heavy Industries	
Nos. of units installed	Nos.	1
Gas turbine heat rate at designed conditions	kCal/kWh	
Nos. of stages		
air compressor	Nos. of stages	14
gas turbine	Nos. of stages	3
Exhaust flue gas flow	Kg/sec	26.45
Exhaust flue gas temperature at turbine outlet	^{0}C	548
Rating for power generation	kW	7000
Rated power factor of generator		0.85
Steam turbine generator data		
Input steam parameters		
Flow	TPH	17
Pressure	Kg/cm^2	24
Temperature	^{0}C	350
Extraction steam parameters		
Flow	TPH	14.5
Pressure	Kg/cm^2	5.1
Temperature	^{0}C	185
Power output at rated power factor	kW	3000
Generation voltage	kV	460
Rated power factor (lag)		0.85
Frequency	Hz	60
Excitation	Self excited, brushless	

Parameter	Unit	Quantity
Waste heat recovery boiler data		
Type of WHRB	Water tube, horizontal, unfired, single pressure, waste heat recovery boiler	
Nos. installed	Nos.	1
Exhaust gas temp at WHRB inlet	^{0}C	550
Exhaust gas temp entering chimney	^{0}C	120
Steam parameters at boiler exit		
flow	MT/hour	17
temperature	^{0}C	350
pressure (g)	Kg/cm^2	24
Vapour absorption chiller data		
Capacity	TR	not provided
Comfort temperature to be maintained	^{0}F / ^{0}C	60 / 15

The fuel fired in the plant is as follows. The fuel specifications are not provided in the article and hence not projected.

Fuel data
Main fuel – Natural gas
Alternate fuel – Distillate No. 2

7.4.2 Normal operating philosophy

i. The telecom-type data center works round the clock providing extremely reliable relevant services to customers. Main technical aspect to be noted is that, the system is experiencing very nominal variations in the demand of power and steam.

ii. The gas turbine is fired with natural gas, however, the distillate No.2 can also be fired as back-up fuel. The gas turbine generates 7 MW power. The surplus power, if any, is sold to the grid.

iii. The exhaust flue gases from the gas turbine are diverted to the WHRB, which generates 17 TPH steam at 24 Kg/cm^2 pressure and 350 ^{0}C temperature. The steam is injected into the steam turbine, which generates 3 MW power.

iv. The gas turbine generator is run in parallel with the grid, which provides advantage in the sense that in the event of tripping of the gas turbine, the data center power load to that extent gets transferred on the grid without any interruption/voltage fluctuation to critical requirement.

7.4.3 Utilisation of power

i. Almost total electric power of 10 MW generated from the gas turbine generator and steam turbine generator is utilised in telecom-type data center, which essentially requires extremely reliable power to maintain its services without interruption of any sort of smallest duration. Almost 100% back-up power facility is also set up in view of requirement of extreme reliability.

ii. When the gas turbine is operated at full load, it maintains optimum heat rate and thereby efficiency. Moreover, the steam availability from WHRB is also maintained to optimum level to supply steam to the steam turbine and in turn to the absorption chiller as well. This system has been observed working maintaining excellent efficiency level and attractive economics for the cost of power and steam.

7.4.4 Utilisation of steam

i. Maximum steam availability is 17 TPH from the WHRB. Total quantity of steam is utilized to run the steam turbine, which generates 3 MW of power. Around 14.5 TPH steam at 5.1 Kg/cm^2 pressure and 185 ^0C is taken out from the extraction stage of the steam turbine and minimum balance quantity is permitted to condense finally.

ii. The extraction steam is sent to the steam fired absorption chiller system in which the heat available in the steam is almost fully utilised. The chilled water generated in chiller is circulated around the data center to maintain controlled environment at temperature of 60 ^0F. The computers in data center are typically mounted in racks on the raised floor and cooled to maintain the said specified operating temperature. The condensate from absorption chiller is taken back to the condenser for recycling along with the steam condensate to the WHRB.

iii. In the event the steam turbine is not in service due to forced or maintenance outage, the steam to absorption chiller plant is maintained at desired level through pressure reducing and de-superheating station (PRDS), as the controlled environment is also extremely critical requirement for the data center. Even back-up motor driven compression chiller plants are also installed to work in the event of extreme emergency.

7.4.5 Power Plant Performance Analysis

Though no factual data for the plant performance is projected in the source of this study, but based on the plant system and its operating philosophy, the performance indices are predicted as follows. A point worth noting here is the design of entire system to provide 99.9% reliability without depending on the back-up equipment and grid supply.

	Plant Load Factor	Overall Efficiency
7000 kW Gas turbine generator 3000 kW Steam turbine generator 17 TPH Waste heat recovery boiler Absorption chiller plant	98-100%	85-90%

Heat balance diagram for the cogeneration system is provided on next page in Fig. 7.5.

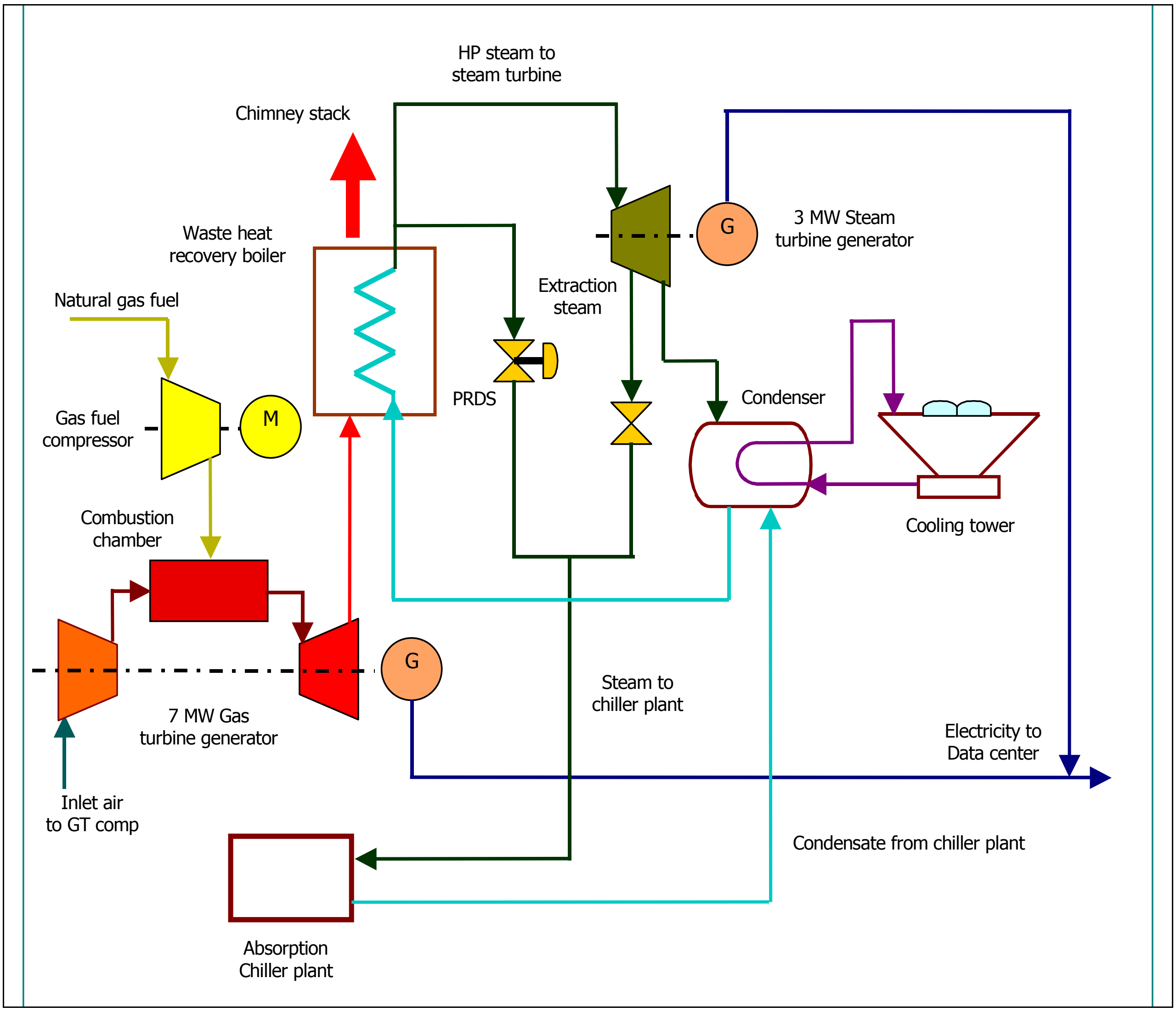


Figure 7-5: Trigeneration-Power, heating and cooling

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

7.5.1 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/cm^2, 250 ^{0}C unfired waste heat recovery boilers as per ratings provided below.

Cogeneration equipment data is mentioned below.

Table 7-11: 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	^{0}C	35
pressure	Kg/cm^2	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	^{0}C	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	^{0}C	405
Exhaust gas temp entering chimney	^{0}C	140
Steam parameters at boiler exit		
flow	MT/hour	3 x 3.5 TPH
temperature	^{0}C	200
pressure (g)	Kg/cm^2	10.5

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

Table 7-12: 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 @ 100 ^{0}C cSt @ 50 ^{0}C	55 730
Density, max @ 15 ^{0}C	gms/ml	0.991
Vanadium, max.	mg/kg	600
Sodium, max.	mg/kg	20-50
Sulphur, max.	% w/w	5.0
Flash Point	^{0}C min.	60
Pour Point, upper max.	^{0}C	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 specification and other relevant technical data is provided below.

Lube-oil composition data	
Type of lube-oil	SAE 40

7.5.2 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.

7.5.3 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.

7.5.4 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.

7.5.5 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 7-13: 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

Parameter	Qty	Unit
Energy output		
Ave. power	14780	kWh
Heat output	127.108	lakh kCal/hr
Electrical efficiency	127.108	330.33
	38.48	%

Steam output		
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 Factor	Overall Efficiency
3 x 6015 kW Reciprocating engine generators 3 x 3.5 TPH Waste heat recovery boilers	90-95%	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.

Heat balance diagram for the cogeneration system is provided on next page in Fig. 7.6

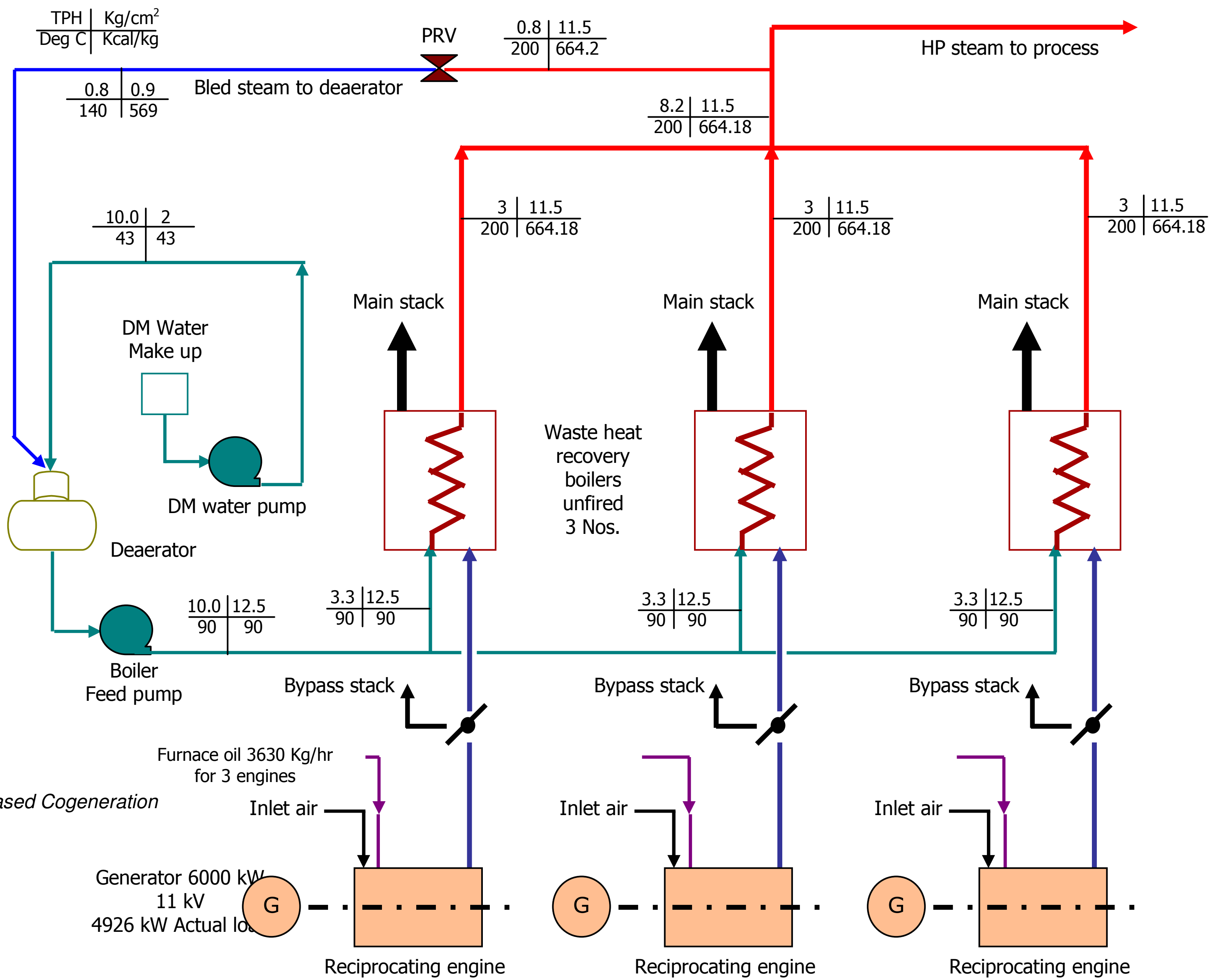


Figure 7-6: Engine Based Cogeneration

7.6 Reciprocating engine System-Automobile Industry

One of the new breed of gas fired reciprocating engine based industrial cogeneration projects proliferating in France is The Peugeot CHP (combined heat and power) installation at Millhouse. This particular case study is taken from “Modern Power Systems” magazine.

7.6.1 Equipments

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

a. 10 x 2500 kVA (1 x 1830 kW) industrial heavy duty gas fired reciprocating engine generator sets.

b. 1 X 11.2 TPH, 16 Kg/cm^2, 201^{0}C unfired waste heat recovery boiler.

c. 2 x 550 m^3/hr, 78 ^{0}C-88 ^{0}C hot water generators.

Cogeneration equipment data is mentioned below.

Table 7-14: Cogeneration equipment data

Reciprocating engine generator data		
Parameter	**Unit**	**Quantity**
Engine data		
Type	Industrial heavy duty	
	Wartsila, CW12V220	
Nos. of units installed	Nos.	10
Rating	bhp	2715
Speed of engine	RPM	1500
Engine inlet design conditions		
air temperature	^{0}C	35
pressure	Kg/cm^2	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	gms/kWh	180.5
Specific lube-oil consumption	gms/kWh	0.8±0.3
Exhaust flue gas flow	Kg/sec	NA
Exhaust flue gas temperature at engine outlet	^{0}C	405
Generator data		
Rating for apparent power	kVA	2500
Power output at rated power factor and ISO conditions	kW	10 x 2033
Power output at rated power factor and site conditions, 9 engines running	kW	9 x 2033
Total heat output	kW_t	9 x 1650
Generation voltage	volt	400
Full load current	Amp	3608.5
Rated power factor (lag)		0.85
Frequency	Hz	50

Parameter	Unit	Quantity
Generator data		
Generator shaft speed	RPM	1500
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.	1
Exhaust gas temp at WHRB inlet	^0C	390
Exhaust gas temp entering hot water generator	^0C	212
Exhaust gas temp at chimney	^0C	125
Steam parameters at boiler exit		
flow	MT/hour	11.2 TPH
temperature	^0C	201
pressure (g)	Kg/cm^2	16
Hot water generator data		
Nos. installed	Nos.	2
Quantity of hot water generated	m^3/hr	2 x 550
Hot water temperature	^0C	78 - 88

The fuel fired in the plant is as follows. The fuel specifications except methane index number are not provided in the article and hence not projected.

Fuel data
Natural gas – methane index number greater than 72

7.6.2 Normal operating philosophy

i. The plant has been set up as joint venture Cummins Wartsila and Peugeot and the operation and maintenance has been provided by Cummins Wartsila. Peugeot is car manufacturing plant with capacity to manufacture 1600 cars per day. It is the largest industrial facility in this region of France

ii. The reciprocating engines are fired with natural gas. Maximum power that the engines can generate is 18.3 MW when 9 engines are in service with one standby. Heat energy available in terms of MW_t is 16.5 in the form of steam and hot water. The generators are operated in parallel with each other with no back-up from the state grid.

iii. The exhaust flue gases from the reciprocating engines are diverted to the WHRB, which generates 11.2 TPH steam at 16 Kg/cm^2 pressure and 201 ^0C temperature. The steam is supplied to the car manufacturing plant.

iv. Balance heat available in the exhaust gases emanating from WHRB is utilised for generation of the hot water. Further, the engines' cooling systems are used to provide the additional heat to generate the hot water via two heat exchangers. The hot water is available within temperature range of 77 – 88 ^0C. The hot water is also utilised in the manufacturing plant.

7.6.3 Utilisation of power

i. Total electric power generated from the cogeneration plant is sent to the grid via 400V/20 kV step up generator transformer and Peugeot is continued to draw power via grid as per the practice prior to setting of cogeneration facility.

ii. When the engines are operated at full load, the plant maintains optimum heat rate and thereby efficiency. Moreover, the steam availability from WHRB is also maintained to optimum level to supply steam to the manufacturing plant. This system has been observed working maintaining excellent efficiency level and attractive economics for the cost of power and steam due to utilisation of substantial energy available in primary source fuel..

7.6.4 Utilisation of steam and hot water

i. The plant is major consumer of process steam heat, which is utilised in the car painting process to its full potential. Wirth stoppage alternate sources of energy for painting, substantial energy saving is also achieved.

ii. The plant is situated in one of France's coldest regions. Hence, the space heating is a must for the working personnel's comfort. Utilisation of hot water has resulted into saving of electrical energy used earlier for providing the space heating.

7.6.5 Power Plant Performance Analysis

Some interesting data for the plant performance for six months has been provided in the article, which is reproduced below.

Guaranteed electrical efficiency	41 %
Guaranteed cogen system efficiency	72 %
Electrical energy generated in cogen plant	647.608 lakh kWh_e
Energy generated in the form of steam	169.337 lakh kWh_r
Energy generated in the form of hot water	258.213 lakh kWh_t
Primary energy consumed, natural gas	175.036 lakh Nm^3

	Plant Heat rate	Overall Efficiency
Assuming LHV of natural gas 7500 $kCal/Nm^3$, the heat rate and cogeneration efficiency	1221 kCal/kWh	70.4 %

Increasing competition in the motor industry is causing the leading players to focus increasing various ways and means to reduce the production cost. Outsourcing of heat energy adopted by the company as solution has resulted into saving of energy. Prior to selection of reciprocating engine, the gas turbines were considered. The competitive advantage of reciprocating engines derives from their higher electrical efficiency. For a given set of conditions and with the same fuel consumption, the electric power produced by reciprocating engines is more than that for turbines, resulting in better economy. Moreover, the reciprocating engines require a lower gas feeding pressure (around 4 bar against 17-20 bar for gas turbines). Hence, gas compressor was not required saving enormous cost of the plant. Auxiliary consumption in reciprocating based power plant is the least among all cogeneration systems.

Heat balance diagram for the cogeneration system is provided on next page in Fig. 7.7.

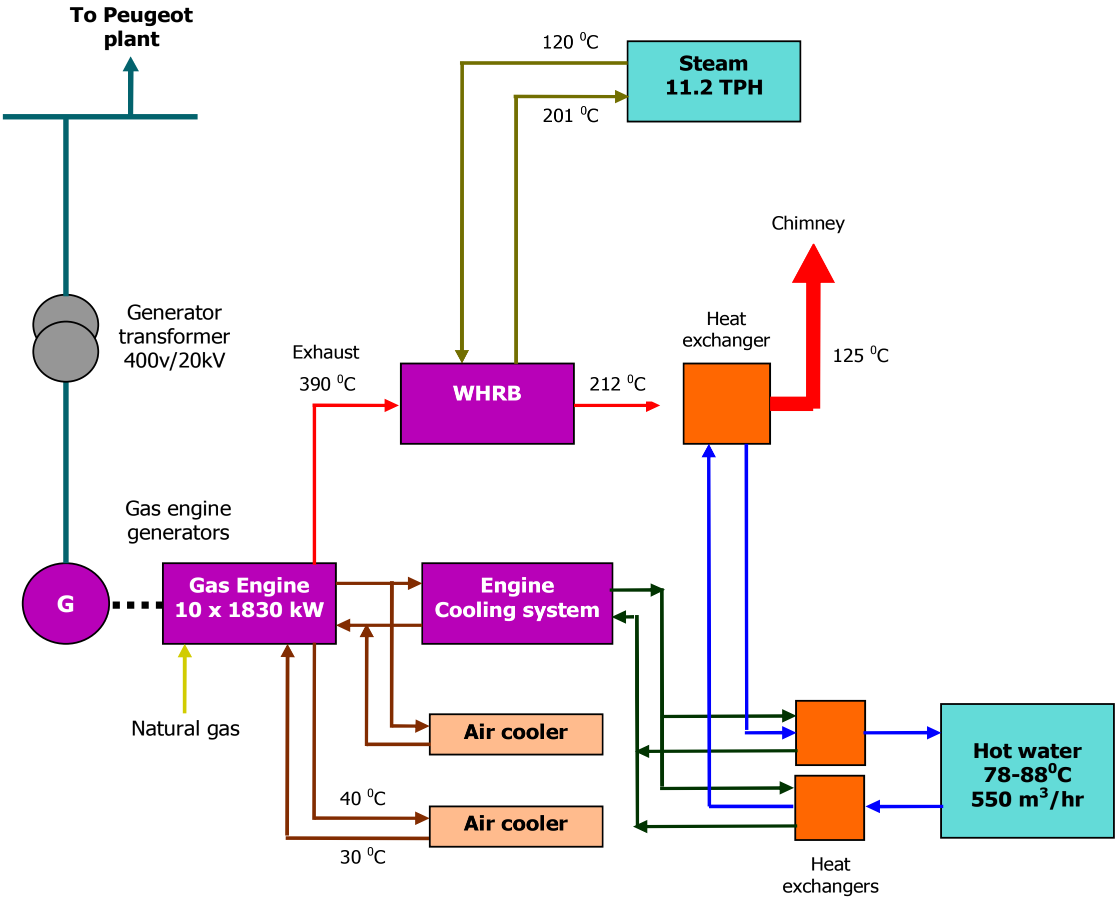


Figure 7-7: Gas engine based cogeneration plant

7.7 Inlet Air Cooling for a Combined Cycle Power Plant-Paper Industry

The 165 MW nameplate rated combined cycle power plant located in Camden, New Jersey, consists of one General Electric Frame 7EA gas turbine, one General Electric auto extracting condensing steam turbine, one dual pressure heat recovery steam generator, one multi-cell mechanical draft cooling tower, and balance of plant equipment.

Steam is supplied to an adjacent paper-making facility and electric power is supplied to Public Service Electric and Gas Corporation.

The project consisted of a complete inlet air cooling system and included a mechanical chiller, cooling coils and their installation, chilled glycol/water pumps and piping, condenser cooling water pumps, piping, electrical and mechanical tie-ins to existing systems. The cooling system was required to meet the following performance criteria:

Combustion turbine inlet air flow = 2,353,551 lbs/hr
Ambient dry bulb/wet bulb temperature = 72°/66°F
Desired inlet air temperature = 50°F
Allowable airside pressure drop = 1.0 in WC

The performance test was conducted and the average ambient conditions during the test were as follows:

Dry bulb temperature = 78.7°F
Wet bulb temperature = 73.2°F
Barometric pressure = 1023 mbar

The other parameters recorded during the test are as follows:

Turbine inlet air temperature = 60.1°F
Duct temperature =59.1°F

Condenser cooling water:
Chiller, in = 86.9°F
Chiller, out = 97.7°F
Flow rate = 6,016 gpm

35% glycol/water mixture:
Chiller, in = 63.8°F
Chiller, out = 52.4 °F
Flow rate = 5,768 gpm

Airside pressure drop:
Prefilters and cooling coils = 0.45 in WC
Prefilters = 0.05 in wc

Power consumption:
Entire system = 1934.8 kW
Cooling water pump = 198.1 kW
Glycol/water pump = 262.3 kW

The standard airflow of 2,276,546 lb/hr at the inlet air temperature of 60.1°F was used in all the calculations. It was verified by heat balance around the cooling coils and from measured turbine exhaust flow.

Chiller Capacity

The chiller capacity was measured by various methods: a) based on the measured glycol flow rate, b) based on measured condenser flow rate. The chiller capacity by the two different methods was found to be 2,398 tons, 2,290 tons respectively. A Schematic of Gas Turbine inlet chilling system is given below.

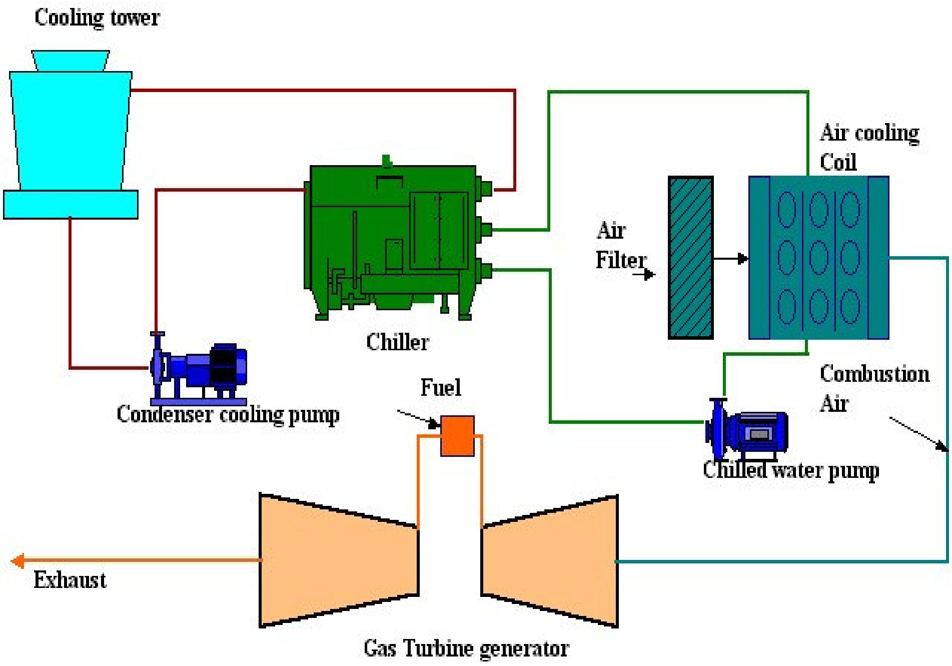


Figure 7-8: Gas turbine inlet air cooling

CONCLUSION

The concept of cooling the inlet air to increase the capacity of the combustion turbine was successfully applied for the Camden Cogeneration plant. The installed inlet cooling system consisted of a 2,000 ton electric driven chiller using R134a as the refrigerant. The guaranteed total power consumption of the chiller, glycol pump and condenser cooling water pump was 1932 kW for 2000 tons of cooling. The total corrected measured power consumption of 1862.4 kW is 3.6 % less than the guaranteed value. The measured chiller capacity of 2,102 tons exceeded the guarantee requirement of 2,000 tons by 5.1%. The corrected measured pressure drop increase of 0.42 in WC was 60% better than the guarantee value. Therefore, the actual system performance was better than the predicted performance. Combustion turbine performance with inlet air cooling met the expected increment of **7.0 MW** at the design ambient conditions.

7.8 Sugar Cogeneration Case Study

The Sugar company is located in Andhra Pradesh. It has a crushing capacity of 8,000 TCD in two mill tandem. Cogeneration was planned in two phase with 13.5 MW capacity in each phase. The performance parameters are shown below.

Table 7-15: Cogeneration Plant Details

Boiler

Type	Single drum water tube radiant with dumping grate
Fuel used	Bagasse/rice husk
Capacity	82 tph
Steam pressure	63 ata
Steam temperature	485 ‘C
Total heating surface	3,913 sq.m
ID fan (2 nos.) with VFDs	162,000m^3/hr each
FD fan (2 nos.) with VFDs	72,000m^3/hr each
SA fan (1 no.)	54,000m^3/hr
Fly ash control	Wet scrubber

Turbo Alternator

Rating	25 MW *
Type	Extraction-cum-condensing
Operating pressure & Temperature	71 ata/ 485'C
Specific steam consumption	6 kg/kWh (season) 4.5 kg/kWh (off-season)
Governor type	Hydraulic (original governor)
Rating	31.5 MVA, 25 MW at 6.3 kV 50 Hz
RPM	3,000 (direct coupling to turbine)
Insulation	Class B

Performance data of the Cogeneration Unit

	2003-2004	2004-2005
No. of days of operation	103	132
Average cost of fuel per ton Bagasse: Husk: Coal:	 Rs.923 Rs.905 Rs.2,176	 Rs.1,004 Rs.1,232 Rs.2,264
Electricity generated, kWh	124,533,700	38,758,690
Electricity exported, kWh	15,670,000	24,184,000
Revenue realized from power export	Rs 53,733,220 @ Rs 3.48/kWh	Rs 64,448,752 @ Rs 3.085/kWh
Crane crushed, tons	851,000	927,000
Average cane crushed, tph	7,340	7,566 (excluding stoppage)
Recovery % cane	10.83	11.57
Fibre % cane	14.21	13.85
Operation time efficiency % (hours lost % available)	9.65	7.73

7.9 Power Generation from Blast Furnace Gas

This case study is from a steel plant, explaining the blast furnace gas cogeneration. CET3 is the acronym of the thermoelectric power plant number 3 of the Taranto Steel Works. This power plant, which is in commercial operation from 1997, is an innovative power plant- a combined cycle fed by recovery fuel gases provided with a post –firing system. At present it is probably the largest combined cycle plant, in commercial operation, fed by low Btu gases.

These gases are produced by the steel work process: blast furnace gas (BFG), coke oven gas (COKE), basic converter gas (LDG). Their average characteristics, in comparison with those of natural gas (NG), are listed in table 7.16.

Table 7-16: Fuel gases characteristics

Composition (vol. % dry)	COKE	BFG	LOG	NG
H_2	60.21	1.2	1	-
CO	5.13	24.8	68	-
N_2	4.87	57.1	15	4
CH_4	24.78	-	-	95
CO_2	1.41	16.9	16	-
$C_2 H_{2N}$	2.49	-	-	1
O_2	0.31	-	-	-
C_6H_6	0.67	-	-	-
C_2H_2	0.05	-	-	-

C_3H_8	0.06	-	-	-
C_3H_6	0.01	-	-	-
C_4H_{10}	0.01	-	-	-
NH_3 (g/m_n^3)	0.03+0.05			
$C_{10}H_8$ (g/m_n^3)	0.1+0.9			
H_2S (g/m_n^3)	5+6			
Density(Kg/ m_n^3)	0.436	1.38	1.35	0.74
Lower Heating Value (KJ/Kg)	43251	2378	6323	48548

- The characteristics of the off gases can change unexpectedly in composition and heat value. The flow rate to final users can also change drastically, even if the internal grids are connected with large gasometers.
- In any case, for environmental reasons, all gases must be utilised in order to avoid their discharge in atmosphere.
- Moreover there must be a convenient use of these fuel gases from an energetic point of view.
- All previous needs have been satisfied by the realization of the new cogeneration plant CET3.

The CET3 consists of three identical combined cycle units capable of delivering more than 500 Mw of electrical power to the national grid (at present , before the upgrading of the steam turbines, the power output is about 600 MW in " all electrical" mode) and industrial steam (until a maximum value of 300 t/h) for steel work consumption.

The plant is composed of three equal, independent modules and common elements. A simplified scheme of one of the three identical combined cycle units is shown in figure 1. In this figure a simplified scheme of the network of gas mixing and feeding is also shown, but really there is only one common network for the whole plant.

More precisely each module includes:

- A recovery gas compression system (GC) provided with double intercooling;
- A gas turbine (GT) equipped with dual-fuel burners for the recovery gas and natural gas firing;
- A heat recovery steam generators (HRSG) with post-firing;
- A steam turbine and condenser.

The combined cycle of the CET3 is very different from a usual combined firing natural gas. This difference is mainly fed by recovery gases. In fact, in order to be used in the gas turbine, off gases require compression up to 20-22 bars obtained by a centrifugal compressor coupled to the gas turbine. Before their use in the gas turbine combustor, gases also require suitable filtration and purification equipment. Moreover, due to the inconsistent flow and calorific value, their mixing with natural gas is necessary, in order to obtain fuel gas with stable characteristics and suitable calorific value (from 6170kJ/Nm^3 to 8370 kJ/Nm^3).

This suitable calorific value range is a consequence of the following limits on the lower heating value of the gas mix:

- Higher than 6170 kJ/Nm^3 to ensure flame stability;

- Lower than 8370 kJ/Nm^3 to ensure low NOx emissions without steam injection (steam injection is impossible because the recovery gas supply involves high volumetric flow rate at the expansor inlet).

Taking into account these operating conditions, natural gas has been chosen to regulate the blower heating value of the gas mix sent to the gas turbine combustors. In table 7.17, this natural gas integration is shown with reference to three typical fuel supply conditions of the plant, which have been statistically defined on the basis of recovery gas availability (A: nominal recovery gas availability, B: high availability, C: low availability). In each fuel supply condition, the amount gases exceeding firing capacity of the gas turbine is sent to the post-firing.

Table 7-17: Typical fuel supply conditions of CET3

Gas	LHV	AVAILABILITY A		AVAILABILITY B		AVAILABILITY C	
	Kj/Nm^3	flow rate Nm^3/h	thermal power MW	flow rate Nm^3/h	thermal power MW	flow rate Nm^3/h	thermal power MW
BFG	3266	546779	495.9	554100	502.5	360381	326.9
COKE	18850	70983	371.7	72400	379	86376	452.3
LDG	8495	68808	162.3	76500	180.5	71001	167.5
GN	35830	28448	283.1	2387	23.75	35313	351.4
Input thermal power			1313		1086		1298

The overall power plant performance related to the fuel supply conditions of the table 7.17 is shown in table 7.18.

Table 7-18: CET3 Performance in the supply conditions

Fuel availability	Net electrical power MWe	Heat rate KJ/kWh	Industrial steam Kg/s
A	547.7	8633	38.9
B	417.2	9374	38.9
C	549.1	8512	38.9

7.10 Cement Plant Cogeneration

This case study is from India Cements, A.P. Utilisation of waste heat from the preheater and AQC gases for power generation. Steam is produced in an heat recovery steam generator and the super heated steam drives a turbo-generator, producing electricity. This system utilising thermal energy which is discharged into the atmosphere, 40% of the input energy in typical systems. Utilising 40% thermal energy discharging into atmosphere. The power generated is about 30 % of total power required for the plant.

The operating parameters of the pre-heater and AQC exhaust gas system is given below.

Table 7-19: Exhaust gas data

ITEMS		UNIT	PH	AQC
Volumetric flow rate		$Nm^{3/}h$	360,750	191,600
Boiler Inlet Pressure (flue gases)		kpaG	-9.01	-0.25
Temperature at Boiler Inlet		Deg. C	340	360
Temperature at Boiler Outlet		Deg. C	230	90
Gas Composition	N_2	Vol %	60	77.6
	O_2	Vol %	4	20.4
	H_2O	Vol %	7	2
	CO_2	Vol %	29	-
Dust Content		G / Nm^3	50 - 60	5*1
Duct Diameter		mm	3800	4300

Details of steam and power generation is given in table 7.20 below.

Table 7-20: Power generation data

ITEMS		UNIT	PH BOILER	AQC BOILER
BOILERS	EVAPORATION RATE	T /H	28.20	14.63
	STEAM PRESSURE	MpaG	1.57	1.70
	STEAM TEMP	Deg. C	315	345
	FEED WATER TEMP	Deg. C	200	56
	HEAT RECOVERY VALUE	kj / h	63,773,337	34,070,001
STEAM TURBINE	OUT PUT	KW	7,700	
GENERATOR	CAPACITY	KVA	9,625	
	POWER FACTOR	%	80	
	TERMINAL VOLTAGE	V	6,600	
	FREQUENCY	Hz	50	

Cost benefit analysis is given below. Note that the auxiliary consumption of the cooling tower , boiler feed pumps, fans etc has been accounted and net power generated is calculated.

Quantity of power generated	KW	7,700
In - house power consumption	KW	800
Net quantity of power generated	KW	6,900
Quantity of cooling water	T / h	26.5
Cooling water pump	KW	180
Reduced power purchased	KW	7,080
Price of power purchased	Rs. /kwh	4.15
Annual reduction of quantity of power purchased	10^6 kwh	56.07
Annual saving of power fee	Million Rs. / y	232.7
Reduced cost per ton of product	Rs. / t	581.8

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