4. COGENERATION

4.1 Need for Cogeneration

Thermal power plants are a major source of electricity supply in India. The conventional method of power generation and supply to the customer is wasteful in the sense that only about a third of the primary energy fed into the power plant is actually made available to the user in the form of electricity (Figure 7.1). In conventional power plant, efficiency is only 35% and remaining 65% of energy is lost. The major source of loss in the conversion process is the heat rejected to the surrounding water or air due to the inherent constraints of the different thermodynamic cycles employed in power generation. Also further losses of around 10–15% are associated with the transmission and distribution of electricity in the electrical grid.

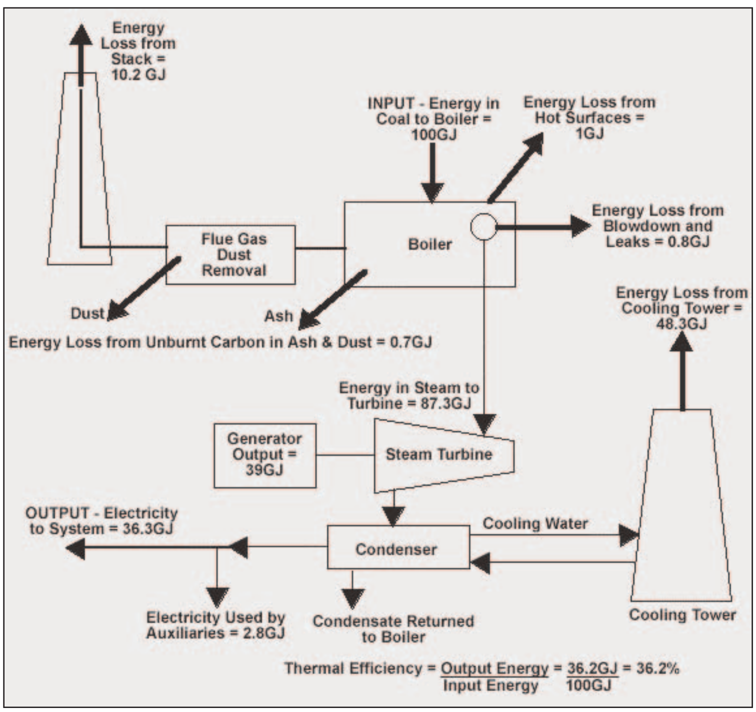


Figure 4.1 BALANCE IN TYPICAL COAL FIRED POWER STATION For an Input Energy of 100 Giga Joules (GJ)

4.2 Principle of Cogeneration

Cogeneration or Combined Heat and Power (CHP) is defined as the sequential generation of two different forms of useful energy from a single primary energy source, typically mechanical energy and thermal energy. Mechanical energy may be used either to drive an alternator for producing electricity, or rotating equipment such as motor, compressor, pump or fan for delivering various services. Thermal energy can be used either for direct process applications or for indirectly producing steam, hot water, hot air for dryer or chilled water for process cooling.

Cogeneration provides a wide range of technologies for application in various domains of economic activities. The overall efficiency of energy use in cogeneration mode can be up to 85 per cent and above in some cases.

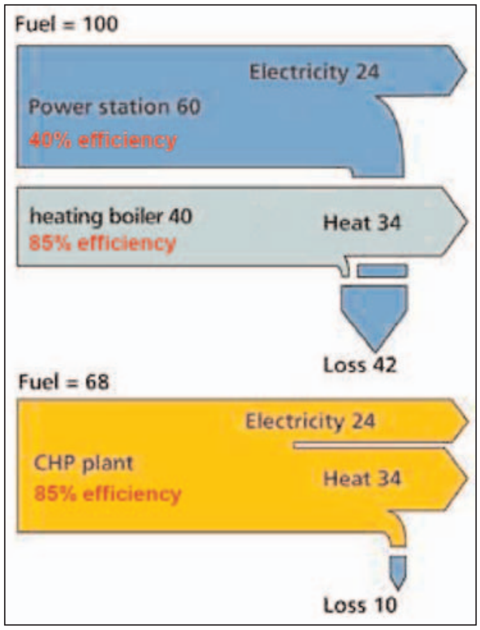


Figure 4.2 Cogeneration Advantage

For example in the scheme shown in Figure 7.2, an industry requires 24 units of electrical energy and 34 units of heat energy. Through separate heat and power route the primary energy input in power plant will be 60 units (24/0.40). If a separate boiler is used for steam generation then the fuel input to boiler will be 40 units (34/0.85). If the plant had cogeneration then the fuel input will be only 68 units (24+34)/0.85 to meet both electrical and thermal energy requirements. It can be observed that the losses, which were 42 units in the case of, separate heat and power has reduced to 10 units in cogeneration mode.

Along with the saving of fossil fuels, cogeneration also allows to reduce the emission of greenhouse gases (particularly CO_2 emission). The production of electricity being on-site, the burden on the utility network is reduced and the transmission line losses eliminated.

Cogeneration makes sense from both macro and micro perspectives. At the macro level, it allows a part of the financial burden of the national power utility to be shared by the private sector; in addition, indigenous energy sources are conserved. At the micro level, the overall energy bill of the users can be reduced, particularly when there is a simultaneous need for both power and heat at the site, and a rational energy tariff is practiced in the country.

4.3 Technical Options for Cogeneration

Cogeneration technologies that have been widely commercialized include extraction/back pressure steam turbines, gas turbine with heat recovery boiler (with or without bottoming steam turbine) and reciprocating engines with heat recovery boiler.

4.3.1 Steam Turbine Cogeneration systems

The two types of steam turbines most widely used are the backpressure and the extraction-Another variation of the steam turbine topping cycle cogeneration system is the extraction-back pressure turbine that can be employed where the end-user needs thermal energy at two different temperature levels. The full-condensing steam turbines are usually incorporated at sites where heat rejected from the process is used to generate power.

The specific advantage of using steam turbines in comparison with the other prime movers is the option for using a wide variety of conventional as well as alternative fuels such as coal, natural gas, fuel oil and biomass. The power generation efficiency of the emand for electricity is greater than one MW up to a few hundreds of MW. Due to the system inertia, their operation is not suitable for sites with intermittent energy demand.

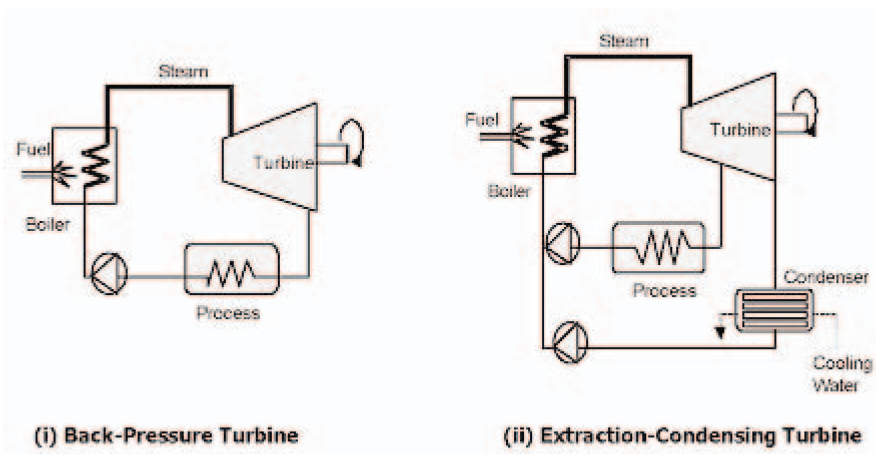


Figure 4.3 Schematic Diagrams of Steam Turbine Cogeneration Systems

4.3.2 Gasturbine Cogeneration Systems

Gas turbine cogeneration systems can produce all or a part of the energy requirement of the site, and the energy released at high temperature in the exhaust stack can be recovered for various heating and cooling applications (see Figure 7.4). Though natural gas is most commonly used, other fuels such as light fuel oil or diesel can also be employed. The typical range of gas turbines varies from a fraction of a MW to around 100 MW.

Gas turbine cogeneration has probably experienced the most rapid development in the recent years due to the greater availability of natural gas, rapid progress in the technology, significant reduction in installation costs, and better environmental performance. Furthermore, the gestation period for developing a project is shorter and the equipment can be delivered in a modular manner. Gas turbine has a short start-up time and provides the flexibility of intermittent operation. Though it has a low heat to power conversion efficiency, more heat can be recovered at higher temperatures. If the heat output is less than that required by the user, it is possible to have supplementary natural gas firing by mixing additional fuel to the oxygen-rich exhaust gas to boost the thermal output more efficiently.

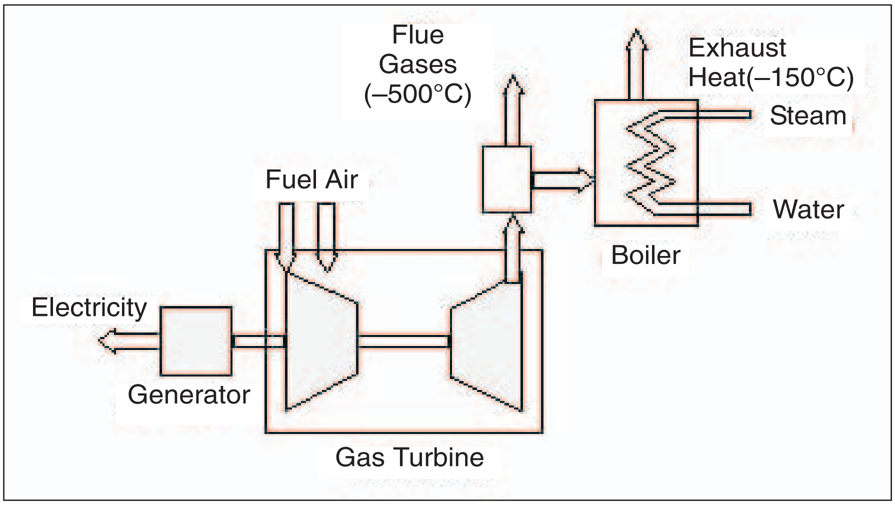


Figure 4.4 Schematic Diagram of Gas Turbine Cogeneration

On the other hand, if more power is required at the site, it is possible to adopt a combined cycle that is a combination of gas turbine and steam turbine cogeneration. Steam generated from the exhaust gas of the gas turbine is passed through a backpressure or extraction-condensing steam turbine to generate additional power. The exhaust or the extracted steam from the steam turbine provides the required thermal energy.

4.3.3 Reciprocating Engine Cogeneration Systems

Also known as internal combustion (I. C.) engines, these cogeneration systems have high power generation efficiencies in comparison with other prime movers. There are two sources of heat for recovery: exhaust gas at high temperature and engine jacket cooling water system at low temperature (see Figure 7.5). As heat recovery can be quite efficient for smaller systems, these systems are more popular with smaller energy consuming facilities, particularly those having a greater need for electricity than thermal energy and where the quality of heat required is not high, e.g. low pressure steam or hot water.

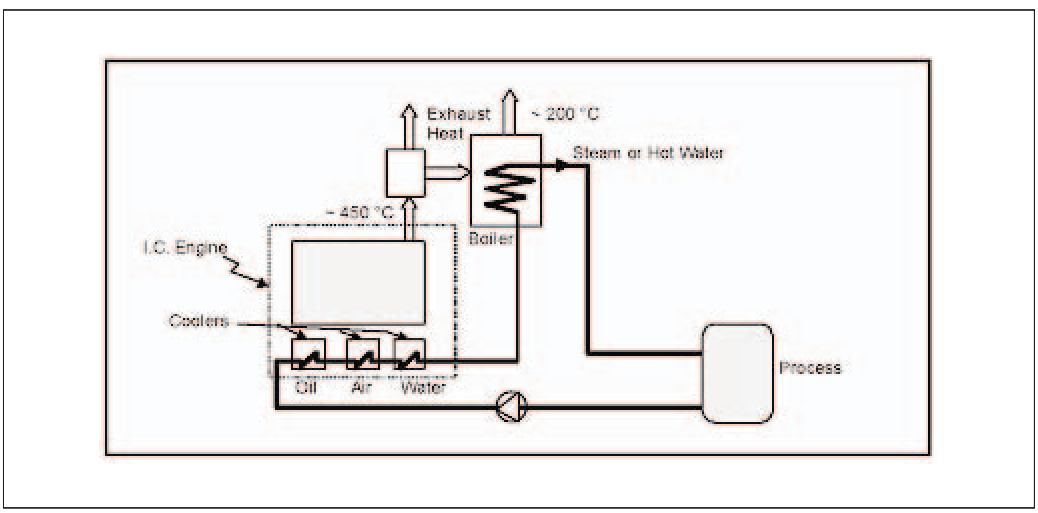


Figure 4.5 Schematic Diagram of Reciprocating Engine Cogeneration

Though diesel has been the most common fuel in the past, the prime movers can also operate with heavy fuel oil or natural gas. These machines are ideal for intermittent operation and their performance is not as sensitive to the changes in ambient temperatures as the gas turbines. Though the initial investment on these machines is low, their operating and maintenance costs are high due to high wear and tear.

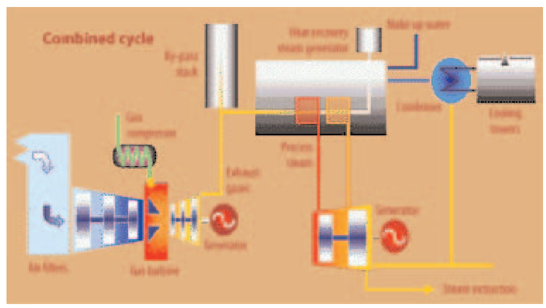
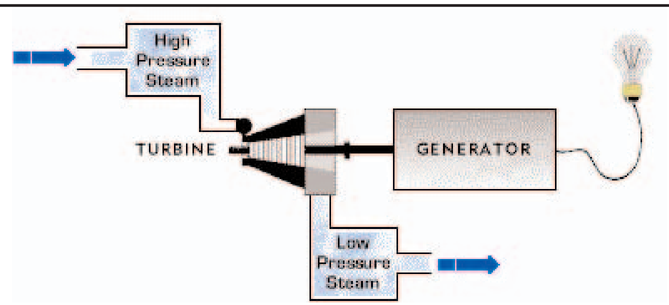
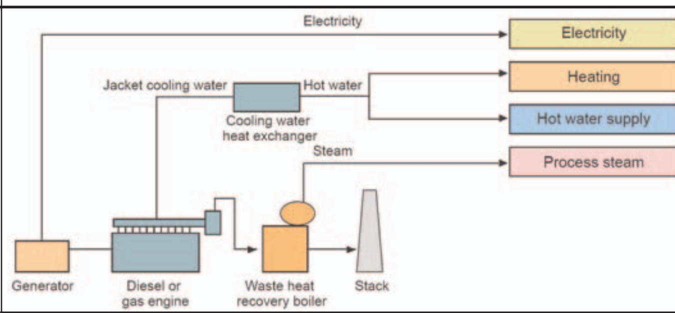
4.4 Classification of Cogeneration Systems

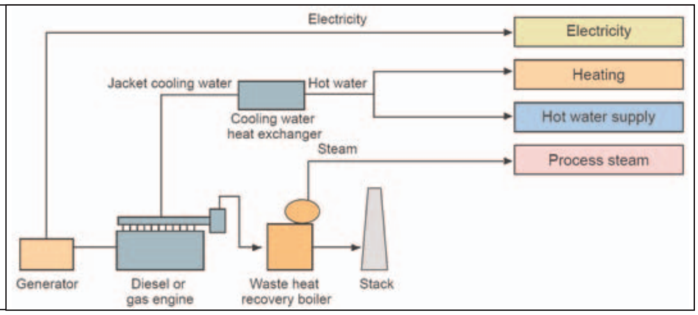
Cogeneration systems are normally classified according to the sequence of energy use and the operating schemes adopted.

A cogeneration system can be classified as either a topping or a bottoming cycle on the basis of the sequence of energy use. In a topping cycle, the fuel supplied is used to first produce power and then thermal energy, which is the by-product of the cycle and is used to satisfy process heat or other thermal requirements. Topping cycle cogeneration is widely used and is the most popular method of cogeneration.

Topping Cycle

The four types of topping cycle cogeneration systems are briefly explained in Table 4.1.

<table>
<tr><th colspan="2">TABLE 7.1 TYPES OF TOPPING CYCLES</th></tr>
<tr><td>A gas turbine or diesel engine producing electrical or mechanical power followed by a heat recovery boiler to create steam to drive a secondary steam turbine. This is called a combined-cycle topping system.</td><td>
</td></tr>
<tr><td>The second type of system burns fuel (any type) to produce high-pressure steam that then passes through a steam turbine to produce power with the exhaust provides low-pressure process steam. This is a steam-turbine topping system.</td><td>
</td></tr>
<tr><td>A third type employs heat recovery from an engine exhaust and/or jacket cooling system flowing to a heat recovery boiler, where it is converted to process steam / hot water for further use.</td><td>
</td></tr>
</table>

The fourth type is a gas-turbine topping system. A natural gas turbine drives a generator. The exhaust gas goes to a heat recovery boiler that makes process steam and process heat	

Bottoming Cycle

In a bottoming cycle, the primary fuel produces high temperature thermal energy and the heat rejected from the process is used to generate power through a recovery boiler and a turbine generator. Bottoming cycles are suitable for manufacturing processes that require heat at high temperature in furnaces and kilns, and reject heat at significantly high temperatures. Typical areas of application include cement, steel, ceramic, gas and petrochemical industries. Bottoming cycle plants are much less common than topping cycle plants. The Figure 4.6 illustrates the bottoming cycle where fuel is burnt in a furnace to produce synthetic rutile. The waste gases coming out of the furnace is utilized in a boiler to generate steam, which drives the turbine to produce electricity.

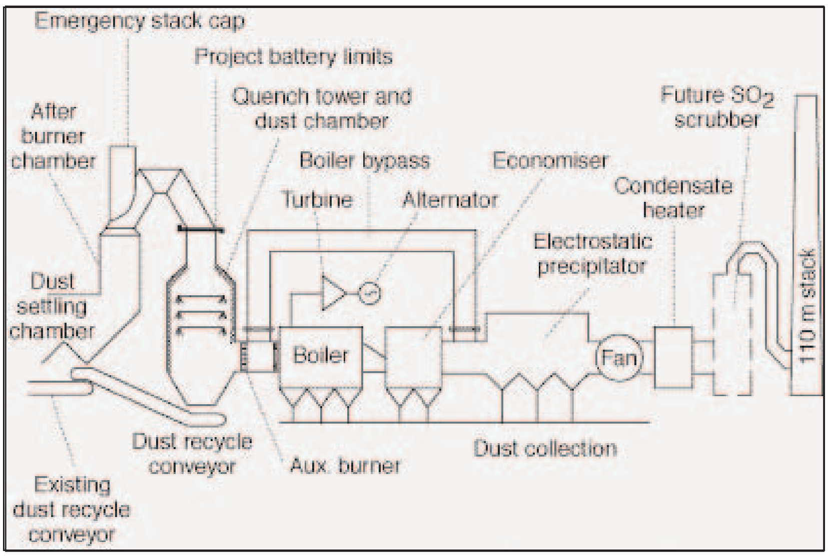


Figure 4.6 Bottoming Cycle

4.5 Factors Influencing Cogeneration Choice

The selection and operating scheme of a cogeneration system is very much site-specific and depends on several factors, as described below:

4.5.1 Base electrical load matching

In this configuration, the cogeneration plant is sized to meet the minimum electricity demand of the site based on the historical demand curve. The rest of the needed power is purchased from the utility grid. The thermal energy requirement of the site could be met by the cogeneration system alone or by additional boilers. If the thermal energy generated with the base electrical load exceeds the plant's demand and if the situation permits, excess thermal energy can be exported to neighbouring customers.

4.5.2 Base Thermal Load Matching

Here, the cogeneration system is sized to supply the minimum thermal energy requirement of the site. Stand-by boilers or burners are operated during periods when the demand for heat is higher. The prime mover installed operates at full load at all times. If the electricity demand of the site exceeds that which can be provided by the prime mover, then the remaining amount can be purchased from the grid. Likewise, if local laws permit, the excess electricity can be sold to the power utility.

4.5.3 Electrical Load Matching

In this operating scheme, the facility is totally independent of the power utility grid. All the power requirements of the site, including the reserves needed during scheduled and unscheduled maintenance, are to be taken into account while sizing the system. This is also referred to as a "stand-alone" system. If the thermal energy demand of the site is higher than that generated by the cogeneration system, auxiliary boilers are used. On the other hand, when the thermal energy demand is low, some thermal energy is wasted. If there is a possibility, excess thermal energy can be exported to neighbouring facilities.

4.5.4 Thermal Load Matching

The cogeneration system is designed to meet the thermal energy requirement of the site at any time. The prime movers are operated following the thermal demand. During the period when the electricity demand exceeds the generation capacity, the deficit can be compensated by power purchased from the grid. Similarly, if the local legislation permits, electricity produced in excess at any time may be sold to the utility.

4.6 Important Technical Parameters for Cogeneration

While selecting cogeneration systems, one should consider some important technical parameters that assist in defining the type and operating scheme of different alternative cogeneration systems to be selected.

4.6.1 Heat-to-Power Ratio

Heat-to-power ratio is one of the most important technical parameters influencing the selection of the type of cogeneration system. The heat-to-power ratio of a facility should match with the characteristics of the cogeneration system to be installed.

It is defined as the ratio of thermal energy to electricity required by the energy consuming facility. Though it can be expressed in different units such as Btu/kWh, kCal/kWh, lb./hr/kW, etc., here it is presented on the basis of the same energy unit (kW).

Basic heat-to-power ratios of the different cogeneration systems are shown in Table 7.2 along with some technical parameters. The steam turbine cogeneration system can offer a large range of heat-to-power ratios.

TABLE 4.2 HEAT-TO-POWER RATIOS AND OTHER PARAMETERS OF COGENERATION SYSTEMS			
Cogeneration System	**Heat-to-power ratio** (kW_{th}/kW_e)	**Power output** (as percent of fuel input)	**Overall efficiency** per cent
Back-pressure steam turbine	4.0-14.3	14-28	84-92
Extraction-condensing steam turbine	2.0-10.0	22-40	60-80
Gas turbine	1.3-2.0	24-35	70-85
Combined cycle	1.0-1.7	34-40	69-83
Reciprocating engine	1.1-2.5	33-53	75-85

Cogeneration uses a single process to generate both electricity and usable heat or cooling. The proportions of heat and power needed (heat: power ratio) vary from site to site, so the type of plant must be selected carefully and appropriate operating schemes must be established to match demands as closely as possible. The plant may therefore be set up to supply part or all of the site heat and electricity loads, or an excess of either may be exported if a suitable customer is available. The following Table 7.3 shows typical heat: power ratios for certain energy intensive industries:

TABLE 7.3 TYPICAL HEAT: POWER RATIOS FOR CERTAIN 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

Cogeneration is likely to be most attractive under the following circumstances:

(a) The demand for both steam and power is balanced i.e. consistent with the range of steam: power output ratios that can be obtained from a suitable cogeneration plant.

(b) A single plant or group of plants has sufficient demand for steam and power to permit economies of scale to be achieved.

(c) Peaks and troughs in demand can be managed or, in the case of electricity, adequate backup supplies can be obtained from the utility company.

The ratio of heat to power required by a site may vary during different times of the day and seasons of the year. Importing power from the grid can make up a shortfall in electrical output from the cogeneration unit and firing standby boilers can satisfy additional heat demand.

Many large cogeneration units utilize supplementary or boost firing of the exhaust gases in order to modify the heat: power ratio of the system to match site loads.

4.6.2 Quality of Thermal Energy Needed

The quality of thermal energy required (temperature and pressure) also determines the type of cogeneration system. For a sugar mill needing thermal energy at about 120°C, a topping cycle cogeneration system can meet the heat demand. On the other hand, for a cement plant requiring thermal energy at about 1450°C, a bottoming cycle cogeneration system can meet both high quality thermal energy and electricity demands of the plant.

4.6.3 Load Patterns

The heat and power demand patterns of the user affect the selection (type and size) of the cogeneration system. For instance, the load patterns of two energy consuming facilities shown in Figure 7.7 would lead to two different sizes, possibly types also, of cogeneration systems.

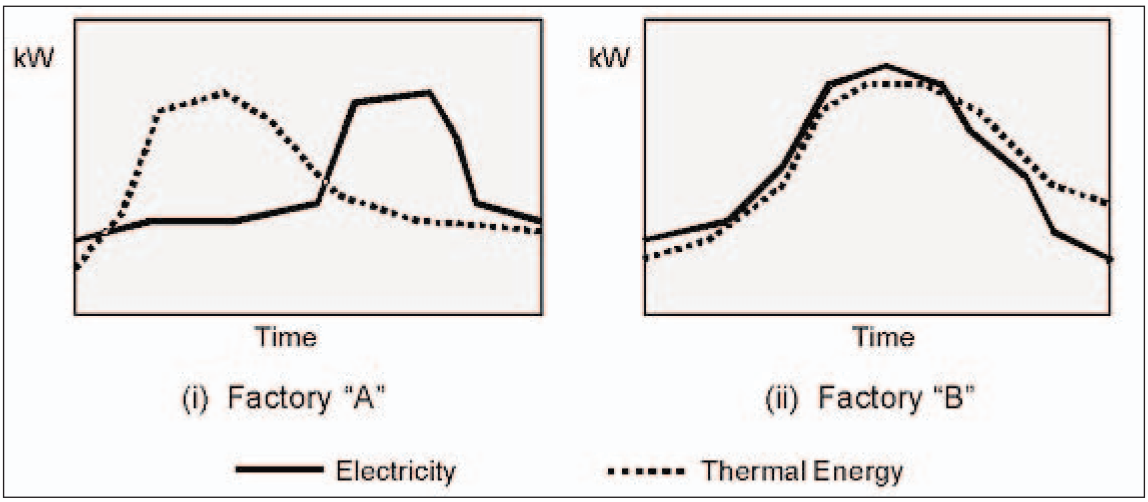


Figure 4.7 Different Heat and Power Demand Patterns in two Factories

4.6.4 Fuels Available

Depending on the availability of fuels, some potential cogeneration systems may have to be rejected. The availability of cheap fuels or waste products that can be used as fuels at a site is one of the major factors in the technical consideration because it determines the competitiveness of the cogeneration system.

A rice mill needs mechanical power for milling and heat for paddy drying. If a cogeneration system were considered, the steam turbine system would be the first priority because it can use the rice husk as the fuel, which is available as waste product from the mill.

4.6.5 System Reliability

Some energy consuming facilities require very reliable power and/or heat; for instance, a pulp and paper industry cannot operate with a prolonged unavailability of process steam. In such instances, the cogeneration system to be installed must be modular, i.e. it should consist of more than one unit so that shut down of a specific unit cannot seriously affect the energy supply.

4.6.6 Grid Dependent System Versus Independent System

A grid-dependent system has access to the grid to buy or sell electricity. The grid-independent system is also known as a "stand-alone" system that meets all the energy demands of the site. It is obvious that for the same energy consuming facility, the technical configuration of the cogeneration system designed as a grid dependent system would be different from that of a stand-alone system.

4.6.7 Retrofit Versus New Installation

If the cogeneration system is installed as a retrofit, the system must be designed so that the existing energy conversion systems, such as boilers, can still be used. In such a circumstance, the options for cogeneration system would depend on whether the system is a retrofit or a new installation.

4.6.8 Electricity Buy-back

The technical consideration of cogeneration system must take into account whether the local regulations permit electric utilities to buy electricity from the cogenerators or not. The size and type of cogeneration system could be significantly different if one were to allow the export of electricity to the grid.

4.6.9 Local Environmental Regulation

The local environmental regulations can limit the choice of fuels to be used for the proposed cogeneration systems. If the local environmental regulations are stringent, some available fuels cannot be considered because of the high treatment cost of the polluted exhaust gas and in some cases, the fuel itself.

4.7 Prime Movers for Cogeneration

4.7.1 Steam Turbine

Steam turbines (Figure 4.8) are the most commonly employed prime movers for cogeneration applications In the steam turbine, the incoming high pressure steam is expanded to a lower pressure level, converting the thermal energy of high pressure steam to kinetic energy through nozzles and then to mechanical power through rotating blades.

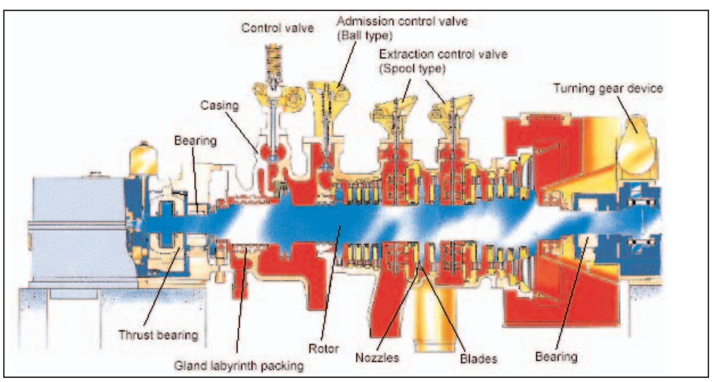


Figure 4.8 Steam Turbine

Back Pressure turbine: In this type steam enters the turbine chamber at High Pressure and expands to Low or Medium Pressure. Enthalpy difference is used for generating power / work.

Depending on the pressure (or temperature) levels at which process steam is required, backpressure steam turbines can have different configurations as shown in Figure 4.9.

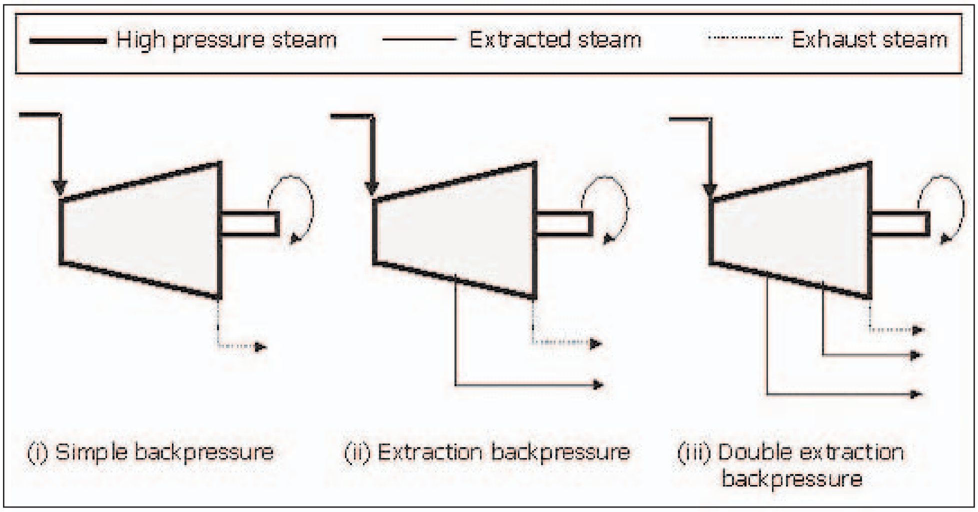


Figure 4.9 Different Configurations for Back Pressure Steam Turbines

In extraction and double extraction backpressure turbines, some amount of steam is extracted from the turbine after being expanded to a certain pressure level. The extracted steam meets the heat demands at pressure levels higher than the exhaust pressure of the steam turbine.

The efficiency of a backpressure steam turbine cogeneration system is the highest. In cases where 100 per cent backpressure exhaust steam is used, the only inefficiencies are gear drive and electric generator losses, and the inefficiency of steam generation. Therefore, with an efficient boiler, the overall thermal efficiency of the system could reach as much as 90 per cent.

Extraction Condensing turbine: In this type, steam entering at High / Medium Pressure is extracted at an intermediate pressure in the turbine for process use while the remaining steam continues to expand and condenses in a surface condenser and work is done till it reaches the Condensing pressure.(vacuum).

In Extraction cum Condensing steam turbine as shown in Figure 7.10, high Pressure steam enters the turbine and passes out from the turbine chamber in stages. In a two stage extraction cum condensing turbine MP steam and LP steam pass out to meet the process needs. Balance quantity condenses in the surface condenser. The Energy difference is used for generating Power. This configuration meets the heat-power requirement

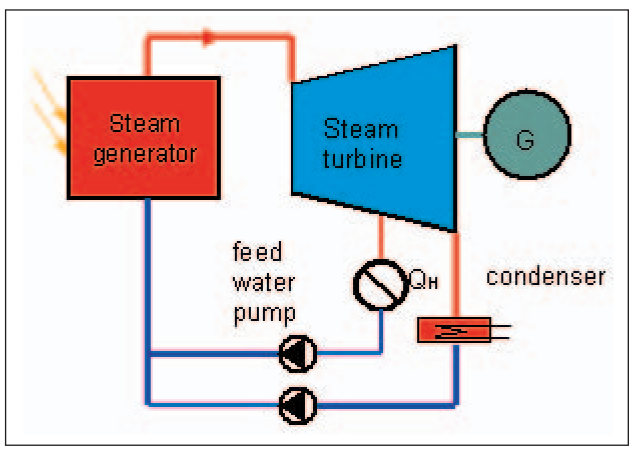


Figure 4.10 Extraction Condensing Turbine

of the process.

The extraction condensing turbines have higher power to heat ratio in comparison with back-pressure turbines. Although condensing systems need more auxiliary equipment such as the condenser and cooling towers, better matching of electrical power and heat demand can be obtained where electricity demand is much higher than the steam demand and the load patterns are highly fluctuating.

The overall thermal efficiency of an extraction condensing turbine cogeneration system is lower than that of back pressure turbine system, basically because the exhaust heat cannot be utilized (it is normally lost in the cooling water circuit). However, extraction condensing cogeneration systems have higher electricity generation efficiencies

4.7.2 Gas Turbine

The fuel is burnt in a pressurized combustion chamber using combustion air supplied by a compressor that is integral with the gas turbine. In conventional Gas turbine (Figure 4.11), gases enter the turbine at a temperature range of 900 to 1000°C and leave at 400 to 500°C. The very hot pressurized gases are used to turn a series of turbine blades, and the shaft on which they are mounted, to produce mechanical energy. Residual energy in the form of a high flow of hot exhaust gases can be used to meet, wholly or partly, the thermal (steam) demand of the site. Waste gases are exhausted from the turbine at 450°C to 550°C, making the gas turbine particularly suitable for high-grade heat supply.

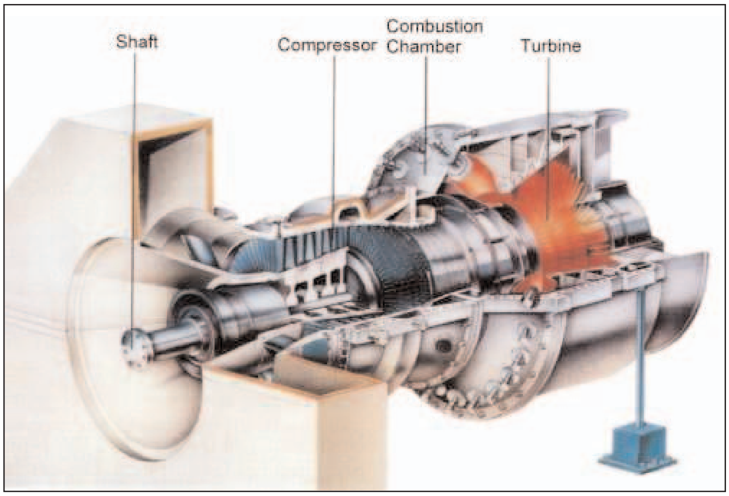


Figure 4.11 Gas Turbine

The available mechanical energy can be applied in the following ways:

- to produce electricity with a generator (most applications);
- to drive pumps, compressors, blowers, etc.

A gas turbine operates under exacting conditions of high speed and high temperature. The hot gases supplied to it must therefore be clean (i.e. free of particulates which would erode the blades) and must contain not more than minimal amounts of contaminants, which would cause corrosion under operating conditions. High-premium fuels are therefore most often used, particularly natural gas. Distillate oils such as gas oil are also suitable, and sets capable of using both are often installed to take advantage of cheaper interruptible gas tariffs. LPGs and Naphtha are also suitable, LPG being a possible fuel in either gaseous or liquid form.

Gas Turbine Efficiency

Turbine Efficiency is the ratio of actual work output of the turbine to the net input energy supplied in the form of fuel. For stand alone Gas Turbines, without any heat recovery system the efficiency will be as low as 35 to 40%. This is attributed to the blade efficiency of the rotor, leakage through clearance spaces, friction, irreversible turbulence etc.

Since Exhaust gas from the Gas Turbine is high, it is possible to recover energy from the hot gas by a Heat Recovery Steam Generator and use the steam for process.

Net Turbine Efficiency

Above efficiency figures did not include the energy consumed by air compressors, fuel pump and other auxiliaries. Air compressor alone consumes about 50 to 60% of energy generated by the turbine. Hence net turbine efficiency, which is the actual energy output available will be less than what has been calculated. In most Gas Turbine plants, air compressor is an integral part of Turbine plant.

4.7.3 Reciprocating Engine Systems

This system provides process heat or steam from engine exhaust. The engine jacket cooling water heat exchanger and lube oil cooler may also be used to provide hot water or hot air. There are, however, limited applications for this.

As these engines can use only fuels like HSD, distillate, residual oils, natural gas, LPG etc. and as they are not economically better than steam/gas turbine, their use is not widespread for co-generation. One more reason for this is the engine maintenance requirement.

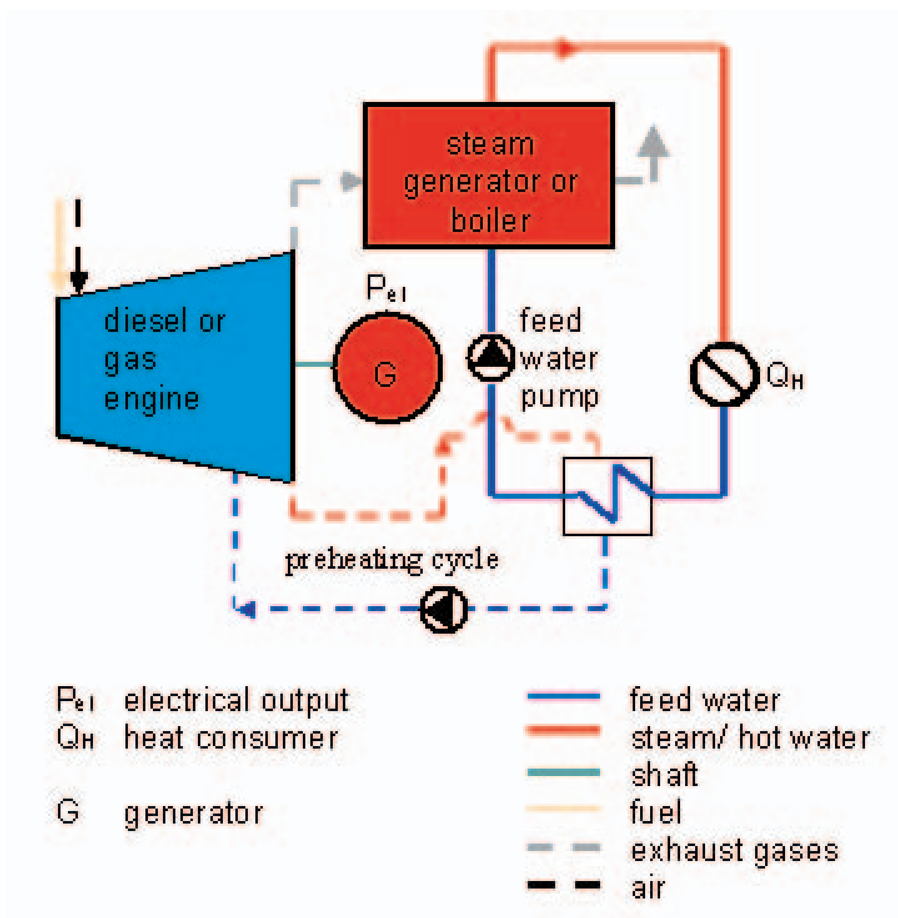


Figure 4.12

4.8 Typical Cogeneration Performance Parameters

The following Table 4.4 gives typical Cogeneration Performance Parameters for different Cogeneration Packages giving heat rate, overall efficiencies etc.

TABLE 7.4 TYPICAL COGENERATION PERFORMANCE PARAMETERS

Prime Mover in Cogen. Package	Nominal Range (Electrical)	Electrical Generation Heat Rate (kCal / kWh	Efficiencies, %		
			Electrical Conversion	Thermal Recovery	Overall Cogeneration
Smaller Reciprocating Engines	10–500 kW	2650–6300	20–32	50	74–82
Larger Reciprocating Engines	500–3000 kW	2400–3275	26–36	50	76–86
Diesel Engines	10–3000 kW	2770–3775	23–38	50	73–88
Smaller Gas Turbines	800–10000 kW	2770–3525	24–31	50	74–81
Larger Gas Turbines	10–20 MW	2770–3275	26–31	50	78–81
Steam Turbines	10–100 MW	2520–5040	17–34	–	–

Note: Adapted from Cogeneration Handbook California Energy Commission, 1982

4.9 Relative Merits of Cogeneration Systems

The following Table 4.5 gives the advantages and disadvantages of various co-generation systems:

TABLE7.5 ADVANTAGES AND DISADVANTAGES OF VARIOUS COGENERATION SYSTEMS

Variant	Advantages	Disadvantages
Back pressure	– High fuel efficiency rating	– Little flexibility in design and operation
Steam turbine & fuel firing in boiler	– Simple plant – Well-suited to low quality fuels	– More capital investment – Low fuel efficiency rating – High cooling water demand – More impact on environment High civil const. cost due to complicated foundations
Gas turbine with waste heat recovery boiler	– Good fuel efficiency – Simple plant – Low civil const. Cost – Less delivery period	– Moderate part load efficiency – Limited suitability for low quality fuels

	– Less impact on environment – High flexibility in operation	
Combined gas & steam turbine with waste heat recovery boiler	– Optimum fuel efficiency rating – Low relative capital cost – Less gestation period – Quick start up & stoppage – Less impact on environment – High flexibility in operation	– Average to moderate part-load efficiency – Limited suitability for low quality fuels
Diesel Engine & waste heat recovery Boiler & cooling water heat exchanger	– Low civil const. Cost due to block foundations & least no. of auxiliaries – High Power efficiency – Better suitability as stand by power source	– Low overall efficiency – Limited suitability for low quality fuels – Availability of low temperature steam – Highly maintenance prone.

4.10 Case Study

Economics of a Gas Turbine based co-generation System

Alternative I – Gas Turbine Based Co-generation

<u>Gas turbine Parameters</u>

Capacity of gas turbine generator	:	4000 kW
Plant operating hours per annum	:	8000 hrs.
Plant load factor	:	90 %
Heat rate as per standard given by gas.turbine supplier	:	3049.77 kCal / kWh
Waste heat boiler parameters – unfired steam output	:	10 TPH
Steam temperature	:	200 °C
Steam pressure	:	8.5 kg /cm_2.
Steam enthalpy	:	676.44 kCal / Kg.
Fuel used	:	Natural gas
Calorific value – LCV	:	9500 kCal/ sm_3
Price of gas	:	Rs 3000 /1000 sm_3
Capital investment for total co-generation plant	:	Rs. 1300 Lakhs

Cost Estimation of Power & Steam From Cogeneration Plant

1. Estimated power generation from Cogeneration plant at 90% Plant Load Factor (PLF)	:	PLF × Plant Capacity × no. of operation hours (90/100)×4000×8000 288.00 × 10^5 kWh per annum
2. Heat input to generate above units	:	Units (kWh) × heat rate 288 x 10^5 × 3049.77 878333.76 × 10^5 kCal
3. Natural gas quantity required per annum	:	Heat input / Calorific value (LCV) of natural gas
	:	878333.76 x 10^5 / 9500

		92.46×105 sm_3
4. Cost of fuel per annum	:	Annual gas consumption.
		× Price
		$92.46 \times 10^5 \times$ Rs.3000./1000 sm_3
		Rs. 277.37 lakhs
5. Cost of capital and operation charges/annum	:	Rs. 298.63. lakhs
6. Overall cost of power from cogeneration Plant	:	Rs. 576.00.lakhs per annum
7. Cost of power	:	Rs. 2.00 /kWh

Alternative-II: Electric Power from State Grid & Steam from Natural Gas Fired Boiler

Boiler Installed in Plant:

Cost of electric power from state grid – average electricity cost with demand & energy charges	:	Rs. 3.00/kWh
Capital investment for 10 TPH, 8.5 kg/sq.cm.200)°C Natural gas fired fire tube boiler & all auxiliaries	:	Rs. 80.00 lakh

Estimation of cost for electric power from grid & steam from direct conventional fired boiler:

1. Cost of Power from state grid for 288 lakh kWh	:	Rs. 864.00 lakh per annum
2. Fuel cost for steam by separate boiler		
(i) Heat output in form of 10 TPH steam per annum	:	Steam quantity × Enthalphy × Operations/annum
		$10 \times 1000 \times 676.44 \times$
		8000
		$=541152 \times 10^5$ kCals
(ii) Heat Input required to generate 10 TPH steam per annum @ 90% efficiency	:	Heat output/boiler efficiency
		$541152 \times 10^5/0.90$
Heat Input	:	601280×10^5 kCal per annum
(iii) Natural Gas Quantity	:	Heat Input/Calorific

		value (LCV) of natural gas
		$601280 \times 10^5/9500$
		63.29×10^5 sm_3 per annum
(iv) Cost of fuel per annum	:	Annual gas consumption × price
		$63.29 \times 10^5 \times 3000$ $/1000\ sm_3$
		Rs. 189.88.lakh per annum
(v) Total cost for Alternative-II	:	Cost of grid power + fuel cost for steam
		Rs. 864 + Rs.189.88 (lakh)
		Rs. 1053.88 lakh per annum
Alternative I - Total cost	:	Rs. 576.00 lakh
Alternative II - Total cost	:	Rs. 1053.88 lakh
Differential cost	:	Rs. 477.88 lakh

(Note: In case of alternative-II, there will be some additional impact on cost of steam due to capital cost required for a separate boiler).

In the above case, Alternative 1 gas turbine based cogeneration system is economical compared to Alternative 2 i.e. electricity from State Grid and Steam from Natural Gas fired boiler.

QUESTIONS	
1.	Explain what do you mean by cogeneration.
2.	Explain how cogeneration is advantageous over conventional power plant.
3.	What is meant by wheeling?
4.	What is meant by combined cycle cogeneration?
5.	Explain the term topping cycles with examples.
6.	Explain the term bottoming cycles with examples.
7.	Explain the term heat-to-power ratio.
8.	Explain with diagrams cogeneration systems using the back pressure turbine, extraction-condensing turbine and double extraction back pressure turbine.
9.	The efficiency of which of the following is the highest (a) condensing (b) back pressure (c) extraction condensing (d) double extraction condensing
10.	Explain the principle of operation of a steam turbine.
11.	Explain the principle of operation of a gas turbine.
12.	What are the common fuels used in gas turbines?
13.	Clean fuels are used in gas turbines because (a) the operate at high speed and high temperature (b) pollution act requires it (c) combustion would be affected (d) they are inexpensive
14.	The system efficiencies of gas turbine units are (a) 35 to 40% (b) 85 to 90% (c) 75 to 80% (d) 55 to 60%
15.	A heat recovery steam generator is used with (a) gas turbines (b) stem turbines (c) back pressure turbines (d) condensing turbines
16.	List the circumstances under which cogeneration will become attractive.
17.	What are the sources of waste heat in a diesel engine?
18.	Explain how you will go about an energy audit of a steam turbine based fully back pressure cogeneration system.

8. RESIDUAL HEAT RECOVERY

8.1 Introduction

Waste heat is heat, which is generated in a process by way of fuel combustion or chemical reaction, and then “dumped” into the environment even though it could still be reused for some useful and economic purpose. The essential quality of heat is not the amount but rather its “value”. The strategy of how to recover this heat depends in part on the temperature of the waste heat gases and the economics involved.

Large quantity of hot flue gases is generated from Boilers, Kilns, Ovens and Furnaces. If some of this waste heat could be recovered, a considerable amount of primary fuel could be saved. The energy lost in waste gases cannot be fully recovered. However, much of the heat could be recovered and loss minimized by adopting following measures as outlined in this chapter.

Heat Losses – Quality

Depending upon the type of process, waste heat can be rejected at virtually any temperature from that of chilled cooling water to high temperature waste gases from an industrial furnace or kiln. Usually higher the temperature, higher the quality and more cost effective is the heat recovery. In any study of waste heat recovery, it is absolutely necessary that there should be some use for the recovered heat. Typical examples of use would be preheating of combustion air, space heating, or pre-heating boiler feed water or process water. With high temperature heat recovery, a cascade system of waste heat recovery may be practiced to ensure that the maximum amount of heat is recovered at the highest potential. An example of this technique of waste heat recovery would be where the high temperature stage was used for air pre-heating and the low temperature stage used for process feed water heating or steam raising.

Heat Losses – Quantity

In any heat recovery situation it is essential to know the amount of heat recoverable and also how it can be used. An example of the availability of waste heat is given below:

- **Heat recovery from heat treatment furnace**

In a heat treatment furnace, the exhaust gases are leaving the furnace at 900 °C at the rate of 2100 m^3/hour. The total heat recoverable at 180ºC final exhaust can be calculated as

$$Q = V \times \rho \times C_p \times \Delta T$$

Q is the heat content in kCal
V is the flowrate of the substance in m^3/hr

ρ is density of the flue gas in kg/m^3
C_p is the specific heat of the substance in kCal/kg °C
ΔT is the temperature difference in °C
Cp (Specific heat of flue gas) = 0.24 kCal/kg/°C

Heat available (Q) = 2100 × 1.19 × 0.24 × ((900-180) = 4,31,827 kCal/hr

By installing a recuperator, this heat can be recovered to pre-heat the combustion air. The fuel savings would be 33% (@ 1% fuel reduction for every 22 °C reduction in temperature of flue gas.

8.2 Classification and Application

In considering the potential for heat recovery, it is useful to note all the possibilities, and grade the waste heat in terms of potential value as shown in the following Table 8.1:

TABLE 8.1 WASTE SOURCE AND QUALITY

S.No.	Source	Quality
1.	Heat in flue gases.	The higher the temperature, the greater the potential value for heat recovery
2.	Heat in vapour streams.	As above but when condensed, latent heat also recoverable.
3.	Convective and radiant heat lost from exterior of equipment	Low grade – if collected may be used for space heating or air preheats.
4.	Heat losses in cooling water.	Low grade – useful gains if heat is exchanged with incoming fresh water
5.	Heat losses in providing chilled water or in the disposal of chilled water	a) High grade if it can be utilized to reduce demand for refrigeration. b) Low grade if refrigeration unit used as a form of heat pump.
6.	Heat stored in products leaving the process	Quality depends upon temperature.
7.	Heat in gaseous and liquid effluents leaving process.	Poor if heavily contaminated and thus requiring alloy heat exchanger.

High Temperature Heat Recovery

The following Table 8.2 gives temperatures of waste gases from industrial process equipment in the high temperature range. All of these results from direct fuel fired processes.

Medium Temperature Heat Recovery

The following Table 8.3 gives the temperatures of waste gases from process equipment in the medium temperature range. Most of the waste heat in this temperature range comes from the exhaust of directly fired process units.

TABLE 8.2 TYPICAL WASTE HEAT TEMPERATURE AT HIGH TEMPERATURE RANGE FROM VARIOUS SOURCES	
Types of Device	**Temperature, °C**
Nickel refining furnace	1370 –1650
Aluminium refining furnace	650–760
Zinc refining furnace	760–1100
Copper refining furnace	760– 815
Steel heating furnaces	925–1050
Copper reverberatory furnace	900–1100
Open hearth furnace	650–700
Cement kiln (Dry process)	620– 730
Glass melting furnace	1000–1550
Hydrogen plants	650–1000
Solid waste incinerators	650–1000
Fume incinerators	650–1450

TABLE 8.3 TYPICAL WASTE HEAT TEMPERATURE AT MEDIUM TEMPERATURE RANGE FROM VARIOUS SOURCES	
Type of Device	**Temperature, °C**
Steam boiler exhausts	230–480
Gas turbine exhausts	370–540
Reciprocating engine exhausts	315–600
Reciprocating engine exhausts (turbo charged)	230–370
Heat treating furnaces	425–650
Drying and baking ovens	230–600
Catalytic crackers	425–650
Annealing furnace cooling systems	425–650

Low Temperature Heat Recovery

The following Table 8.4 lists some heat sources in the low temperature range. In this range it is usually not practical to extract work from the source, though steam production may not be completely excluded if there is a need for low-pressure steam. Low temperature waste heat may be useful in a supplementary way for preheating purposes.

TABLE 8.4 TYPICAL WASTE HEAT TEMPERATURE AT LOW TEMPERATURE RANGE FROM VARIOUS SOURCES

Source	Temperature, °C
Process steam condensate	55–88
Cooling water from:	
Furnace doors	32–55
Bearings	32–88
Welding machines	32–88
Injection molding machines	32–88
Annealing furnaces	66–230
Forming dies	27–88
Air compressors	27–50
Pumps	27–88
Internal combustion engines	66–120
Air conditioning and refrigeration condensers	32–43
Liquid still condensers	32–88
Drying, baking and curing ovens	93–230
Hot processed liquids	32–232
Hot processed solids	93–232

8.3 Benefits of Waste Heat Recovery

Benefits of 'waste heat recovery' can be broadly classified in two categories:

Direct Benefits:

Recovery of waste heat has a direct effect on the efficiency of the process. This is reflected by reduction in the utility consumption & costs, and process cost.

Indirect Benefits:

a) **Reduction in pollution:** A number of toxic combustible wastes such as carbon monoxide gas, sour gas, carbon black off gases, oil sludge, Acrylonitrile and other plastic chemicals etc, releasing to atmosphere if/when burnt in the incinerators serves dual purpose i.e. recovers heat and reduces the environmental pollution levels.

b) **Reduction in equipment sizes:** Waste heat recovery reduces the fuel consumption, which leads to reduction in the flue gas produced. This results in reduction in equipment sizes of all flue gas handling equipments such as fans, stacks, ducts, burners, etc.

c) **Reduction in auxiliary energy consumption:** Reduction in equipment sizes gives additional benefits in the form of reduction in auxiliary energy consumption like electricity for fans, pumps etc..

8.4 Development of a Waste Heat Recovery System

Understanding the process

Understanding the process is essential for development of Waste Heat Recovery system. This can be accomplished by reviewing the process flow sheets, layout diagrams, piping isometrics, electrical and instrumentation cable ducting etc. Detail review of these documents will help in identifying:

a) Sources and uses of waste heat
b) Upset conditions occurring in the plant due to heat recovery
c) Availability of space
d) Any other constraint, such as dew point occurring in an equipments etc.

After identifying source of waste heat and the possible use of it, the next step is to select suitable heat recovery system and equipments to recover and utilise the same.

Economic Evaluation of Waste Heat Recovery System

It is necessary to evaluate the selected waste heat recovery system on the basis of financial analysis such as investment, depreciation, payback period, rate of return etc. In addition the advice of experienced consultants and suppliers must be obtained for rational decision.

Next section gives a brief description of common heat recovery devices available commercially and its typical industrial applications.

8.5 Commercial Waste Heat Recovery Devices

Recuperators

In a recuperator, heat exchange takes place between the flue gases and the air through metallic or ceramic walls. Duct or tubes carry the air for combustion to be pre-heated, the other side contains the waste heat stream. A recuperator for recovering waste heat from flue gases is shown in Figure 8.1.

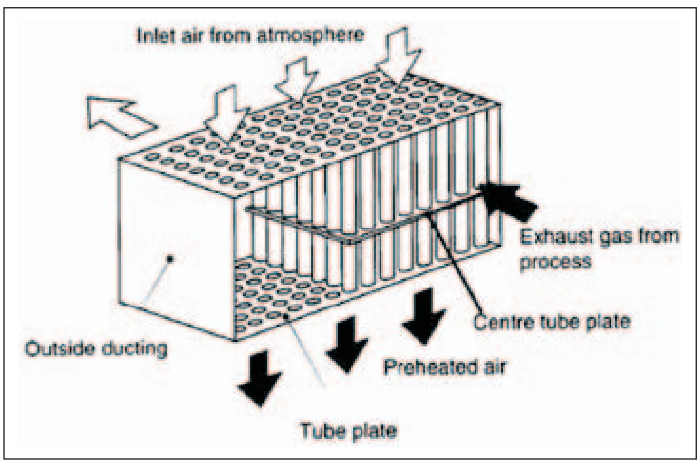


Figure 8.1 Waste Heat Recovery using Recuperator

The simplest configuration for a recuperator is the metallic radiation recuperator, which consists of two concentric lengths of metal tubing as shown in Figure 8.2.

The inner tube carries the hot exhaust gases while the external annulus carries the combustion air from the atmosphere to the air inlets of the furnace burners. The hot gases are cooled by the incoming combustion air which now carries additional energy into the combustion chamber. This is energy which does not have to be supplied by the fuel; consequently, less fuel is burned for a given furnace loading. The saving in fuel also means a decrease in combustion air and therefore

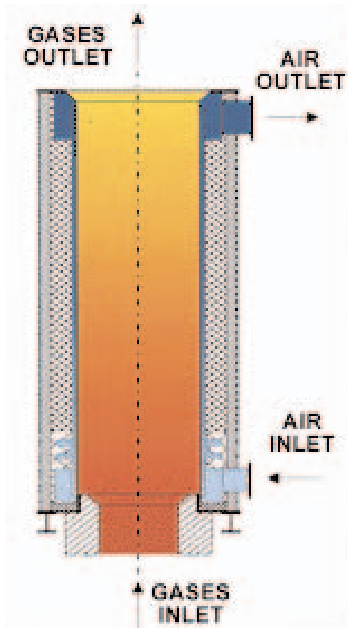


Figure 8.2 Metallic Radiation Recuperator

stack losses are decreased not only by lowering the stack gas temperatures but also by discharging smaller quantities of exhaust gas. The radiation recuperator gets its name from the fact that a substantial portion of the heat transfer from the hot gases to the surface of the inner tube takes place by radiative heat transfer. The cold air in the annuals, however, is almost transparent to infrared radiation so that only convection heat transfer takes place to the incoming air. As shown in the diagram, the two gas flows are usually parallel, although the configuration would be simpler and the heat transfer more efficient if the flows were opposed in direction (or counterflow). The reason for the use of parallel flow is that recuperators frequently serve the additional function of cooling the duct carrying away the exhaust gases and consequently extending its service life.

A second common configuration for recuperators is called the tube type or convective recuperator. As seen in the figure 8.3, the hot gases are carried through a number of parallel small diameter tubes, while the incoming air to be heated enters a shell surrounding the tubes and passes over the hot tubes one or more times in a direction normal to their axes.

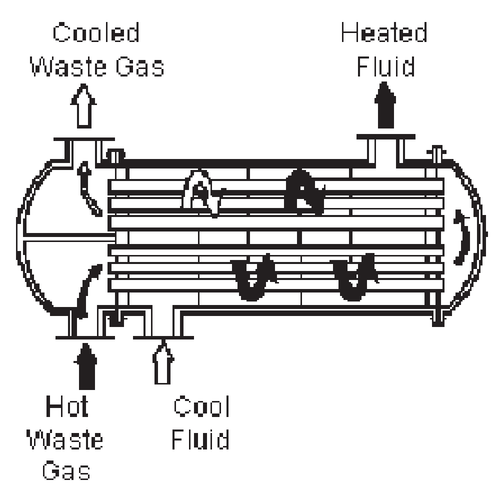


Figure 8.3 Convective Recuperator

If the tubes are baffled to allow the gas to pass over them twice, the heat exchanger is termed a two-pass recuperator; if two baffles are used, a three-pass recuperator, etc. Although baffling increases both the cost of the exchanger and the pressure drop in the combustion air path, it increases the effectiveness of heat exchange. Shell and tube type recuperators are generally more compact and have a higher effectiveness than radiation recuperators, because of the larger heat transfer area made possible through the use of multiple tubes and multiple passes of the gases.

Radiation/Convective Hybrid Recuperator:

For maximum effectiveness of heat transfer, combinations of radiation and convective designs are used, with the high-temperature radiation recuperator being first followed by convection type.

These are more expensive than simple metallic radiation recuperators, but are less bulky. A Convective/radiative Hybrid recuperator is shown in Figure 8.4

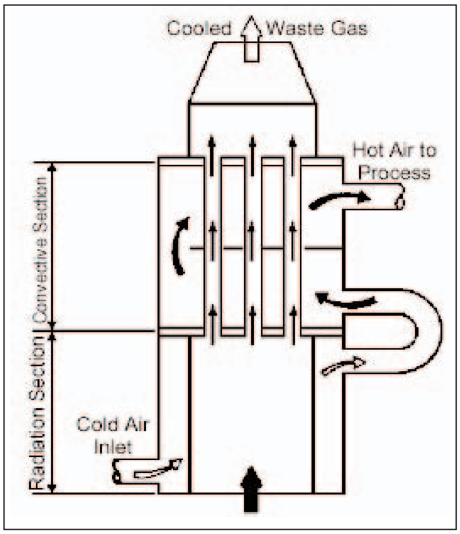


Figure 8.4 Convective Radiative Recuperator

Ceramic Recuperator

The principal limitation on the heat recovery of metal recuperators is the reduced life of the liner at inlet temperatures exceeding 1100°C. In order to overcome the temperature limitations of metal recuperators, ceramic tube recuperators have been developed whose materials allow operation on the gas side to 1550°C and on the preheated air side to 815°C on a more or less practical basis. Early ceramic recuperators were built of tile and joined with furnace cement, and thermal cycling caused cracking of joints and rapid deterioration of the tubes. Later developments introduced various kinds of short silicon carbide tubes which can be joined by flexible seals located in the air headers.

Earlier designs had experienced leakage rates from 8 to 60 percent. The new designs are reported to last two years with air preheat temperatures as high as 700°C, with much lower leakage rates.

Regenerator

The Regeneration which is preferable for large capacities has been very widely used in glass and steel melting furnaces. Important relations exist between the size of the regenerator, time between reversals, thickness of brick, conductivity of brick and heat storage ratio of the brick.

In a regenerator, the time between the reversals is an important aspect. Long periods would mean higher thermal storage and hence higher cost. Also long periods of reversal result in lower average temperature of preheat and consequently reduce fuel economy. (Refer Figure 8.5).

Accumulation of dust and slagging on the surfaces reduce efficiency of the heat transfer as the furnace becomes old.

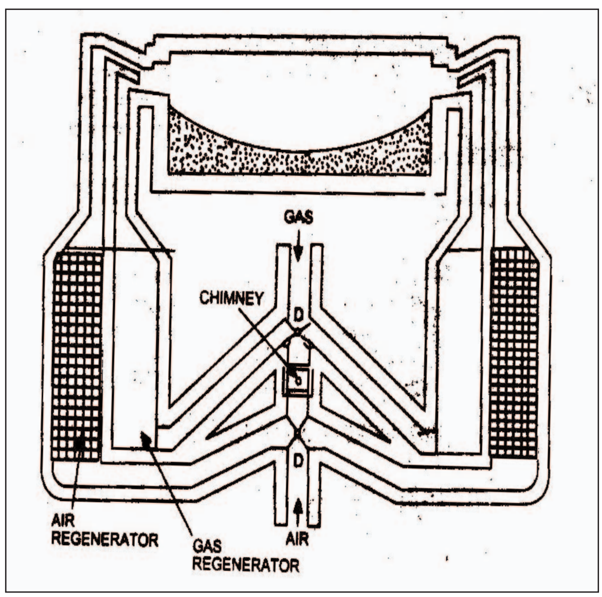


Figure 8.5 Regenerator

Heat losses from the walls of the regenerator and air in leaks during the gas period and out-leaks during air period also reduces the heat transfer.

Heat Wheels

A heat wheel is finding increasing applications in low to medium temperature waste heat recovery systems. Figure 8.6 is a sketch illustrating the application of a heat wheel.

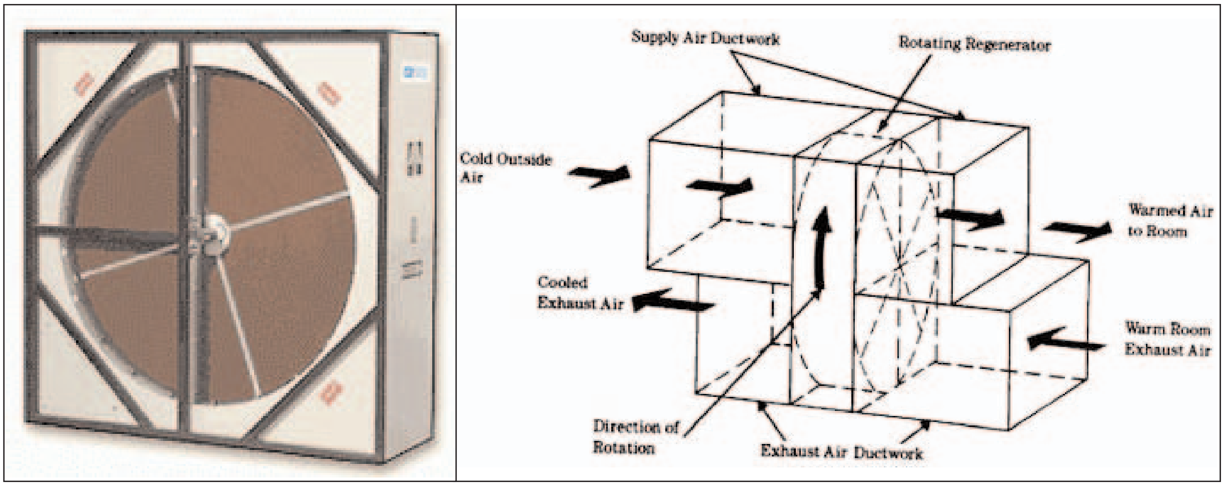


Figure 8.6 Heat Wheel

It is a sizable porous disk, fabricated with material having a fairly high heat capacity, which rotates between two side-by-side ducts: one a cold gas duct, the other a hot gas duct. The axis of the disk is located parallel to, and on the partition between, the two ducts. As the disk slowly rotates, sensible heat (moisture that contains latent heat) is transferred to the disk by the hot air and, as the disk rotates, from the disk to the cold air. The overall efficiency of sensible heat transfer for this kind of regenerator can be as high as 85 percent. Heat wheels have been built as large as 21 metres in diameter with air capacities up to 1130 m^3 / min.

A variation of the Heat Wheel is the rotary regenerator where the matrix is in a cylinder rotating across the waste gas and air streams. The heat or energy recovery wheel is a rotary gas heat regenerator, which can transfer heat from exhaust to incoming gases.

Its main area of application is where heat exchange between large masses of air having small temperature differences is required. Heating and ventilation systems and recovery of heat from dryer exhaust air are typical applications.

Case Example

A rotary heat regenerator was installed on a two colour printing press to recover some of the heat, which had been previously dissipated to the atmosphere, and used for drying stage of the process. The outlet exhaust temperature before heat recovery was often in excess of 100°C. After heat recovery the temperature was 35°C. Percentage heat recovery was 55% and payback on the investment was estimated to be about 18 months. Cross contamination of the fresh air from the solvent in the exhaust gases was at a very acceptable level.

Case Example

A ceramic firm installed a heat wheel on the preheating zone of a tunnel kiln where 7500 m^3/hour of hot gas at 300°C was being rejected to the atmosphere. The result was that the flue gas temperature was reduced to 150°C and the fresh air drawn from the top of the kiln was preheated to 155°C. The burner previously used for providing the preheated air was no longer required. The capital cost of the equipment was recovered in less than 12 months.

Heat Pipe

A heat pipe can transfer up to 100 times more thermal energy than copper, the best known conductor. In other words, heat pipe is a thermal energy absorbing and transferring system and have no moving parts and hence require minimum maintenance.

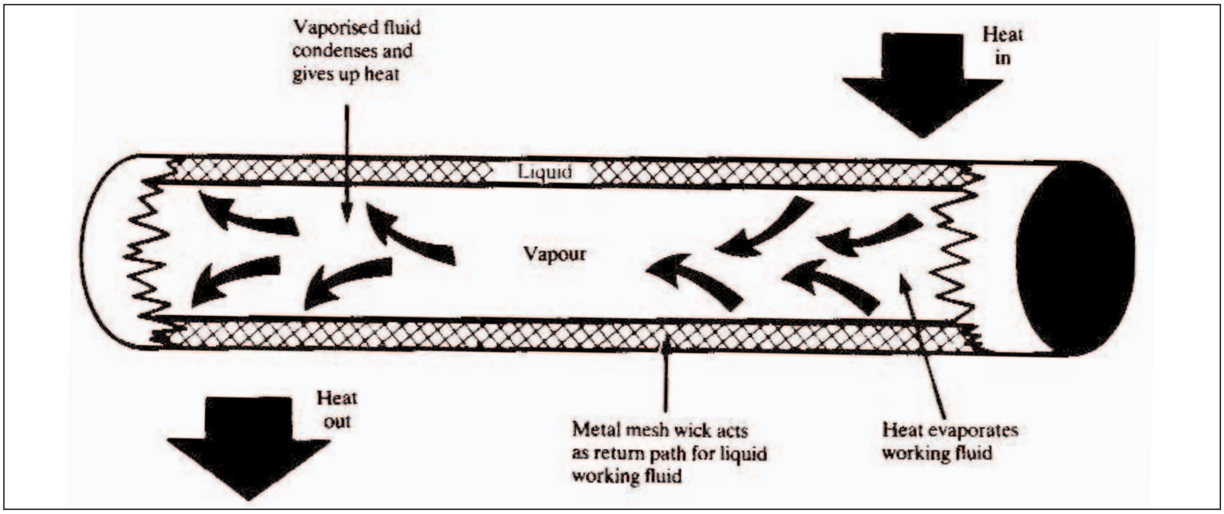


Figure 8.7 Heat Pipe

The Heat Pipe comprises of three elements - a sealed container, a capillary wick structure and a working fluid. The capillary wick structure is integrally fabricated into the interior surface of the container tube and sealed under vacuum. Thermal energy applied to the external surface of the heat pipe is in equilibrium with its own vapour as the container tube is sealed under vacuum. Thermal energy applied to the external surface of the heat pipe causes the working fluid near the surface to evaporate instantaneously. Vapour thus formed absorbs the latent heat of vapourisation and this part of the heat pipe becomes an evaporator region. The vapour then travels to the other end the pipe where the thermal energy is removed causing the vapour to condense into liquid again, thereby giving up the latent heat of the condensation. This part of the heat pipe works as the condenser region. The condensed liquid then flows back to the evaporated region. A figure of Heat pipe is shown in Figure 8.7

Performance and Advantage

The heat pipe exchanger (HPHE) is a lightweight compact heat recovery system. It virtually does not need mechanical maintenance, as there are no moving parts to wear out. It does not need input power for its operation and is free from cooling water and lubrication systems. It also lowers the fan horsepower requirement and increases the overall thermal efficiency of the system. The heat pipe heat recovery systems are capable of operating at 315°C. with 60% to 80% heat recovery capability.

Typical Application

The heat pipes are used in following industrial applications:

a. Process to Space Heating: The heat pipe heat exchanger transfers the thermal energy from process exhaust for building heating. The preheated air can be blended if required. The requirement of additional heating equipment to deliver heated make up air is drastically reduced or eliminated.

b. Process to Process: The heat pipe heat exchangers recover waste thermal energy from the process exhaust and transfer this energy to the incoming process air. The incoming air thus become warm and can be used for the same process/other processes and reduces process energy consumption.

c. HVAC Applications:

Cooling: Heat pipe heat exchangers precools the building make up air in summer and thus reduces the total tons of refrigeration, apart from the operational saving of the cooling system. Thermal energy is supply recovered from the cool exhaust and transferred to the hot supply make up air.

Heating: The above process is reversed during winter to preheat the make up air.

The other applications in industries are:

- Preheating of boiler combustion air
- Recovery of Waste heat from furnaces
- Reheating of fresh air for hot air driers
- Recovery of waste heat from catalytic deodorizing equipment
- Reuse of Furnace waste heat as heat source for other oven
- Cooling of closed rooms with outside air
- Preheating of boiler feed water with waste heat recovery from flue gases in the heat pipe economizers.
- Drying, curing and baking ovens
- Waste steam reclamation
- Brick kilns (secondary recovery)
- Reverberatory furnaces (secondary recovery)
- Heating, ventilating and air-conditioning systems

Case Example

Savings in Hospital Cooling Systems

Volume	140 m^3/min Exhaust
Recovered heat	28225 kCal/hr
Plant capacity reduction	9.33 Tons of Refrigeration
Electricity cost (operation)	Rs. 268/Million kCal (based on 0.8 kW/TR)
Plant capacity reduction cost (Capital)	Rs.12,000/TR
Capital cost savings	Rs. 1,12,000/-
Payback period	16570 hours

Economiser

In case of boiler system, economizer can be provided to utilize the flue gas heat for pre-heating the boiler feed water. On the other hand, in an air pre-heater, the waste heat is used to heat combustion air. In both the cases, there is a corresponding reduction in the fuel requirements of the boiler. An economizer is shown in Figure 8.8.

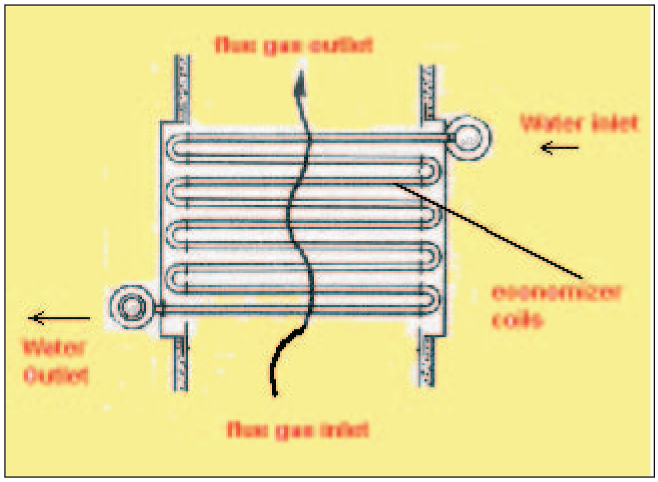


Figure 8.8 Economiser

For every 22°C reduction in flue gas temperature by passing through an economiser or a pre-heater, there is 1% saving of fuel in the boiler. In other words, for every 6°C rise in feed water temperature through an economiser, or 20°C rise in combustion air temperature through an air pre-heater, there is 1% saving of fuel in the boiler.

Shell and Tube Heat Exchanger:

When the medium containing waste heat is a liquid or a vapor which heats another liquid, then the shell and tube heat exchanger must be used since both paths must be sealed to contain the pressures of their respective fluids. The shell contains the tube bundle, and usually internal baffles, to direct the fluid in the shell over the tubes in multiple passes. The shell is inherently weaker than the tubes so that the higher-pressure fluid is circulated in the tubes while the lower pressure fluid flows through the shell. When a vapor contains the waste heat, it usually condenses, giving up its latent heat to the liquid being heated. In this application, the vapor is almost invariably contained within the shell. If the reverse is attempted, the condensation of vapors within small diameter parallel tubes causes flow instabilities. Tube and shell heat exchangers are available in a wide range of standard sizes with many combinations of materials for the tubes and shells. A shell and tube heat exchanger is illustrated in Figure 8.9.

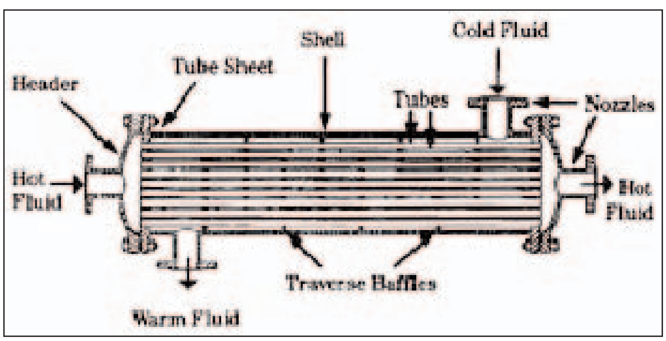


Figure 8.9 Shell & Tube Heat Exchanger

Typical applications of shell and tube heat exchangers include heating liquids with the heat contained by condensates from refrigeration and air-conditioning systems; condensate from process steam; coolants from furnace doors, grates, and pipe supports; coolants from engines, air compressors, bearings, and lubricants; and the condensates from distillation processes.

Plate heat exchanger

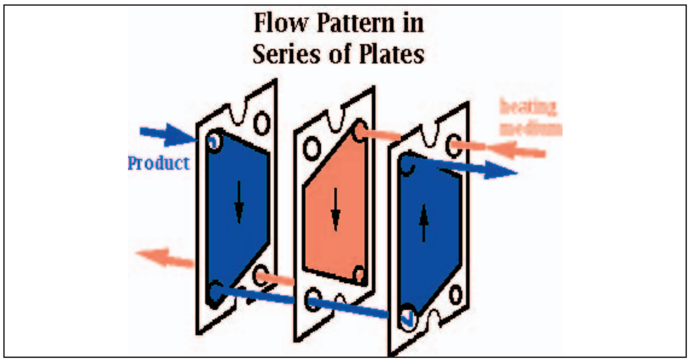


Figure 8.10 Plate Heat Exchanger

The cost of heat exchange surfaces is a major cost factor when the temperature differences are not large. One way of meeting this problem is the plate type heat exchanger, which consists of a series of separate parallel plates forming thin flow pass. Each plate is separated from the next by gaskets and the hot stream passes in parallel through alternative plates whilst the liquid to be heated passes in parallel between the hot plates. To improve heat transfer the plates are corrugated.

Hot liquid passing through a bottom port in the head is permitted to pass upwards between every second plate while cold liquid at the top of the head is permitted to pass downwards between the odd plates. When the directions of hot & cold fluids are opposite, the arrangement is described as counter current. A plate heat exchanger is shown in Figure 8.10.

Typical industrial applications are:

– Pasteurisation section in milk packaging plant.

– Evaporation plants in food industry.

Run Around Coil Exchanger

It is quite similar in principle to the heat pipe exchanger. The heat from hot fluid is transferred to the colder fluid via an intermediate fluid known as the Heat Transfer Fluid. One coil of this closed loop is installed in the hot stream while the other is in the cold stream. Circulation of this fluid is maintained by means of circulating pump.

It is more useful when the hot land cold fluids are located far away from each other and are not easily accessible.

Typical industrial applications are heat recovery from ventilation, air conditioning and low temperature heat recovery.

Waste Heat Boilers

Waste heat boilers are ordinarily water tube boilers in which the hot exhaust gases from gas turbines, incinerators, etc., pass over a number of parallel tubes containing water. The water is vaporized in the tubes and collected in a steam drum from which it is drawn off for use as heating or processing steam.

Because the exhaust gases are usually in the medium temperature range and in order to conserve space, a more compact boiler can be produced if the water tubes are finned in order to increase the effective heat transfer area on the gas side. The Figure 8.11 shows a mud drum, a set of tubes over which the hot gases make a double pass, and a steam drum which collects the steam generated above the water surface. The pressure at which the steam is generated and the rate of steam production depends on the temperature of waste heat. The pressure of a pure vapor in the presence of its liquid is a function of the temperature of the liquid from which it is evaporated. The steam tables tabulate this relationship between saturation pressure and temperature.

If the waste heat in the exhaust gases is insufficient for generating the required amount of process steam, auxiliary burners which burn fuel in the waste heat boiler or an after-burner in the exhaust gases flue are added. Waste heat boilers are built in capacities from 25 m^3 almost 30,000 m^3 / min. of exhaust gas.

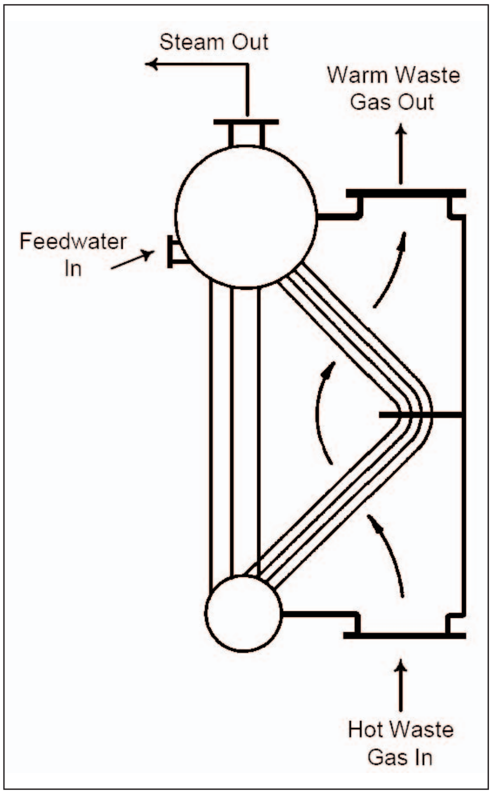


Figure 8.11 Two-Pass Water Tube Waste Heat Recovery Boiler

Typical applications of waste heat boilers are to recover energy from the exhausts of gas turbines, reciprocating engines, incinerators, and furnaces.

Case Example

Gases leaving a carbon black plant rich in carbon monoxide which are vented to the atmosphere.

Equipment Suggested	Carbon monoxide incinerator along with waste heat boiler and steam turbine
Estimated equipment cost	Rs.350 Lakhs
New boiler efficiency	80%
Savings by way of power generated	~Rs.160 Lakhs /annum
Indirect benefits	Reduction in pollution levels

Heat Pumps:

In the various commercial options previously discussed, we find waste heat being transferred from a hot fluid to a fluid at a lower temperature. Heat must flow spontaneously "downhill", that is from a system at high temperature to one at a lower temperature. When energy is repeatedly transferred or transformed, it becomes less and less available for use. Eventually that energy has such low intensity (resides in a medium at such low temperature) that it is no longer available at all to perform a useful function. It has been taken as a general rule of thumb in industrial operations that fluids with temperatures less than 120°C (or, better, 150°C to provide a safe margin), as limit for waste heat recovery because of the risk of condensation of corrosive liquids. However, as fuel costs continue to rise, even such waste heat can be used economically for space heating and other low temperature applications. It is possible to reverse the direction of spontaneous energy flow by the use of a thermodynamic system known as a heat pump.

The majority of heat pumps work on the principle of the vapour compression cycle. In this cycle, the circulating substance is physically separated from the source (waste heat, with a temperature of T_{in}) and user (heat to be used in the process, T_{out}) streams, and is re-used in a cyclical fashion, therefore called 'closed cycle'. In the heat pump, the following processes take place:

1. In the evaporator the heat is extracted from the heat source to boil the circulating substance;
2. The circulating substance is compressed by the compressor, raising its pressure and temperature; The low temperature vapor is compressed by a compressor, which requires external work. The work done on the vapor raises its pressure and temperature to a level where its energy becomes available for use
3. The heat is delivered to the condenser;
4. The pressure of the circulating substance (working fluid) is reduced back to the evaporator condition in the throttling valve, where the cycle repeats.

The heat pump was developed as a space heating system where low temperature energy from the ambient air, water, or earth is raised to heating system temperatures by doing compression work with an electric motor-driven compressor. The arrangement of a heat pump is shown in figure 8.12.

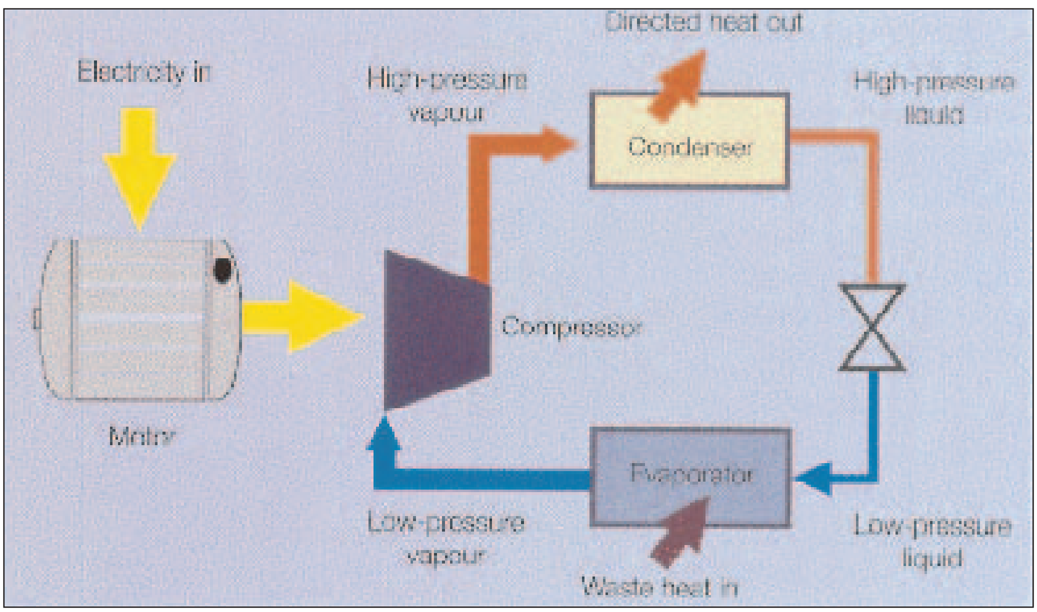


Figure 8.12 Heat Pump Arrangement

The heat pumps have the ability to upgrade heat to a value more than twice that of the energy consumed by the device. The potential for application of heat pump is growing and number of industries have been benefited by recovering low grade waste heat by upgrading it and using it in the main process stream.

Heat pump applications are most promising when both the heating and cooling capabilities can be used in combination. One such example of this is a plastics factory where chilled water from a heat is used to cool injection-moulding machines whilst the heat output from the heat pump is used to provide factory or office heating. Other examples of heat pump installation include product drying, maintaining dry atmosphere for storage and drying compressed air.

Thermocompressor :

In many cases, very low pressure steam are reused as water after condensation for lack of any better option of reuse. In many cases it becomes feasible to compress this low pressure steam by very high pressure steam and reuse it as a medium pressure steam. The major energy in steam, is in its latent heat value and thus thermocompressing would give a large improvement in waste heat recovery.

The thermocompressor is a simple equipment with a nozzle where HP steam is accelerated into a high velocity fluid. This entrains the LP steam by momentum transfer and then recompresses in a divergent venturi. A figure of thermocompressor is shown in Figure 8.13.

It is typically used in evaporators where the boiling steam is recompressed and used as heating steam.

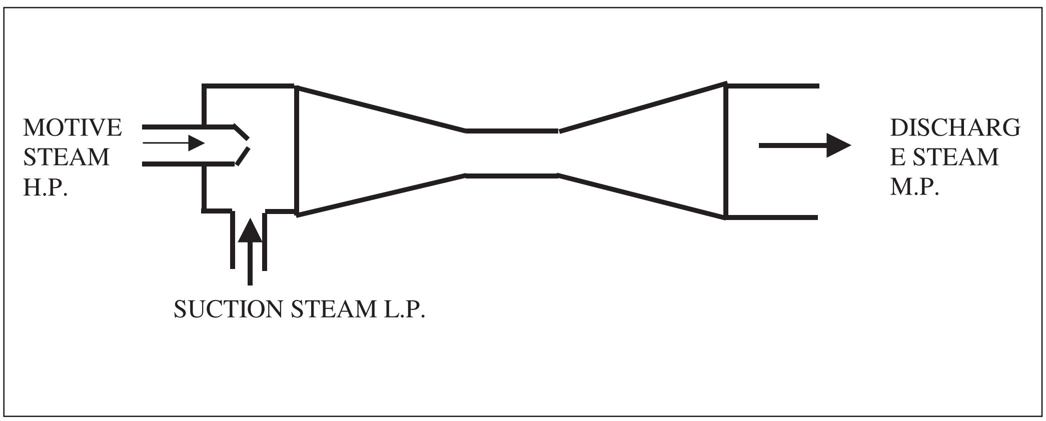


Figure 8.13 Thermocompressor

Case Example

Exhaust steam from evaporator in a fruit juice concentrator plant was condensed in a precondenser operation on cooling water upstream of a steam jet vaccum ejector

Equipment Suggested	Alt-1 Thermocompressor Alt-2 shell &tube exchanger
Cost of thermocompressor	Rs.1.5 Lakhs
Savings of jacket steam due to recompression of vapour	Rs.5.0 Lakhs per annum
Cost of shell &tube exchanger to preheat boiler feed water	Rs.75,000/-
Savings in fuel cost	~Rs.4.5 Lakhs per annum

Direct Contact Heat Exchanger :

Low pressure steam may also be used to preheat the feed water or some other fluid where miscibility is acceptable. This principle is used in Direct Contact Heat Exchanger and finds wide use in a steam generating station. They essentially consists of a number of trays mounted one over the other or packed beds. Steam is supplied below the packing while the cold water is sprayed at the top. The steam is completely condensed in the incoming water thereby heating it. A figure of direct contact heat exchanger is shown in Figure 8.14. Typical application is in the deaerator of a steam generation station.

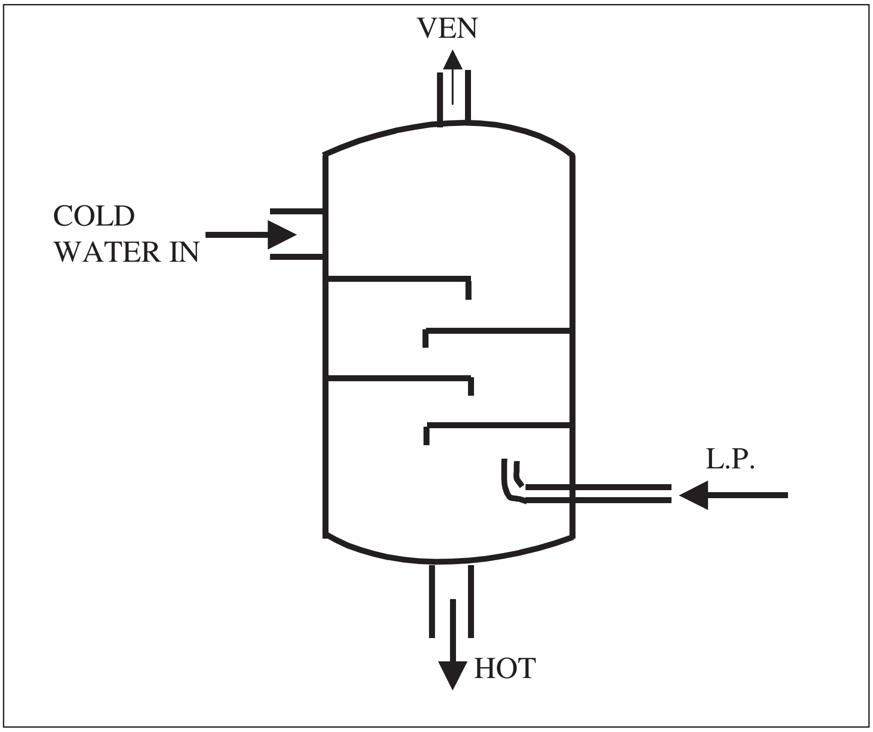


Figure 8.14 Direct Contact Condenser

QUESTIONS	
1.	What do you understand by the term waste heat?
2.	The heat recovery equipment will be the cheapest when the temperature of flue gases are (a) 200°C (b) 400°C (c) 600°C (d) 800°C
3. **4.**	Give two examples of waste heat recovery. What are the direct and indirect benefits of waste heat recovery?
5.	How will you go about developing a waste heat recovery system?
6.	Explain the various types of recuperators.
7.	The ceramic recuperators can withstand temperatures upto (a) 400°C (b) 1700°C (c) 1300°C (d) 1400°C
8.	Explain the operating principle of a regenerator.
9.	What are heat wheels? Explain with sketch.
10.	Explain the principle of operation of a heat pipe.
11.	What are the typical applications of a heat pipe in heat exchangers ?
12.	Explain the operation of an economizer.
13.	How does a shell and tube heat exchanger work? Give typical examples.
14.	How does a plate heat exchanger work? Give typical examples.
15.	Explain the operating principle of a run around coil exchanger
16.	Explain the operating principle of a waste heat recovery boiler with examples.
17.	Explain the operating principle of a heat pump with examples.