Module-05

Lecture-36 : Combined Heat and Power Design(using steam Turbine)

Key words: CHP, Steam Turbine, Gas turbine,

Chemical processing sites require heat as well as power to heat process streams and drive electrical machines /appliances /instruments such as electric motors, pumps, fans, compressors, instruments lighting, etc. Nearly all processing sites import it from grid and pay to the supplier. In most cases, power is generated from heat engines-a device which converts heat into power. The high-temperature heat required for this purpose is produced by burning coal, oil, natural gas, biomass or other fossil fuels or may be supplied from a nuclear reaction. This high temperature heat, in power stations, is used to evaporate water to make high-pressure steam which is then passed into a turbine to produce shaft power. The exhaust steam emerges at low pressure is often condensed (latent heat is thus lost) and re-cycled to the boilers for reuse. The thermal efficiency of these heat engine is at the most 40%. Other heat engines like, the internal combustion engine burns natural gas, petrol or diesel oil and produces power and releases heat to atmosphere in terms of exhaust gas. Similarly, in gas turbine, fuel is mixed with compressed air and burnt to produce hot gas at a high temperature and pressure. This hot gas is then passed through a turbine to produces power. The hot exhaust (450°-600°C) at low pressure is vent to atmosphere or used in recuperator to preheat air. Heat to power ratio of these turbines is little less than 1.5 to about 5. Electrical efficiency is in the range of 20-40% (50% for designs with cooled turbine blades).

The low efficiency of heat engines is due to the fact that it rejects a large amount of heat to atmosphere unutilized. If it can somehow be used, in process plants then the overall efficiency of heat engine will improve. Further, chemical processing sites use heat as well as power. Thus, it will be an excellent idea to use heat engines on the plant site to produce power and to use the available heat as hot utility for the process heating, thus improving the efficiency of the system. This is the concept of Combined Heat and Power (CHP). Thus, CHP (also Cogeneration) is the use of a heat engine or a power station to simultaneously generate both electricity and useful heat for process. CHP systems are highly efficient, making use of the heat which would otherwise be wasted when generating electrical or mechanical power and typically has an efficiency of over 80%. Such a system, however, must be tailored to ensure that the heat produced is at a useful level meaning that heat should be at the temperatures that is required in the plant.

The cogeneration possibility of a Gas Turbine as well as steam turbine is shown in Fig.36.1
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Other systems which link heat and power is a heat pumps. These work in a reversed order in comparison to heat engine. It uses power as input to upgrade heat from a low temperature to a higher temperature. A common example of heat pump is a vapour recompression systems and refrigerator.

Basics of Heat Engine

The thermodynamic concept of the heat engine is shown in Fig.36.2. It operates between two levels of temperature, higher temperature ($T_1$) - the source and the lower temperature ($T_2$) - the sink. It takes heat $Q_1$ from the source($T_1$), rejects heat $Q_2$ to the sink($T_2$) and doing so produces work $W$.

Fig. 36.1 Cogeneration (a) using gas turbine (b) Using Stream turbine

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Fig. 36.2 Thermodynamic concept behind Heat Engine
By the First Law of Thermodynamics:
\[ W = Q_1 - Q_2 \] ...(36.1)

The Second Law of Thermodynamics (Carnot Equation) postulates that all the heat cannot be converted into work, and there is a definite upper limit controlled by the temperature limit under which the heat engine operates:
\[ W = Q_1 \eta_{mech} \frac{(T_1 - T_2)}{T_1} \] ...(36.2)

\( \eta_{mech} \) in Eq.36.2 is the mechanical efficiency for thermodynamically reversible engines. All real engines report an efficiency below this ideal efficiency. The factor \((T_1 - T_2)/T_1\) is called the Carnot efficiency \( \eta_c \), which represents the maximum possible conversion of heat to work and where \( T_1 \) and \( T_2 \) are in absolute temperatures. Carnot efficiency (\( \eta_c \)) is the maximum theoretical efficiency a friction-free heat engine could have. It is always less than 100% and for real heat engines may be less than 80%. Add friction and other losses and the actual efficiency is typically less than 50%.

From the Carnot equation it is obvious that for a given heat source temperature \( T_1 \), if the heat sink temperature \( T_2 \) is increased, the delivered power falls. Since, in a CHP system, \( T_2 \) is the level at which that hot utility (Steam/Gas turbine exhaust) is to be supplied, the correct choice of \( T_2 \) is vital.

**Heat engines used in Industry**

An industrial CHP uses a heat engine which burns fuel (coal, oil, gas, biomass), generates shaft work (using turbine) and produces exhaust heat which can be used in the process to meet its hot utility requirements.

In general three types of machines are used:

(a) **Steam turbines (Rankine cycle):** High pressure steam is generated in a high pressure boiler using a variety of fuels. This steam is passed through steam turbines to generate shaft work and consequently power with the help of a generator. The exhaust steam from the turbine is used for process heating. Figs.36.3 & 36.5 show such an arrangement.

(b) **Gas turbines:** Fuel along with compressed air is burnt in a combustion chamber. The resulting hot and high pressure gases (1000-1500°C) is sent to a turbine to generate shaft work and subsequently power. In such a system, about two third of shaft work produced is employed in compressing the ambient air. The exhaust gases at around 450–550°C is used as hot utility to provide process heating or can be used for generating steam in a waste heat boiler. Fig.36.1(a) shows such an arrangement.

(c) **Reciprocating engines:** Fuel along with ambient air is burnt in an internal combustion engine which generates shaft work and subsequently power. The hot exhaust gases, at
around 300–400°C can be used as hot utility for process heating. Fig.36.4 shows such a machine.

Fig.36.3 Different configurations of steam

(a) Back pressure steam turbine
(b) Condensing steam turbine
(c) Extraction steam turbine
(d) Induction steam turbine

The classic steam Rankine cycle is shown in Fig.35.5. This has been used in large numbers of electricity generating stations, whether coal-fired, oil-fired, nuclear or other fuel fired, and has been refined to give the optimal level of power by increasing its complexity.

Fig.36.4 Reciprocating engine
Steam is produced at high pressure in a superheated state by the boiler, and then expanded through a cascade of back-pressure power turbine stages. From the turbine, Medium Pressure (MP) and Low Pressure (LP) steam is taken out as necessary to meet site needs. For a condensing steam turbine (Fig.36.3(b)), most of the steam is expanded to sub-atmospheric pressure (VLP), and then condensed using cooling water; these condensing turbines are optional for a site CHP system.

In a CHP system there are cold streams such as boiler feed water and combustion air which need to be heated up using the steam itself rather than using process hot streams so that these become self-contained. The fresh make-up water along with condensate is deaerated using lowest pressure back-pressure steam, then heated by condensate and boiler blowdown stream followed by LP and MP steam and finally by hot flue gas. The schematic of a steam turbine based CHP is shown in Fig.36.5(a) and its temperature-entropy in Fig.36.5(b). In such a system as the flue gas temperature can’t be brought down below 200°C the boiler feed water should be raised to temperature of about 200°C using MP steam before entering to the economizer section of boiler. After, giving heat to boiler feed water, enough heat is retained in the flue gas which is used for air preheating. Finally the flue gas leaves at about 140°C which provides a boiler efficiency of about 90% or more.

CHP systems are highly efficient, making use of the heat which would otherwise be wasted when generating electrical or mechanical power and typically has an efficiency of over 80%. The Sankey diagram, Fig.36.6 doesn’t feature absolute figures, but flows are scaled in relation to the baseline of 100 units energy generation in a power plant vis-à-vis a CHP unit. In a cogeneration unit 160 units of heat energy would be produced for 100 units of power and heat losses are 65 units in the CHP. To produce the equivalent energy(100 units) in a conventional power unit would cause losses 165 units. In the boiler providing heat of 160 units about 40 units are lost giving an efficiency of 25%. Overall losses in conventional generating station are 205(165+40) units compared to 65 units in a CHP.
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Fig. 36.6 Sankey Diagram of a CHP system using steam power generation

Steam turbine CHP is usually the technology of choice when a cheap, non-premium fuel (e.g. waste material) is available that can only be used once the energy it contains has been released and turned into steam. It is also particularly suited to sites where the heat requirement is high in relation to the power demand. The number of such sites is declining as the use of electricity increases. However, steam turbines can be used in conjunction with a gas turbine to increase the total output of electricity. In these ‘combined cycle’ applications, high-grade exhaust heat from the gas turbine is fed to a heat recovery boiler, and the steam produced is passed to a steam turbine to generate additional electricity. The lower pressure steam from the steam turbine is then available for site use.

At moderate temperatures, steam turbine produce large amount of heat for process consumption. It is a known fact that, very less amount of power is generated when high pressure steam is expanded in a turbine up to 15 bar(corresponding saturation temperature 200°). Thus, steam generators are not good choice for CHP when heat is demanded on or above 200°C. However, in most of the sites where loads are more than 10MW, and the load demands are fairly constant from 100-200°C, the steam turbines are good choice.

Regardless all this efforts, the efficiency of standalone steam power generation rarely exceeds 40%, as the majority of the heat (about 60%) is being thrown away in cooling towers for cooling the hot cooling water which condenses the steam. The overall power generation of a steam turbine CHP system is lower, as less power is generated from MP and LP turbines than condensing turbine, but this is compensated by the prospect to make better use of the available heat in the MP and LP steam and reclaiming some amount of the lost heat equivalent to 60%.

Sizing a gas turbine system
A gas turbine (GT) has a fairly narrow range of heat-to-power ratio (0.67-0.2) as well as turn down as a result matching with variable heat and power needs of site becomes difficult. Further, it runs best at about full load conditions. Gas turbines can be sized either to meet the heat requirement or the power requirement. In effect there are four options:

1. Match the heat output of CHP system to process without considering power output. If power output is less import the deficit power. If more export the power. For the last case economics is dependent on cost of export.

2. Match power output of CHP to the site. If CHP heat output is less than site, make-up the deficit heat either with a additional boiler or by supplementary firing of the exhaust of gas turbine to increase heat output.

3. Power output of CHP system matches to the site. However, CHP heat output is greater than the site requirement. This is an undesirable situation, as excess heat is to be thrown. If the turbine does not have a recuperator, add a recuperator for air pre heating to bring down the excess heat available.

The choice between these alternatives will depend on the system economics. For sizing of a gas turbine power-generation efficiency can be taken as 30% and the exhaust gas temperature of 500°C. The temperature-entropy diagram for a gas turbine is shown in Fig.36.7

![Fig.36.7 Gas Turbine](image)

The temperature-entropy diagram for a gas turbine along with schematic is shown in Fig.36.7.

Combined cycle systems are usually applied to gas turbine sets, as these produce the highest grade heat. This heat allows steam to be generated at a pressure that is high enough to optimize steam turbine power while still providing the site with low-pressure steam or its equivalent in the form of hot water. Combined cycles of this type convert 40% or more of the original fuel energy into electricity and, if supplementary firing is also employed, provide the most flexible CHP systems currently available. The application of combined cycle technology is particularly suited to sites that require both low- and high-pressure steam, as the latter will
dictate the selection of a high-pressure boiler plant regardless of the CHP plant. The illustration shows a typical combined cycle plant in schematic and Sankey diagram form as shown in Fig.36.8.

**Fig. 36.8 A typical combined Cycle plant with Sankey diagram**

Exhaust gas release from Gas Turbine (GT) can be used as a hot utility for sensible high temperature heating from 550°C or below in places like high temperature reactors and hot-air driers. It is a fact that for similar process heat duty GT produce much more power than steam turbine. Gas turbines are broken into three main categories: heavy frame, aeroderivative, and microturbine and are available in the range of 27 kW to 250 MW.

GT can be particularly efficient up to 60% when waste heat from the gas turbine is recovered by a heat recovery steam generator to power and a conventional steam turbine in a combined cycle configuration. A large single cycle gas turbine typically produces 100 to 400 megawatts of power and has 35–40% thermal efficiency.

Gas and Diesel Engines produce large quantity of power but relatively less heat to be used in process though its exhaust can reach 400°C. Further, for diesel engines, it has been reported that acid gas corrosion can take place below 200°C limiting its use. However, reciprocating
engines can be used to provide heat to processes like space heating for loads in 70-90°C range where the heat from water jacket can be used.

How to select a Particular Engine for CHP

1. If the site power requirement is below 1 MW go for reciprocating engine and if above 5 MW then go for gas and steam turbines
2. Check for heat to power ratio is > 5 and heating range is 100-200°C then select steam turbine, if it is 1.5 to 5 and the temperature range is between 100-500°C select Gas turbine and if it is between 0.8 to 2 and temperature range is 100-300 °C go for Gas and Diesel Engines.
3. One of the most important point is matching of heat release profile of the CHP system with process GCC above the pinch. Take that engine which gives best match with GCC of the process. This fact is explained in Fig.36.9 Particularly if the heating load is above 200°C select gas turbine. If pinch temperature is above 70°C do not go for reciprocating engines.

Figure 36.9 shows all the above three system matched with the process heat requirement through GCC. Once, dominant CHP system, steam turbine are now not used for CHP due to their low power production capability and advances that taken place in Gas Turbine system. A large number of process plant have a pinch temperature little more than 100°C and Gas Turbines are the preferred choice for these plants. Further, if steam is used as a process heating medium in the industry, then it can be generated from the exhaust gases of Gas Turbine using a waste heat boiler thus cutting down the need for a steam turbine exhaust. For a gas turbine system if process requirements are higher than normal heat to power ratio then using supplementary firing (a temperature up to 850°C can be obtained) the requirement can be satisfied. If the pinch of the process is near ambient temperature and heat loads are typically less than 1 MW, the reciprocating engines are preferred ones for CHP. Contrary to CHP concept it is not always necessary that one should generate electricity from the shaft work produced by a machine. This can be used to drive compressor, pumps or other equipment which requires shaft work. In this way efficiency will be slightly higher than if one produces electricity and then using it drives compressor and pumps, etc. However, electrical energy provided more flexibility in use than shaft work or mechanical coupling.

Economics of CHP

The economic evaluation CHP systems is not easy. The CHP economics depend significantly on the cost of heat, the cost of power, and the ratio between them which is a function of time and change substantially. Thus long term predictions, based on economics, for a CHP system is difficult as fuel and thus power costs have fluctuated drastically.
Fig. 36.9 Well matched heat release profiles of different engines with suitable process GCCs
**Illustrative Example**

The stream data for a heat recovery problem are given in Table 36.1 below:

<table>
<thead>
<tr>
<th>Stream No.</th>
<th>Type</th>
<th>$T_s$ (°C)</th>
<th>$T_T$ (°C)</th>
<th>Heat Capacity Flow rate (MW.K$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hot</td>
<td>425</td>
<td>45</td>
<td>0.25</td>
</tr>
<tr>
<td>2</td>
<td>Hot</td>
<td>40</td>
<td>30</td>
<td>1.4</td>
</tr>
<tr>
<td>3</td>
<td>Cold</td>
<td>20</td>
<td>375</td>
<td>0.20</td>
</tr>
<tr>
<td>4</td>
<td>Cold</td>
<td>20</td>
<td>380</td>
<td>0.05</td>
</tr>
<tr>
<td>5</td>
<td>Cold</td>
<td>119</td>
<td>120</td>
<td>21</td>
</tr>
</tbody>
</table>

Compute the heat cascade & hot utility requirement of the above process for a $\Delta T_{min} = 20$ °C. The process also has a requirement of 6 MW of power. Two alternative options for cogeneration are available:

a) A steam turbine with its exhaust saturated at 150°C is one of the options to be considered for process heating. Superheated steam is generated in the central boiler house at 40 bar and 290°C. The superheated steam can be expanded in a single-stage turbine with an isentropic efficiency of 90%. Calculate the maximum power generation possible by matching the exhaust stream against the process.

b) A second possible option may be a gas turbine with an air flow rate of 93 Kg. s$^{-1}$, which has an exhaust temperature of 390 °C. Calculate the power generation if the gas turbine has an efficiency of 28%. Ambient temperature = 12°C.

c) The cost of heat from fuel for the gas turbine is $4.4$ GW$^{-1}$. The cost of imported electricity is $18.8$ GW$^{-1}$. Electricity can be exported with a value of $13.4$ GW$^{-1}$. The cost of fuel for steam generation is $3.1$ GW$^{-1}$. The overall efficiency of steam generation and distribution is 85%. Which option is more economical?

**Solution:**

The grid diagram for the above problem is shown in Fig. 36.10. The corresponding heat cascade is shown in table 36.2. From the heat cascade, it is evident that the above process has a hot utility requirement of 15 MW.
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Fig. 36.10 Grid diagram of problem in Table 36.1

Table 36.2 Heat flow cascade for problem given in Table 36.1

<table>
<thead>
<tr>
<th>$T^*$ (°C)</th>
<th>Cascade heat flow (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>415</td>
<td>15</td>
</tr>
<tr>
<td>390</td>
<td>21.25</td>
</tr>
<tr>
<td>385</td>
<td>22.25</td>
</tr>
<tr>
<td>130</td>
<td>22.25</td>
</tr>
<tr>
<td>129</td>
<td>1.25</td>
</tr>
<tr>
<td>35</td>
<td>1.25</td>
</tr>
<tr>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>14</td>
</tr>
</tbody>
</table>

The grand composite curve for the problem is shown in Fig. 36.11
a) This option is shown in Fig. 36.12. The steam condensing interval temperature is 140 °C.

Now, Heat flow required form the turbine exhaust = 15 MW

Also, from steam tables, inlet conditions at T₁ = 290 °C and 40 bars are:
\[ H_1 = 2933 \text{ kJ/kg} \]
\[ S_1 = 6.32 \text{ kJ/kg/K} \]

Therefore, turbine outlet condition considering isentropic expansion to 150°C using steam table is:

\[ P_2 = 4.761 \text{ bars} \]
\[ S_2 = 6.32 \text{ kJ/kg/K} \]

The wetness fraction \((X)\) can now be calculated using equation:

\[ S_2 = X \cdot S_L + (1-X) \cdot S_v \]

Where, 
\(S_L\) and \(S_v\) are saturated liquid and vapor entropies taken from steam table.

Thus,

\[ 6.32 = 1.842X + 6.838(1-X) \]

Or,

\[ X = 0.103683 \]

Now,

The turbine outlet enthalpy for an isentropic expansion can now be calculated from:

\[ H_2 = X \cdot H_L + (1-X) \cdot H_v \]

Where, 
\(H_L\) and \(H_v\) are the saturated liquid and vapor enthalpies. Taking saturated liquid and vapor enthalpies from steam table sat 150°C and 4.761 bars:

\[ H_2 = 0.103683 \times 632.16 + 0.896317 \times 2745.9 \]
\[ = 2526.74 \text{ kJ/kg} \]

Now, if we consider a single stage expansion with isentropic efficiency of 90 \%, then

\[ H_2' = H_1 - \eta_s (H_1 - H_2) \]
\[ = 2933 - 0.9 \times (2933 - 2526.74) \]
\[ = 2933 - 365.634 = 2567.26 \text{ kJ/kg} \]

The actual wetness fraction can now be calculated as:

\[ H_2' = X' \cdot H_L + (1-X') \cdot H_v \]
\[ 2567.26 = X' \times 632.16 + (1-X') \times 2745.9 \]

\[ X' = (178.64/2113.74) = 0.0845 \]
Now, if we assume that the saturated steam and condensate are separated after the turbine and the only the saturated steam is used for processing heating.

Steam flow to process = \( \frac{15000}{(2745.9 - 632.16)} = \frac{15000}{2113.74} = 7.096 \text{ kg/s} \)

Therefore, the stream flow through the turbine = \( \frac{7.096}{(1- 0.0845)} = 7.75 \text{ kg/s} \)

Power generated = \( 7.75 \times (H_1 - H_2') = 7.75 \times (2933 - 2567.26) = 2.835 \text{ MW} \)

b) This option is shown in Fig. 36.13

![Heat release curve with process GCC for option ‘b’ of problem in Table 36.1](image)

The exhaust from the gas turbine is can be considered to be primarily air with a small amount of combustion gases. Hence, we can assume the CP of the exhaust to be that of the airflow. 

Now, \( C_p \) for air = 1.03 kJ/ kg/ K.

Therefore, \( CP \) for exhaust = \( 93 \times 1.03 = 95.79 \text{ kW/ K} \)

Also, we know that,

\[
Q_{EX} = CP_{EX} \times (T_{EX} - T_0) = 95.79 \times (390 - 12) = 36.208 \text{ MW}
\]

Now,

\[
Q_{FUEL} = Q_{EX} / (1- \eta_{GT}) = 26.63 / (1- 0.28) = 36.208 / 0.72 = 50.3 \text{ MW}
\]
Thus,

\[ W = Q_{\text{fuel}} - Q_{\text{ex}} = 50.3 - 36.208 = 14.08 \, \text{MW} \]

c) Now, we will consider the economics of the two options:

**Steam turbine economics:**

\[
\text{Cost of Fuel} = \frac{(\text{Heat from steam turbine exhaust} \ + \ \text{Power generated}) \times (\text{cost of fuel for steam turbine per GW})}{\eta_{SG&D}}
\]

Where

\[ \eta_{SG&D} = \text{Steam generation and distribution efficiency} \]

Hence,

\[
\text{Cost of fuel} = \frac{((15 + 2.835) \times 10^{-3}) \times 3.1)}{0.85} = 0.065/\text{s}
\]

Also,

\[
\text{Cost of imported electricity} = ((6 - 2.835) \times 10^{-3}) \times 18.8 = 0.0595/\text{s}
\]

Hence,

\[
\text{Net cost} = 0.1245/\text{s}
\]

**Gas turbine economics:**

\[
\text{Cost of fuel} = (50.3 \times 10^{-3}) \times 4.4 = 0.2213/\text{s}
\]

\[
\text{Electricity credit} = (((14.08 - 6) \times 10^{-3}) \times 13.4) = 0.1082/\text{s}
\]

Hence,

\[
\text{Net Cost} = 0.1131/\text{s}
\]

Hence, gas turbine is most economical in terms of energy costs. However, capital cost of the two must also be considered before coming to any final conclusion.

References
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4. Joe L. Davis Jr & Nicola Knight, Integrating process unit energy metrics into plant energy management systems, KBC Advanced Technologies, Inc, Houston, Texas