LEARNING GUIDE

Module 1: Introduction to thermal power plants

1.1. Objectives

On completion of this module, you should be able to:

- explain the purpose of a modern power plant and its components
- identify the nature of the power plants
- describe the objectives of the plant owners
- understand interaction of various cost components of power plants
- understand the long-term view of an operating plant
- explain the importance of power and energy
- describe the various sources of energy and recognised that some are renewable and some are non-renewable.

1.2. Overview

The purpose of a modern thermal power plant is to transfer the chemical energy in fuel to thermal and elastic potential energy in high temperature, high-pressure steam. The high-pressure steam is then expanded through turbines, providing mechanical power to drive electric generators which, in turn produce electricity. The basic components of a fossil-fuel thermal or vapour power plant are shown in Figure 1. The overall plant can be broken down into four major sub-systems identified by A to D in the figure. Energy conversion from heat to work occurs in sub-system A. The objective of sub-system B is to supply the energy required to vaporise water passing through the boiler. In fossil-fuel power plants, this is done by heat transfer to the working fluid passing through the boiler tubes and drums from the hot gases produced by the combustion of a fossil fuel. In nuclear plants, the energy is produced by nuclear reaction taking place in an isolated reactor. Pressurised water, or a liquid metal reactor coolant, is used to transfer energy to the working fluid through specially designed heat exchangers. In solar power plants, solar troughs or collectors receive solar radiation to vaporise the working fluid. Regardless of the source of energy, the vapour produced in the boiler passes through a turbine where it expands to a lower pressure. The shaft of the turbine is connected to an electric generator, which is shown in sub-system D. The vapour leaving the turbine passes through the condenser. While passing through the condenser, it condenses on the outside of tubes carrying cooling water. The cooling tower circuit is shown in sub-system C. The cooling water is sent to a cooling tower where energy taken-up in the condenser is rejected to the atmosphere, and then the water is recirculated through the condenser.
In Queensland, most of the power plants are vapour power plants that operate on fossil fuel, in particular, on coal. Hence, coal-fired steam generation plants are analysed and discussed in detail in this course. Figure 2, adapted from Babcock and Wilcox Company (cited in Singer 1991, p. 7-21) shows different components of a modern pulverised coal-fired steam generation plant. Although the purpose of the major components has been covered in prerequisite courses, a brief description of basic components and their purpose is provided below for completeness.

**Pulverised fuel (PF) supply**

A buffer storage of raw coal is held in bunkers with enough capacity to run the plant at full load for twelve hours or more. It passes through feeders where the coal flow is measured and metered, and then through pulverisers to burners firing into the furnace. Pulverised fuel firing is employed because of its rapid reaction rate, which is the result of the small fuel particle size and the consequent large specific surface area. Some plants hold PF in storage in order to be able to start up on PF rather than on more expensive fuels.

**Air supply**

Air is the usual source of oxygen for combustion of the fuel. Atmospheric air is drawn through measuring devices into forced draft (FD) fans which provide enough pressure to drive the air through airheaters, ductwork, windboxes and burners to the furnace.

Air passes through the airheaters in order to increase its temperature with the dual purpose of recovering heat from the flue gas leaving the boiler, and to enhance combustion rates by increasing the initial reaction rate with the PF. Hot air in the windbox is termed Secondary Air.
Most plants take some of this high-pressure air and increase its pressure further in primary air (PA) fans to provide air to dry the coal and to transport the PF through the pulverisers and pipework to the burners. Cold air may be mixed with the hot prior to combining with the coal stream to control the primary air temperature, so that the pulveriser discharge temperature is maintained at the desired level. (usually 80 to 90 °C).

Figure 2: Pulverised coal-fired reheat steam generation plant
(Source: Singer 1991, p. 7-21, adapted from Babcock & Wilcox Company)
Pulverisers rely on having free-flowing coal, so pre-drying to remove surface and inherent moisture is imperative. There must be enough energy in the primary air to provide this drying capacity. Pulveriser discharge temperature must be high enough to have a safe margin above the air/water vapour mixture dew point, but not so high as to create a risk of premature combustion in the PF pipes and burners.

More advanced plants may fire on oxygen separated from air, bypassing the nitrogen from the air around the combustion process.

**Combustion and heat transfer**

Fuel enters the furnace through burners, which are intended to provide optimised conditions for the mixing of fuel and secondary air. This enables controlled initiation of combustion and encourages complete burnout of the fuel. Some modern burners have several stages of air addition in order to control the stoichiometry (i.e. sufficient amount of oxygen required for complete combustion) of the combustion process to inhibit the formation of oxides of nitrogen (NOx).

Combustion takes place in suspension in the furnace, with flame temperatures reaching as high as 1700 °C. This is usually hot enough to melt the non-combustible mineral matter in the coal to form globules of liquid ash. Surface tension causes the molten particles to adopt a spherical shape, which they retain as they later cool and solidify.

Most boilers in the Queensland power industry are provided with a divided rear convection heat transfer pass, with the primary (low temperature) superheater in one and the low temperature reheater in the other. Dampers divide the flow between the two passes, usually in such a manner as to control reheat steam temperature. Tilting burners in CE design boilers is another method for reheater temperature control.

An economiser is provided at the bottom of the rear pass, to extract further heat from the combustion products and to preheat water on its way into the boiler. The flue gas then passes through air heaters where it gives up the last of its readily-available heat to the incoming air. Sugar mills have recently installed economisers and higher pressure boilers during recent years to gain the benefits of ‘green electricity’ from the combustion of bagass fibre from the sugar cane stalk.

**Flue gas cleaning**

Flue gas cleaning systems, comprising inertial separators such as cyclones, electrostatic precipitators, fabric filters, scrubbers and the like remove undesirable solids and gases from the flue gas before it passes through Induced Draft (ID) fans and then passed to the stack for eventual discharge to the atmosphere. The sugar industry has a preference for scrubbers due to their combined problems of water removal by evaporation as well as dust removal from the stack. Future systems may include CO₂ removal, (Callide A oxyfiring trials) leaving virtually no discharge into the atmosphere.

**Pressure parts**

The pressure parts comprise all those components that contain the working fluid—i.e. water and steam. Feedwater enters the boiler at the economiser, a tubular heat exchange section heated by low temperature flue gas just before it leaves the boiler casing. Some economisers utilise extensive finning on the gas side to increase heat transfer. The heated feedwater then passes to the furnace heat exchange stage.
Sub-critical units usually operate with a boiler drum, a large diameter cylinder located at the highest point in the evaporation circuit. Feedwater enters the drum and passes down downcomers to furnace lower waterwall headers where it enters the furnace waterwalls. Radiant heat from the furnace heats the water, transforming some of it to steam. Natural convection carries the steam-water mixture to the drum where the saturated steam is separated and directed to the following superheaters, while the water re-enters the downcomers for further evaporation in the furnace waterwalls. As the water entering the drum from the waterwalls has just lost part of its mass as saturated steam, it will have the highest concentration of impurities within the evaporation circuit. Water blowdown from the drum is used to maintain boiler water purity at desired levels.

Some boilers have assisted circulation, where circulation pumps provide additional driving head to force water through the waterwall tubes in a desired flow pattern. Orifices may be fitted to some tubes or groups of tubes to ensure that the water flow distribution amongst the tubes is correctly balanced.

Benson boilers are a once-through design without a drum or downcomers, where water flow is directly from waterwall tubes to superheaters, sometimes through a small steam separator vessel. This design eliminates the drum and downcomers. Supercritical boilers are inherently once-through water flow, as at supercritical conditions there is no evaporation phase change. The heated fluid from the furnace waterwall tubes passes directly to the superheaters. For startup and sliding pressure operation, steam separator vessels may be provided, with recirculation pumps to return liquid water to the start of the waterwall flow.

Saturated steam passes to the primary (low temperature) superheaters in the rear pass of the boiler where heat transfer is by convection from the flue gas. The steam is then heated above saturation temperature. On its passage from the primary superheaters the steam passes through desuperheaters, where its temperature is reduced by the evaporation of high-pressure water so that the temperature of the steam leaving the final superheaters is controlled to the desired value. Further stages of desuperheating may be inserted between other higher temperature superheating stages.

Secondary superheaters are usually positioned in the top of the furnace where they experience direct radiation from the furnace.

Tertiary superheaters are placed above the furnace nose, where they are shielded from direct radiation from the furnace. This is the final stage of superheating before the steam travels through the main steam pipework to the high-pressure turbine.

The expansion in the HP turbine cools the steam, and it is returned to the boiler via the Cold Reheat pipework to the Low Temperature reheater in the divided rear pass. Spray desuperheaters may be provided at the inlet to the LT Reheater for additional control of final reheat steam temperature. The steam then passes to the High Temperature Reheater above the furnace nose where it is heated further by convection and radiation before returning to the Intermediate Pressure Turbine via the Hot Reheat Pipework.

In single-reheat plant the steam leaving the IP turbine flows directly to the LP turbine, after which the low temperature steam passes to the condenser.

**Condensing and feed-heating plant**

The condenser removes latent heat of evaporation from the steam (now at a very low-pressure and temperature), causing the steam to condense to the liquid phase. Some non-condensable gases will remain, and these are removed by vacuum pumps or steam ejectors and discharged to the atmosphere.
Water is extracted from the condenser with condensate extraction pumps and either the full flow or part of it is passed through Condensate Polishers—ion exchange systems intended to remove mineral impurities and corrosion products from the condensate. (In lower pressure units such as Callide A, with pressures less than 10Mpa, there is no requirement for a polisher). Note that condensate polishers cannot remove clays and sugars from water due to their non ion properties.

The water then passes through low-pressure feedwater heaters. These regenerative heaters extract bled steam from the low-pressure turbine, with the condensed steam flowing to the condenser. The final stage of low-pressure feedheating is the deaerator, where bled steam passes in intimate contact with the feedwater, heating it and liberating any dissolved gases. These gases pass to the condenser. The deaerators are attached to a large reserve tank where the hot feedwater is held prior to passing to the boiler feedwater pump.

The feedwater pump is required to pump water close to boiling temperature, and hence requires substantial net positive suction head (NPSH). This is provided either by mounting the deaerator storage tank at a high level and allowing gravity to provide the head to the boiler feed pump at a lower level, or by means of a booster pump. Installation simplicity in modern plants is usually achieved with slow speed (usually 1500rpm ) booster pumps.

The boiler feed pumps (BFPs) are usually high speed centrifugal pumps, and are the largest single parasitic load in a conventional Rankine cycle plant. They increase the pressure of the feedwater to slightly above boiler drum pressure.

Feedwater is heated further in high-pressure feedwater heaters which also draw bled steam from the main turbine. Bypass valves are provided to allow feedwater to short-circuit one or more of the HP heaters in the event of problems with the heaters, or to achieve higher power output from the main turbine by forcing the steam which would otherwise flow to the HP heaters, to flow through the lower-pressure stages of the main turbine. If the highest-temperature HP heaters are bypassed, the feedwater entering the boiler will be at a lower temperature, requiring more energy from fuel to raise its temperature to boiling.

What is advanced power plant?

The advanced power plant (APP) is a pulverised fuel combustion advanced supercritical (ASC) boiler/steam turbine power plant suitable for clean coal power generation. The APP technology with steam conditions of 300 bar / 600 °C / 620 °C gives an efficiency of 46–48 percent net based on lower heating value (LHV). This limit is primarily determined by the combination of supercritical boiler and turbine technologies, with the commercially available materials for the higher temperature parts of the boiler, turbine and pipework. The plant location, i.e. inland or coastal, is also a factor in determining how high efficiency can be achieved. APP would be fitted with high-quality selective catalytic reduction (SCR) for NOx reduction, flue gas desulphurisation (FGD) for SO2 reduction and an electrostatic precipitator (ESP) or baghouse filter, as appropriate, for particulates removal. The APP would meet the requirement of standard industrial emission level. For high temperatures ferritic, martensitic and austenitic steels are used in APP. Future plant currently under development in the Advanced (‘700 °C”) PF Power Plant Project Changshu Power Station, China 3 x 600MWe Mitsui Babcock once-through supercritical wall-fired boilers 2 (AD700) will achieve 50–55 percent net efficiency. To achieve these efficiencies a step-change in steam conditions to 350 bar / 700 °C / 720 °C is necessary and this requires the use of nickel alloys in the highest temperature regions of the superheater, reheater, turbine and pipework.
1.3. Nature of power plants

Power plants can be divided into two categories—stand-alone and integrated. Stand-alone power plants are the most familiar to power plant engineers, as they are purpose-designed to optimise performance and efficiency to convert chemical energy to electrical energy. The overall thermal efficiency of these plants is limited by the Carnot cycle efficiency for the temperature limits employed, and in fact, is considerably lower than this at the practical Rankine cycle efficiency. Changes in the efficiency of the cycle are immediately felt as changes in output or in fuel consumption.

Integrated power plants (as the name suggests) are integrated with another process, usually one requiring the use of extensive quantities of heat. Some examples are sugar mills, steel plants, alumina refineries and other chemical plants. In these plants the power cycle may be:

- A high temperature power process (a topping cycle) delivering waste heat to another process at lower temperatures. Typical examples are combined heat and power plants where the waste heat from a power plant is used for building or district heating. Some advanced alumina refineries have a high temperature power cycle delivering waste heat through a reboiler to a lower temperature Bayer process.

- A high temperature process delivering waste heat to a lower temperature power cycle (a bottoming cycle). Examples are: (a) combined cycle power plants where a gas turbine exhausts to a heat recovery steam generator which is the high temperature end of a Rankine cycle steam plant, and (b) high temperature metallurgical processes, (especially exothermic ones) which provide waste heat to a lower temperature Rankine cycle steam plant.

Integrated power plants with a power topping cycle can be inherently more efficient than stand-alone power plants because a greater proportion of the energy supplied is put to use. The Rankine cycle rejects heat to another process, which would have required heat anyway, and this heat is then not rejected directly to the surroundings. It could be claimed that the efficiency of power generation in this scheme is nearly 100 percent, and is the product of the boiler efficiency and the turbine mechanical efficiency.

1.4. Objectives of plant owners

A modern power plant would typically consist of large quantities of high temperature equipment including boilers, high-pressure pipe-work, turbines, and other pressure vessels. The aims of the business are to provide a service (usually at minimum cost) and to make a profit for the owners—generally the greater the better.

Modern plants are designed on an economic basis, where there is a trade-off of capital cost against running cost. In a well-designed plant, high peak cycle temperatures translate into high efficiency with the benefits of reduced fuel cost, and reduced plant size for a given output. These same high peak temperatures mean either higher plant capital cost or higher maintenance costs, and often both. Conversely, low peak temperatures will result in low efficiency, higher fuel cost, and larger plant size for a given output. Materials suitable for high temperatures and stresses are more expensive than those suitable only for lower temperatures.

There are elements of uncertainty about various aspects of the business environment, including integrity of design, construction, materials, and the operation and maintenance functions. Fuel properties almost always vary from optimum values. The financial and regulatory environments can change substantially, while the demands of protecting the
physical environmental can change. All of these influences constitute elements of risk, which must be managed carefully for a business to be successful.

Thus the owner must take into account coal supply, technology, water supply (dry cooling may be necessary) people supply and skills (Stanwell was built near the people of Rockhampton rather than on the mine mouth) and pollution level (the carbon trading schemes of the future).

1.5. Interaction of various cost elements

A business intended to provide a service at minimum cost will always be interested in reducing costs. If the aim is to maximise profits, the drivers are to increase income and decrease costs.

Income will usually be derived under the relationship of:

\[
\text{Income} = \text{Volume} \times \text{Price}
\]

where, volume can be translated as peak capacity, availability, capacity factor, or units produced.

Price is influenced by reliability and availability to take advantage of price variations. Customers are often prepared to pay a premium for reliability of supply.

There can be numerous components of cost in ownership and operation of plant. Some of these are:

- capital charges
- operating costs
- maintenance costs
- environmental protection and compliance
- decommissioning/disposal.

**Predictability**

A business can be more stable and predictable if the cash flows are known with some certainty. This can easily be translated into reduced financing costs, and will also be reflected in share prices (where applicable). An owner in full control of a business must know all of the cost components which apply. Whole-of-life costing is a necessity so that future cash flows are not hidden or missed entirely.

**Methods of cost reduction**

Cost of plant ownership and operation can be reduced by many methods, some of which are:

- Extend the life of existing plant to avoid the higher costs of construction of a completely new plant.
- Improve the thermal efficiency of existing plant to reduce fuel costs.
- Reduce the number and duration of shutdowns for maintenance and inspection, giving longer operating runs and higher earning capacity.
- Reduce numbers of staff. Where an operation requires continuous shiftwork, reduction in one shift position can result in a reduction of several staff.
- Use cheaper fuel. This may increase other costs due to erosion, blockages, increased handling and milling costs, etc.
Power Generation Skills Development

- Maintenance practice improvement—reliability centred maintenance.
- Training of staff to operate and maintain plant effectively.

A universal language

Large plants involve large financial commitments and large cash flows. Plants are usually run under budgetary control, expressed in monetary terms ($). Information and arguments expressed in $ can be understood by everyone, therefore communication is improved. (This line of reasoning has limits, i.e. it loses validity when applied indiscriminately to things which are not man-made.) Plant life issues need to be quantified in monetary terms ($) to get the attention they deserve.

A long-term view of an operating plant

In order for a plant manager to be in proper control of the business, the questions given in Table 1 should be under continual review:

Table 1: Questionnaires for proper control of power plant business
(Source: Leinster 2007)

<table>
<thead>
<tr>
<th>Questions</th>
<th>Response</th>
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<tbody>
<tr>
<td>Where are we?</td>
<td>• All important features of the plant design are known.</td>
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<tr>
<td></td>
<td>• The plant condition is known as the result of formalised life assessment.</td>
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<tr>
<td>What do we want to be?</td>
<td>Sensible goals are set, with all assumptions justified and documented.</td>
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<tr>
<td></td>
<td>• Required future life.</td>
</tr>
<tr>
<td></td>
<td>• Required future performance.</td>
</tr>
<tr>
<td></td>
<td>• Future financial goals.</td>
</tr>
<tr>
<td>How do we get there?</td>
<td>Informed planning takes place, including:</td>
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<td></td>
<td>• Life prediction/design studies are carried out to determine the effects of future operation on plant life and costs.</td>
</tr>
<tr>
<td></td>
<td>• Future operation and maintenance strategies planned to ensure that life and cost objectives are met.</td>
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<tr>
<td></td>
<td>• Re-rating/life extension of plant is planned and implemented.</td>
</tr>
<tr>
<td></td>
<td>• Project planning and budgeting are in place for whole of the remaining life of the plant. Decommissioning costs should be included. All assumptions are justified and documented.</td>
</tr>
<tr>
<td>What can go wrong?</td>
<td>• Risk assessment is carried out to determine the cost of each potential situation or event.</td>
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<td></td>
<td>• Risk mitigation is put in place to control the impact of each potential situation or event to acceptable levels. Mitigation could be as simple as a design review or inspection, or as serious as shutting down the plant.</td>
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<td>• Outputs of this stage feed back into the previous three (3) questions.</td>
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</table>
1.6. Energy sources and their conversion

All energy is derived from some source as they cannot be created or destroyed. Figure 3 summarises the sources of energy that can be used in power plant for power generation. It can be seen from Figure 3 that energy exists in different forms, but only one form is suitable for a particular application. At least, a conversion process is necessary to convert energy from one form to another usable form. For example, in nature solar energy is converted to mechanical energy through heat engines. In many cases, several processes may be necessary. Figure 4 shows a series of conversion steps. Most conversion processes involve a loss of usable energy. The efficiency of conversion is most important and is given by the following equation:

\[ \eta = \frac{Usable\ energy\ output}{Energy\ input} \]  \hspace{1cm} (Eq. 1)

![Figure 3: Sources of energy](source: re-drawn from Kinsky 1996, p. 9)
The energy that is available continuously is known as renewable energy and consists essentially of solar, wind, biomass, tidal and geothermal energy. Energy that derives from a source that cannot be re-created is known as non-renewable (or stored) energy and consists essentially of nuclear energy and fossil fuel energy. The discussion on different types of energy sources, both renewable and non-renewable, has been provided in prerequisites course ‘Introduction to Power Plant (EPG01)’.
Summary

When you finish this module you should be able to explain and recognise the nature and purpose of a modern power plant, the importance of power and energy and their sources, the objectives of plant owners and the interaction of various cost components of power plants.

The learning objectives at the start of this module provide a detailed breakdown of the task described above. Make sure that you can do each activity listed in the learning objectives. If you feel that you cannot achieve the learning outcomes for this module, work through this Study Guide again and read the relevant sections from recommended books.

Remember that if you need assistance in your study, the lecturer and other University staff are there to assist you. We are only a phone call away.

Checklist

Use the following checklist to identify whether you achieved the essential elements of each learning objective in this module.

<table>
<thead>
<tr>
<th>Performance criteria</th>
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<tbody>
<tr>
<td>Power Plant</td>
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<tr>
<td>□ Describe the purpose of the plant</td>
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<tr>
<td>□ Identify nature of the plant</td>
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<tr>
<td>□ Explain sources and conversion process of energy for plant</td>
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<tr>
<td>□ Explain the purpose of various components</td>
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<tr>
<td>□ Define advanced power plant</td>
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<tr>
<td>Plant Owner and cost components</td>
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<tr>
<td>□ Describe the objectives of plant owners</td>
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<tr>
<td>□ Explain the interaction of various cost components</td>
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<tr>
<td>□ Identify the long-term view of an operating plant</td>
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</table>

References


Recommended reading list


