Lectures of the Department of Mechanical Engineering

Subject Title: Power Plant

Class: 4th

Lecture Contents	Lecture sequences:1	First lecture Introduction to power plant	Instructor Name: Dr. Mohammed Saleh
	1-intruduction **2-Power Plant Classifications** **3-Energy and Environment** **4-Energy Demand Curve** **5- Comparison of Various Power Plant** **6- Power Plant in Iraq**		

1. Introduction

2. Power Plant Classification

2.1. In general, power plants can be divided into two categories - conventional and non-conventional power plants**.**

2.1.1. Conventional power plants are

a. *Fossil fuel power plants*: Generates electric power by burning fossil fuels like coal, natural gas or diesel.
b. *Nuclear power plants:* Controlled nuclear reaction is maintained to generate electricity.
c. *Hydroelectric power plants*: Electricity is produced by building dams on suitable rivers.

2.1.2. Non-conventional power plants are:

a. *Wind power plants*: The kinetic energy of wind is used to create power.

b. Solar power plants: Generates power by collecting solar radiation.
c. Geothermal power plants: Uses the natural heat found in the deep levels of the earth to generate electricity.
d. *Biomass power plants*: Natural organic matter is burnt to produce electricity.

2.2. On the Basis of Primary Source / Fuel

2.2.1. Nuclear Power Plants

2.2.2. Geothermal Power Plants

2.2.3. Fossil-Fuel Power Plants

2.2.4. Biomass-Fueled Power Plants

2.2.5. Solar Thermal Power Plants

2.3. On the Basis of Prime Mover

2.3.1. Steam Turbine Power Plants

2.3.2. Gas Turbine Power Plants

2.3.3. Combined Cycle Power Plants

2.3.4. Internal combustion

Reciprocating engines are used for small cogeneration plants likes - Hospitals, office buildings, industrial plants, and other critical facilities.

2.3.5. Micro turbines,

Micro turbines are small combustion turbines approximately the size of a refrigerator with outputs of 25 kW to 500 kW. They evolved from automotive and truck turbochargers, auxiliary power units for airplanes

2.4. On the Basis of Duty

2.4.1. Base Load Power Plants –

Base Load Power Plants run nearly continually to provide that component of system load that doesn't vary during a day or week.

2.4.2. Peaking Power Plants –

Peaking power plants meet the daily peak load, which may only be for a one or two hours each day. While their incremental operating cost is always higher than base load plants

2.4.3. Load Following Power Plants –

Load following power plants can economically follow the variations in the daily and weekly load, at lower cost than peaking plants and with more flexibility than base load plants.

Each power plant technology has advantages and disadvantages.

For example, nuclear power plants provide large quantities of reliable power with low levels of greenhouse gas emissions. Fossil fuel power plants deliver on-demand, consistent and reliable energy when the resources are available. Hydro, solar and wind power plants generate renewable electricity, thereby delivering emissions-free electricity.

3. Energy and environment

1. **Intrudution to Energy**
2. **World's population and world energy consumption**
3. **Electricity Generation and Consumptions**
4. **World Economic and its Impact on Energy**
5. **Environmental Problems**

3.1. Solutions to reduce emissions and global worming

a *The first option is to increase the efficiency of energy conversion at which fuel is being consumed. This can be done by improving the thermal efficiency of power plants, thus, burning by that less fuel per unit power produced.*

b *The second option is to switch to low carbon fuels, if there is a possibility. Among all fossil fuels, natural gas consumption results in the lowest levels of greenhouse gas emissions.*

c *The third option is to increase the contribution of renewable energy sources, such as solar and wind power, and nuclear power plants, apart from using fossil fuels. From the above options considered, the first two would be the most favourable options. It is more convenient to pursue improving the efficiency of a power plant, or switching to a low carbon fuel, than to replace the entire power plant itself.*

3.2. Introduction to Energy demand curve

4. Comparison of Various Power Plants

1. Power stations in Iraq
    1. Steam Turbine Power Plant
    2. Gas Turbine Power Plant
    3. Combined Cycle Power Plant
    4. Hydroelectric Power Plant

Lecture sequences:2	Second lecture Production and Distribution of Electricity	Instructor Name: Dr. Mohammed Saleh

Lecture Contents

1. **Introduction**
2. **Load Curve and Load-Duration Curves**
3. **Types of Loads**
4. **Important Terms and Factors:**
5. **Power Plant Economics**
6. **Examples**

1. Introduction

The function of a power station is to deliver power to a large number of consumers. However, the power demands of different consumers vary in accordance with their activities. The result of this variation in demand is that load on a power station is never constant, rather it varies from time to time. Most of the complexities of modern power plant operation arise from the inherent variability of the load demanded by the users. Unfortunately, electrical power cannot be stored and, therefore, the power station must produce power as and when demanded to meet the requirements of the consumers. On one hand, the power engineer would like that the alternators in the power station should run at their rated capacity for maximum efficiency and on the other hand, the demands of the consumers have wide variations. This makes the design of a power station highly complex.

Variable Load on Power Station

The load on a power station varies from time to time due to uncertain demands of the consumers and is known as variable load on the station. A power station is designed to meet the load requirements of the consumers. An ideal load on the station, from stand point of equipment needed and operating routine, would be one of constant magnitude and steady duration. However, such a steady load on the station is never realized in actual practice. The consumers require their small or large block of power in accordance with the demands of their activities. Thus the load demand of one consumer at any time may be different from that of the other consumer. The result is that load on the power station varies from time to time.

Effects of variable load. The variable load on a power station introduces many perplexities in its operation. Some of the important effects of variable load on a power station are:

a. Need of additional equipment.
b. Increase in production cost.

2. Load Curve and Load-Duration Curves

2.1. Load curve

The curve showing the variation of load on the power station with respect to time is known as a load curve. The load on a power station is never constant; it varies from time to time. These load variations during the whole day (i.e., 24 hours) are recorded half-hourly or hourly and are plotted against time on the graph. The curve thus obtained is known as *daily load curve* as it shows the variations of load w.r.t. time during the day. Figure 1. shows a typical daily load curve of a power station.

The monthly load curve can be obtained from the daily load curves of that month. The monthly load curve is generally used to fix the rates of energy.

The yearly load curve is obtained by considering the monthly load curves of that particular year. The yearly load curve is generally used to determine the annual load factor.

What is the importance of the daily load curves?

a. The daily load curve shows the variations of load on the power station during different hours of the day.
b. The area under the daily load curve gives the number of units generated in the day.
c. The highest point represents the maximum demand on the station on that day.
d. The area under the daily load curve divided by the total number of hours' gives the *average load* on the station in the day

$$\boldsymbol{avarage\ load} = \frac{Area\ (in\ kWh)\ under\ daily\ load\ curve}{24\ hours}$$

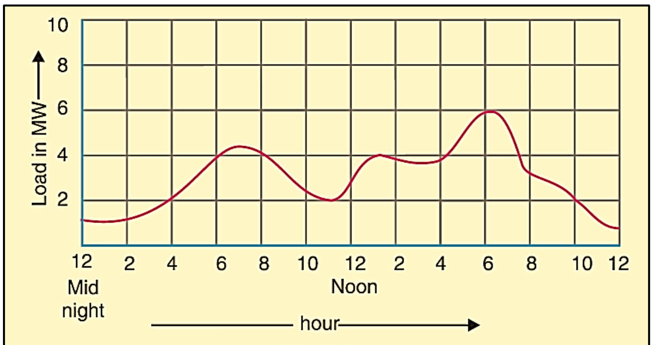


Fig. 3.2

Figure 1 daily load curve

2.2. Load duration curve

When the load elements of a load curve are arranged in the order of descending magnitudes, the curve thus obtained is called a load duration curve.

The load duration curve is obtained from the same data as the load curve but the ordinates are arranged in the order of descending magnitudes. In other words, the maximum load is represented to the left and decreasing

loads are represented to the right in the descending order. Hence the area under the load duration curve and the area under the load curve are equal.

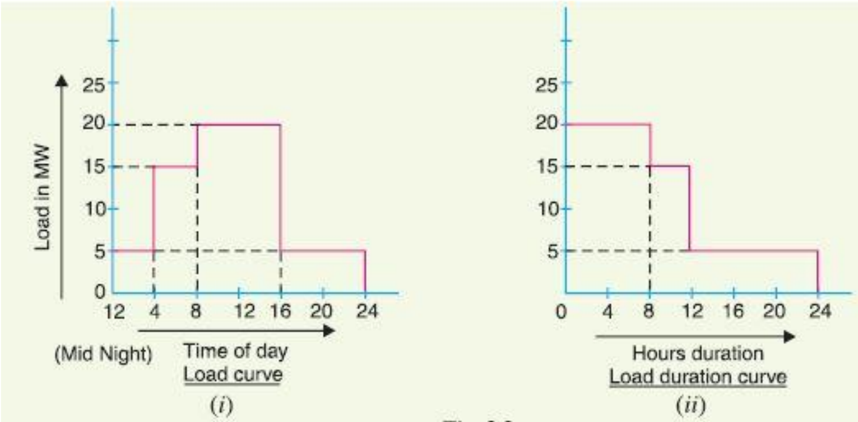


Figure 2 load curve and load-duration curve

2.3. Types of Loads

2.3.1. Types of electrical consumers

The load may be resistive (e.g., electric lamp), inductive (e.g., induction motor), capacitive or some combination of them. The various types of loads on the power system are:

a *Domestic load. Domestic load consists of lights, fans, refrigerators, heaters, television, small motors for pumping water etc. Most of the residential load occurs only for some hours during the day (i.e., 24 hours) e.g., lighting load occurs during night time and domestic appliance load occurs for only a few hours. For this reason, the load factor is low (10% to 12%).*

b *Commercial load. Commercial load consists of lighting for shops, fans and electric appliances used in restaurants etc. This class of load occurs for more hours during the day as compared to the domestic load. The commercial load has seasonal variations due to the extensive use of air conditioners and space heaters.*

c *Industrial load. Industrial load consists of load demand by industries. The magnitude of industrial load depends upon the type of industry. Thus small scale industry requires load up to 25 kW, medium scale industry between 25kW and 100 kW and large-scale industry requires load above 500 kW. Industrial loads are generally not weather dependent.*

d *Municipal load. Municipal load consists of street lighting, power required for water supply and drainage purposes. Street lighting load is practically constant throughout the hours of the night. For water supply, water is pumped to overhead tanks by pumps driven by electric motors. Pumping is carried out during the off-peak period, usually occurring during the night. This helps to improve the load factor of the power system.*

e *Irrigation load. This type of load is the electric power needed for pumps driven by motors to supply water to fields. Generally, this type of load is supplied for 12 hours during night.*

f *Traction load. This type of load includes tram cars, trolley buses, railways etc. This class of load has wide variation. During the morning hour, it reaches peak value because people have to go to their work place. After morning hours, the load starts decreasing and again rises during evening since the people start coming to their homes.*

2.4. Load on power station

A close look at the load curve reveals that load on the power station can be considered in two parts, namely;

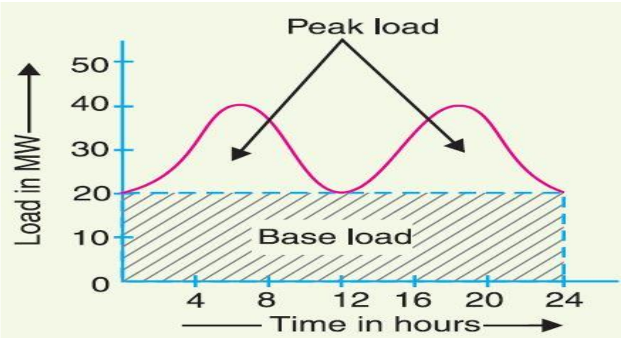
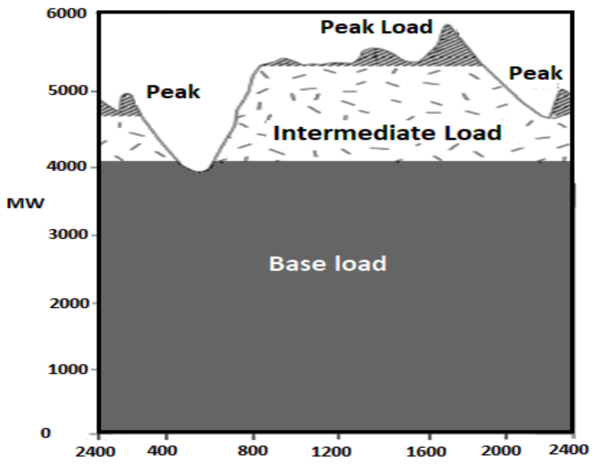


Figure 3 base and peak load

a. Base-Load

It is clear from the above that electricity demand fluctuates throughout every 24-hour period as well as through the week, and also seasonally. It also varies from place to place and from city to city and from country to country depending on the demand type, the climate, industry



and other factors.

Figure 4 Load curve variation of the electricity consumption throughout a weekday

A daily load curve for an electricity system is shown in Figure 4Figure 4. From this it can be seen that there is a base-load of about 60% of the maximum load for a weekday. This load is typical for developed countries.

Base-load is the most economical rate of electricity to be supplied, it must be generated all days and always running by the national utility of electricity. Base-load power plants must be designed to minimize fuel cost. its high capital cost can be tackled by the production of large amount of electricity continuously over its life time (more than 20 years).

Therefore, the base-load demand for reliable, continuous supply of a large amounts of electricity is the key figure in any system. The main investment of electric utility is to meet that kind of demand.

2.4.1. Intermediate and Peak Load

Intermediate or cycling loads forms around 40% of the total demand. Intermediate and peak load may occur every day throughout the years but more likely to involve in summer season because of having air conditioning, while in winter due to space heating and other types of heating.

Intermediate-load and peak-load stations must be capable of being brought on line and shut down quickly once or twice daily. A variety of techniques are used for intermediate and peak load generation including gas turbine, large diesel engine and hydro-electric power plants.

3. Important Terms and Factors:

3.1. Connected load

It is the sum of continuous ratings of all the equipment's connected to supply system. For instance, if a consumer has connections of five 100-watt lamps and a power point of 500 watts, then connected load of the consumer is (5 × 100 + 500 = 1000) watts. The sum of the connected loads of all the consumers is the connected load to the power station.

3.2. Maximum demand (peak load)

It is the greatest demand of load on the power station during a given period. Referring back to the load curve of Fig. 3, the maximum demand on the power station during the day is 6 MW and it occurs at 6 P.M. Maximum demand is generally less than the connected load because all the consumers do not switch on their connected load to the system at a time.

What is the importance of the maximum demand knowledge?

It is very important as it helps in determining the installed capacity of the station, the station must be capable of meeting the maximum demand.

3.3. Demand factor

Demand factor is the ratio of maximum demand of a system to the total connected load of the system. Thus, in a residence the maximum demand would not be the sum of all lighting and appliance loads, but would be some values less than that, since it would be extremely unlikely that all lights and appliance be in operation at the same time.

$$Demand\ factor = \frac{Maximum\ demand}{Total\ connected\ \ load}$$ usually less than 1

The knowledge of demand factor is vital in determining the capacity of the plant equipment.

3.4. Average load

Average load may be defined as the amount of total electric power generated during a specified period of time. For example, if the period of time is taken to be a year, then: -

$$Average\ \ load\ = \frac{power\ generated\ \ per\ year}{Number\,of\ \ \ hours\ \ \ in\,a\ \ year}$$

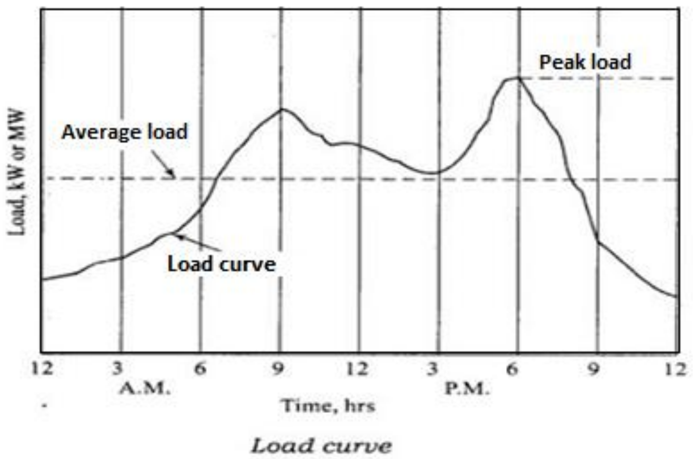


Figure 5 Load curve

3.5. Load factor

Load factor may be defined as the ratio of average load over a specified period of time to the peak load occurring in that period. The maximum demand may also be measured over various length of time as a 15- min, half hour, or an hour period. The load factor will have an important bearing on the cost of power.

$$Load\ factor = \frac{Average\ load}{Peak\ \ load}$$

3.6. Diversity factor

Diversity factor is the ratio of sum of each individual maximum demand of various subdivisions of a system to the maximum demand of the whole system

$$Diversty\ factor = \frac{\sum\ individual\ \max imum\ \ load}{\max imum\ demand\ of\ \ the\ system}$$

The diversity factor is illustrated in Figure 6. It is given to be

$$div = \frac{a+b+c}{d}$$

Diversity helps to improve the load factor and economic operation of the power plant. Figure 6 (b) shows the load curves of an industrialized country, the annual peak occurring in winter. The seasonal variation in the load influences the maintenance program of the power plants. Major maintenance work (cleaning, overhauling etc.) has to be done during the off-peak season.

A high load factor is, in general, an indication of balanced load curve with relatively small load changes. High values of demand factor, load factor, diversity factor and capacity factor are desired for economic operation of the plant and to produce electricity at less cost.

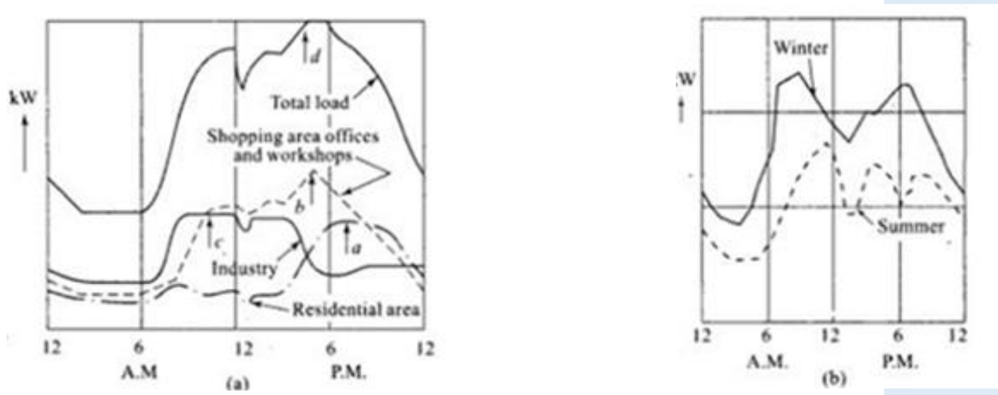


Figure 6 a) diversity of loads consumer groups b) load curve on an industrialized country on summer and winter

$$\text{Load factor} = \frac{\text{Average load}}{\text{Peak load}}$$

$$\text{Use factor} = \frac{\text{Peak load}}{\text{Plant capacity}}$$

$$\text{Capacity factor} = \frac{\text{Average load}}{\text{Plant capacity}}$$

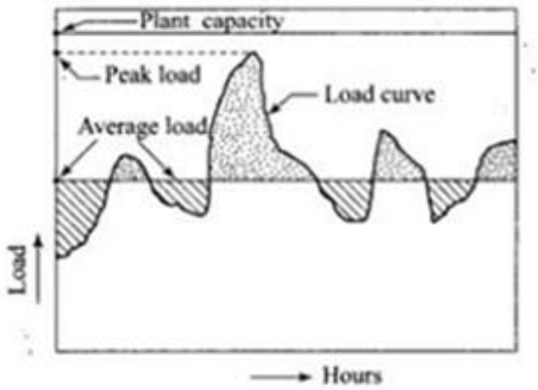


Figure 7 load factor, use factor and capacity factor

It is the ratio of energy produced in a given time to the maximum possible energy that could have been produced during the same time of operation. If the operating time is 1 year or 8760 hrs, the plant use factor is equal to the capacity factor (i.e., $u = n$)

As the plant-use factor approaches l, it indicates the need for additional capacity of the plant. The plant capacity is always designed to be greater than the peak load to take extra loads coming in future. The high value of the plant use factor indicates that the plant is operating quite efficiently. In some inter- connected systems, the plant use factor may exceed unity (e.g., l.l or 1.2) indicating that the loads carried are in excess of the rated capacity since an equipment is always designed to take 10 to 20% more load than rated. The different factors arc indicated in Figure 7.

3.7. Capacity factor

Capacity factor is the ratio of average load of the machine or equipment for the period of time considered to the rating of the machine or equipment, when applied to a plant, this is called plant factor or plant capacity factor.

$$Capacity\ factor = \frac{Average\ \ load\ \ on\,a\ \ plant}{Installed\ \ Capacity}$$

3.8. Operation factor

Operation factor is the ratio of the duration of actual service of a machine or equipment to total duration of the period of time considered. also may be defined as the difference between the use factor and capacity factor.

$$Operating\ \ factor = \ Use\ \ factor - \ Capacity\ \ factor$$

3.9. Utilization factor

Utilization factor is the ratio of maximum demand of a system or part of a system, to the rated capacity of the system, or part of the system. The similarity between this factor and demand factor should be noted. However, their differences lie in the fact that the utilization factor is usually applied to the generating system, while the demand factor is usually applied to equipment's using electric current.

3.10. Use factor

Use factor is the ratio of actual energy produced to the plant capacity actual operating hours.

$$Use\ factor\ = \frac{energy Generated}{Plant\ capacity\ \times operating hours}$$

$$Use\ factor, \mathrm{u}\ = \frac{kW_{gen}}{kW_{ins} \times operating\ hours}$$

4. Power Plant Economics

A power plant should provide a reliable supply of electricity at minimum cost to the consumer. The cost per kWhnet, is determined by:

Fixed costs (FC),

Mainly interest, depreciation, insurance, taxes, depending on the capital invested, i.e. on the construction costs of the plant including the cost of the land.

Operation and maintenance (O & M) costs

covering salaries and wages, overhauling of equipment, repairs including spare parts, water, lubricating oil, chemicals and miscellaneous expenses.

Fuel costs

These costs are dependent on the market and the amount of electricity generated.

The total annual costs (C)

Total annual costs in a power plant can be calculated from

$$C_t = \frac{I + D + T}{100} C_c + (W + R + M) + C_f$$

where I is the interest, %; *D* is depreciation, %; *T* is taxes and insurance, %; C_c the construction cost; *W* is wages and salaries; *R* is repairs (maintenance); *M* is miscellaneous; and C_f the fuel cost.

kWh_{net} of electricity sent out per year.

The annual amount of electricity sent out by a power plant (kWh_{ncl}) is given by

$$kWh_{net} = kW_{inst} \times 8760 \times \left(1 - \frac{L_{aux}}{100}\right) \times n$$

where kW_{insI} is the rated (installed) output of generators; L_{aux} the power consumption by the auxiliaries. %; *n* the plant capacity factor, and 8760 = 24 x 365 hours per year.

In order to calculate the electric power cost to a consumer, in addition to the production cost (fixed cost, operation and maintenance, and fuel cost), the transmission cost, distribution cost, administrative expenses, and return or profit on the investment have to be taken into consideration. A measure for the reliability of a power plant is the forced outage rate defined by the annual ratio of

Examples

Example 1

A power station supplies the following loads to the consumer

Time in hours	0-6	6-10	10-12	12-16	16-20	20-22	2-2
Load in MW	30	70	90	60	100	80	0

a. Draw the load curve and estimate the load factor of plant
b. What is the load factor of a standby equipment of 30 MW capacity if it takes up all loads above 70 MW? what is the use factor

Example 2.

The maximum demand on a power station is 100 MW. If the annual load factor is 40%, calculate the total energy generated in a year.

Example 3.

A generating station has a connected load of 43MW and a maximum demand of 20 MW; the units generated being $61{\cdot}5 \times 10^6$ per year. Calculate

	(i) the demand factor and (ii) load factor. Example 4. A 100 MW power station delivers 100 MW for 2 hours, 50 MW for 6 hours and is shut down for the rest of each day. It is also shut down for maintenance for 45 days each year. Calculate its annual load factor.

Lecture Contents	Lecture sequences:3	Third lecture Vapor Power Plant Cycles	Instructor Name: Dr. Mohammed Saleh
	1. Introduction 2. Rankine Cycle 3. Supercritical Ideal Reheat Cycle 4. Cogeneration 5. binary Vapour Cycle 6. Combined Gas Turbine-Vapor Power Cycle		

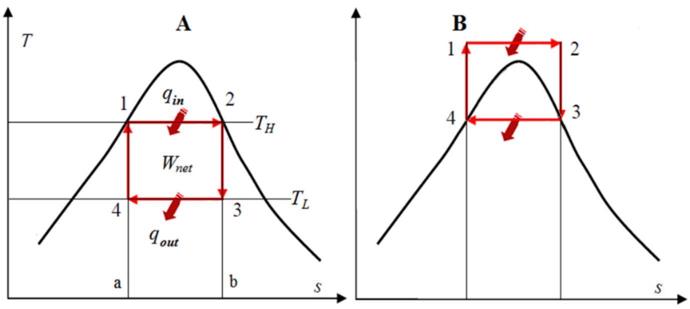
1. Introduction

Steam is the most common working fluid which used in vapor power cycles because of its many desirable characteristics such as: -

1- low cost
2- Availability
3- High enthalpy of vaporization

Steam power plant are commonly referred to as coal plants, nuclear plants and natural gas plants, depending on type of fuel used to supply to steam. The objective of the present chapter is to study vapor power plants in which the working fluid is alternately vaporized and condensed.

The Carnot cycle is the most efficient cycle operating between two specified temperature limits



Thermal efficiency of the Carnot cycle can be calculated from:

$$\eta_{th} = 1 - \frac{T_{min}}{T_{max}}$$

Figure 1-1 Carnot Cycle

Carnot cycle can't be practically implemented because of the following limitation. It's a useful theoretical construct.

Limiting the maximum temperature in the cycle also limits the thermal efficiency.

a. Any attempt to raise the maximum temperature in the cycle will involve heat transfer to the working fluid in a single phase, which is not easy to accomplish isothermally.
b. the turbine will have to handle steam with low quality, that is, steam with high moisture content
c. . The isentropic compression process (process 4-1) involves the compression of a liquid-vapor mixture to a saturated liquid. There are two difficulties associated with this process

Components of a Vapor Power Plant

Main Component on Steam Power Plant: Boiler. Steam Turbine. Condenser.

5. Rankine Cycle

In a steam power plant supply and rejection of heat is more easily realized at constant pressure than at constant temperature. It was William John Macquorn Rankine, after whom the Rankine cycle is named, who first calculated the maximum possible work that could be developed by an engine using dry saturated steam between the pressure limits of the boiler and condenser. The simplest steam cycle using dry saturated steam as the working fluid has the following basic components (Figure 2.1):

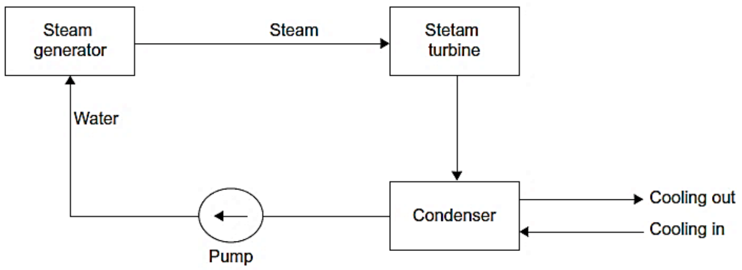


Figure 5-1 Simplest steam cycle.

The most commonly used vapor power cycle is the Rankine cycle. The ideal Rankine cycle does not involve any internal irreversibility and consists of the following four processes:

1-2 isentropic compression in a pump
2-3 constant pressure heat addition in a boiler
3-4 isentropic expansion in a turbine
4-1 constant pressure heat rejection in a condenser

All four components of the Rankine cycle are steady-state steady-flow devices. The potential and kinetic energy effects can be neglected. The first law per unit mass of steam can be written as:

Pump	$q = 0$	$w_p = h_2 - h_1$	or $w_p = v(P_2 - P_1)$	5-1
Boiler	$w = 0$	$q_{in} = h_3 - h_2$		5-2
Turbine:	$q = 0$	$w_{turbine} = h_3 - h_4$		5-3
Condensor:	$w = 0$	$q_{out} = h_4 - h_1$		5-4

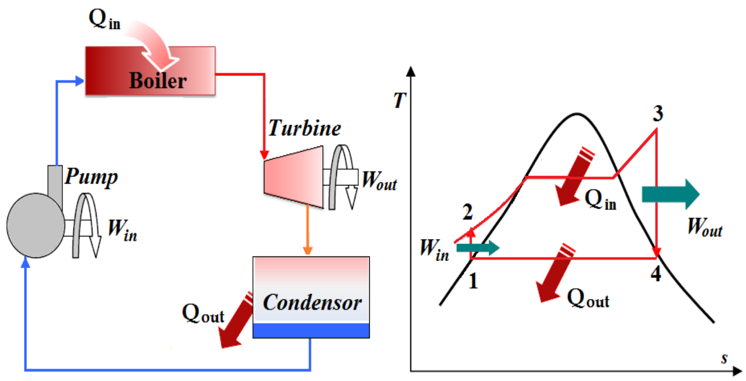


Figure 5-2: Ideal Rankine cycle

The thermal efficiency of the cycle is determined as:

$$\eta_{th} = \frac{W_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} \qquad 5\text{-}5$$

where

$$W_{net} = q_{in} - q_{out} = W_{turbine\,,out} - W_{pump,in} \qquad 5\text{-}6$$

Specific steam consumption (SSC) is the steam flow in kg/h required to develop 1 kW

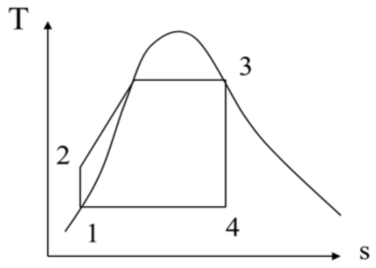
$$W * SSC = 1 * 3600\ kj/h$$

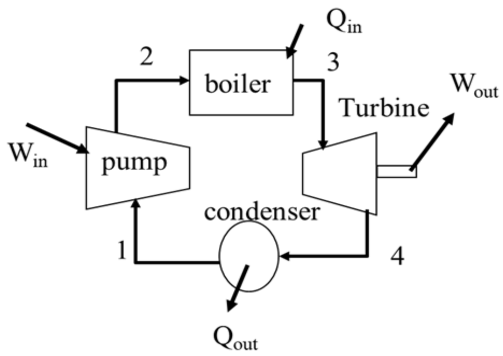
$$SSC = \frac{3600}{W}\frac{kg}{kWh} = \frac{3600}{h_3 - h_4}$$

Example (1):- A steam power plant operate on ideal Rankine cycle the steam enters the turbine at 3 MPa and 350 °C and is condensed in the condenser at a pressure of 75 kPa. Determine the thermal efficiency, work ratio and specific steam consumption if the unit develop a power output of 80 MW.

Example - 2

Consider the Rankine power cycle as shown. Steam enters the turbine as 100% saturated vapor at 6 MPa and saturated liquid enters the pump at a pressure of 0.01 MPa. If the net power output of the cycle is 50 MW. Determine (a) the thermal efficiency, (b) the mass flow rate of the system, (c) the rate of heat transfer into the boiler, (d) the mass flow rate of the cooling water from the condenser, in kg/s, if the cooling water enters at 20°C and exits at 40°C.





Example 3:- Referring to Figure 1.1 calculate the net work output, cycle efficiency, and specific steam consumption (s.s.c) using steam operating between pressures 8 MPa and 9.6 kPa.

5.1. Power Cycle Review

a. The second law of thermodynamics requires the thermal efficiency to be less than 100%. Most of today's vapor power plants have thermal efficiencies ranging up to about 40%.
b. Thermal efficiency tends to increase as the average temperature at which energy is added by heat transfer increases and/or the average temperature at which energy is rejected by heat transfer decreases.
c. Improved thermodynamic performance of power cycles, as measured by increased thermal efficiency, for example, also accompanies the reduction of irreversibilities and losses.
d. The extent of improved power cycle performance is limited, however, by constraints imposed by thermodynamics and economics.

5.2. Deviation of Actual Vapor Power Cycle from Ideal Cycle (Real Rankine cycle)

As result of irreversibilities in various components such as fluid friction and heat loss to the surroundings, the actual cycle deviates from the ideal Rankine cycle. The deviations of actual pumps and turbines from the isentropic ones can be accounted for by utilizing isentropic efficiencies defined as (Figure 5-4): Hence, the efficiency of the ideal Rankine cycle may be regarded as the highest efficiency achievable in practice with a straight condensing machine. However, in real Rankine cycle the efficiency that could be achieved is less than the efficiency of the ideal Rankine cycle, since none of the compression and expansion processes are isentropic.

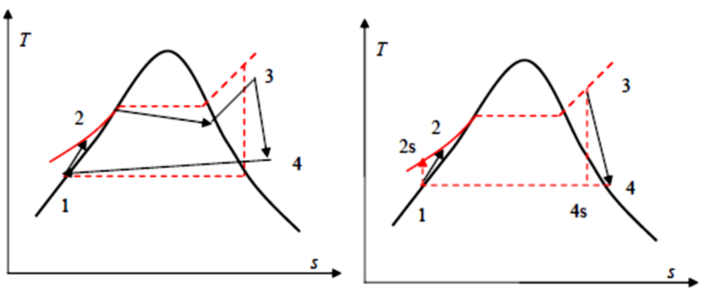


Figure 5-3

$$\eta_{PUMP} = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_a - h_1}$$ 5-7

And

$$\eta_{TURBINE} = \frac{w_a}{w_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$ 5-8

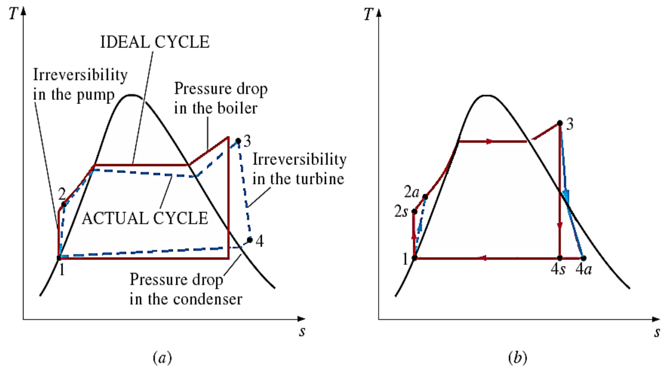


Figure 5-4: Deviation from ideal Rankine cycle.

Increasing the Efficiency of Rankine Cycle. We know that the efficiency is proportional to:

$$\eta_{th} \propto 1 - T_L / T_H \quad .$$

That is, to increase the efficiency one should increase the average temperature at which heat transferred to the working fluid in the boiler, and/or decrease the average temperature at which heat rejected from the working fluid in the condenser

5.3. Methods Can be Used to Increase Rankine Cycle Efficiency

Steam power plants are responsible for the production of most electric power in the world. Therefore, any small increase in thermal efficiency can mean large saving from the fuel requirement. The basic idea behind all is to increase the average temperature at which heat supplied to the working fluid (steam) in the boiler, or decrease the average temperature at which heat is rejected from the working fluid (steam) in the condenser. Generally, the following methods may be used to raise the ranking cycle thermal efficiency: -

5.3.1. Lowering the condenser pressure.

The effect of lowering the condenser pressure on the Rankine cycle efficiency is shown in figure (2.6). Obviously, the work output have been increased due to the lowering the condenser pressure (represented by the area 44’11’) as shown in figure. The heat input requirement also increase (represented by the area under the curve 2'-2), but this increase very small. Thus the overall effect of lowering the condenser pressure is an increase in thermal efficiency of the cycle.

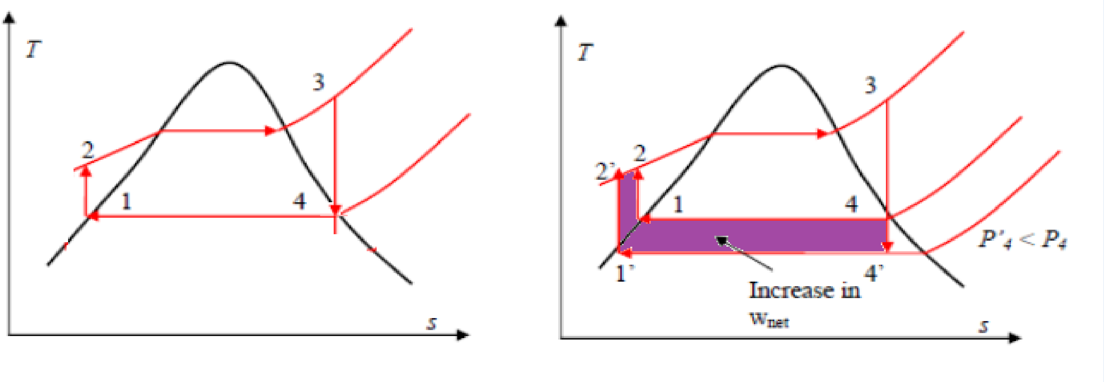


Figure 5-5-5 Effect of lowering the condenser pressure on ideal Rankine cycle

5.3.2. Superheating the Steam to High Temperature.

The average at which heat is added to the steam can be increased without increasing the boiler pressure by superheating the steam to high temperature. The effect of superheating on the performance of Rankine cycle is pictured on a T-s diagram pictured on a figure (2.6). The area 33'4'4 represents the increase in the network. The total area under the process curve 33' represent the increase in the heat input. The overall effect is an increase in thermal efficiency.

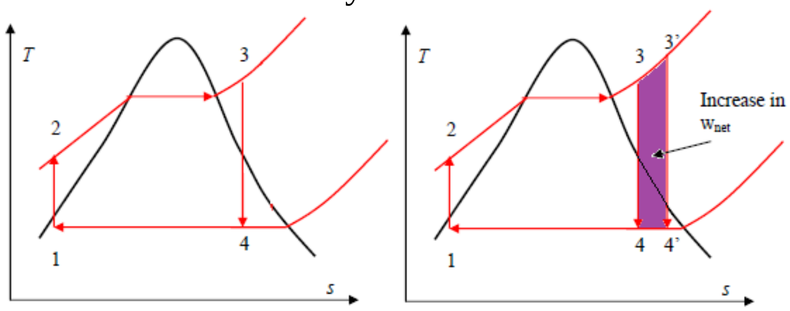


Figure 5-6 The effect of increasing the boiler pressure on the ideal Rankine cycle

5.3.3. Increasing the Boiler pressure

Another way of increasing the average temperature during heat supplied process is to increase the operating pressure of the boiler , which eventually raises the temperature at which boiling take place. The effect of increasing the boiler pressure on the performance of Rankine cycle is shown in figure (2.7). Notice that for fixed turbine inlet temperature, the cycle shifts to the left and the moisture content at the turbine exit increase. This undesirable side effect can be corrected, however, by reheating the steam. Today many modern steam power plants operate at super critical pressure (p> 22.09 MPa) and have thermal efficiencies of about 40% for fossil fuel and 34% for nuclear plant. The lower efficiencies of nuclear power plants are due to the lower maximum temperatures used in those plants for safety reasons.

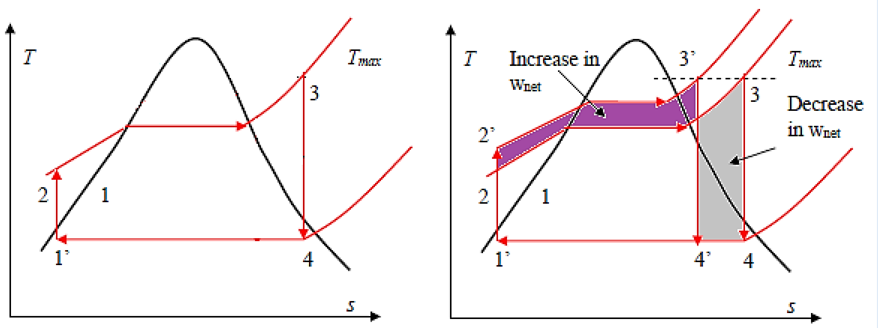


Figure 5-7 the effect of increasing the boiler pressure on the ideal cycle.

5.4. The Ideal Reheat Rankine Cycle

We noted in the last section that increasing the boiler pressure increases the thermal efficiency of the Rankine cycle, but it also increases the moisture content of the steam to unacceptable levels. Then it is natural to ask the following question:

How can we take advantage of the increased efficiencies at higher boiler pressures without facing the problem of excessive moisture at the final stages of the turbine?

Two possibilities come to mind:

a. Superheat the steam to very high temperatures before it enters the turbine. This would be the desirable solution since the average temperature at which heat is added would also increase, thus increasing the cycle efficiency. This is not a viable solution, however, since it requires raising the steam temperature to metallurgical unsafe levels.
b. Expand the steam in the turbine in two stages, and reheat it in between. In other words, modify the simple ideal Rankine cycle with a reheat process. Reheating is a practical solution to the excessive moisture problem in turbines, and it is commonly used in modern steam power plants.

The T-s diagram of the ideal reheat Rankine cycle and the schematic of the power plant operating on this cycle are shown in figure below. The ideal reheat Rankine cycle differs from the simple ideal Rankine cycle in that the expansion process takes place in two stages. In the first stage (the high- pressure turbine), steam is expanded isentropically to an intermediate pressure and sent back to the boiler where it is reheated at constant pressure, usually to the inlet temperature of the first turbine stage. Steam then expands isentropically in the second stage (low-pressure turbine) to the condenser pressure. Thus the total heat input and the total turbine work output for a reheat cycle become

$$q_{in} = q_{primery} + q_{reheat} = (h_3 - h_2) + (h_5 - h_4)$$

$$w_{turbine\ out} = w_{H-P\ turbine} + w_{L-P\ turbine} = (h_3 - h_4) + (h_5 - h_6)$$

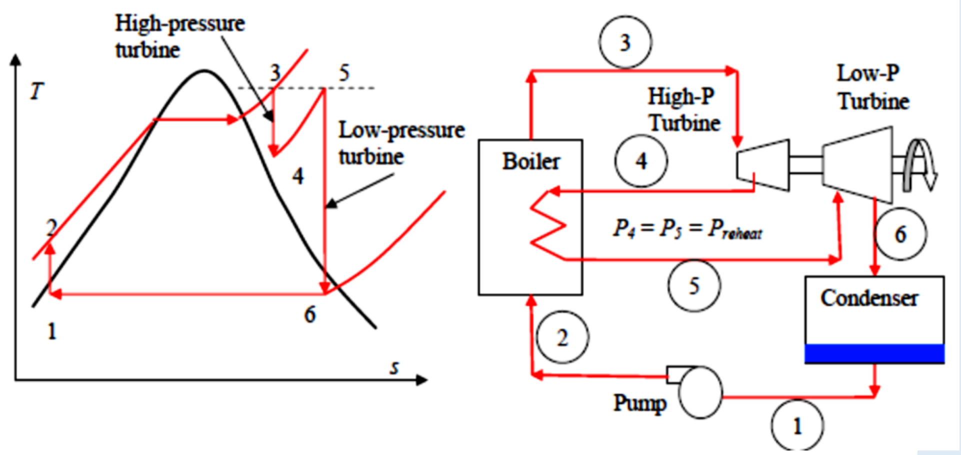


Figure 5-8 the ideal reheat Rankine cycle.

The incorporation of the single reheat in a modern power plant improves the cycle efficiency by 4 to 5 percent by increasing the average temperature at which heat is transferred to the steam.

Example 4

Consider a steam power plant operating on the ideal reheat Rankine cycle. Steam enters the high-pressure turbine at 15 MPa and 600°C and is condensed in the condenser at a pressure of 10 kPa. If the moisture content of the steam at the exit of the low-pressure turbine is not to exceed 10.4 percent, determine (a) the pressure at which the steam should be reheated and (b) the thermal efficiency of the cycle. Assume the steam is reheated to the inlet temperature of the high-pressure turbine.

	Lecture sequences:4	Forth lecture Regenerative Rankine Cycle	Instructor Name: Dr. Mohammed Saleh

Lecture Contents

1. **Introduction**
2. **Regenerative Rankine Cycle with Open Feedwater Heaters**
3. **Regenerative Rankine Cycle with close Feedwater Heaters**
4. **Supercritical Ideal Reheat Cycle**

1. Introduction

An examination of the T-s diagram of the Rankine cycle pictured in figure (2-11) reveals that heat is supplied to the working fluid (steam) during process 2-2' at a relatively low temperature. This lowers the average heat – addition temperature and thus reduce the cycle efficiency. To overcome this phenomena, we have to increase the temperature of liquid leaving the pump by what called (Feed water) before enters the boiler.

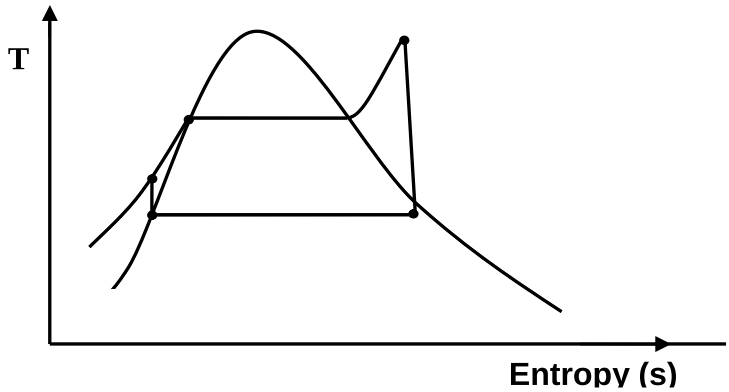


Figure 1-1 Simple Rankine Cycle

A practical regeneration process in steam power plant is accomplished by extracting, or "bleeding" steam from the turbine at various points. This steam which could have produce more work by expanding further in the turbine, is used to heat the feedwater instead. This device where the feedwater is heated by regeneration is called a regenerator, or feedwater heater. A feedwater heater is basically a heat exchanger where heat is transferred from the steam to the feedwater either by mixing the two fluid streams (open feedwater heaters) or without mixing them (closed feedwater heaters).

Regeneration not only improves cycle efficiency, but also provides a convenient means of deaerating the feedwater (removing the air that leaks in the condenser) to prevent corrosion in the boiler. It also helps control the large volume flow rate of the steam at the final stage of the turbine (due to large specific volume at low pressures). Therefore, regeneration is used in all modern steam power plants.

6. Regenerative Rankine Cycle with Open Feedwater Heaters

- Open (Direct-Contact) Feedwater Heaters

An open feedwater heater FWH is basically a mixing chamber, where the steam extracted from turbine mixes with the feedwater exiting the pump. The mixture leaves the heater as a saturated liquid at the heater pressure. The schematic of a steam power plant with one open feedwater heater and the T-S diagram of the cycle are shown in figure (2-12).

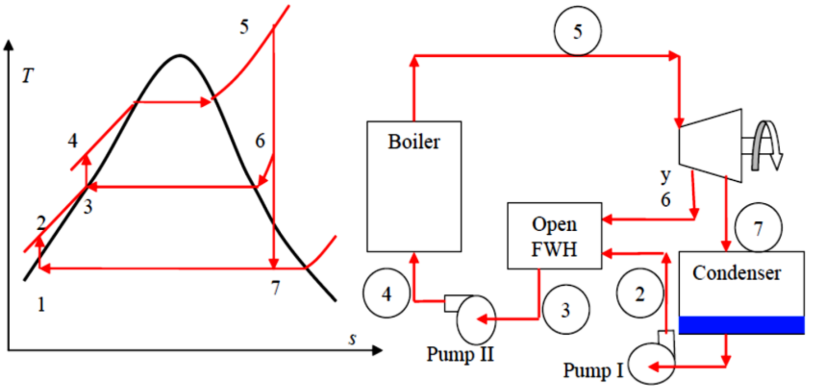


Figure 6-1The ideal regenerative Rankine cycle with an open FWH.

Using Fig. (2-12), the heat and work interactions of a regenerative Rankine cycle with one FWH can be expressed per unit mass of steam flowing through the boiler as:

$$q_{in} = h_5 - h_4$$

$$q_{out} = (1 - y) \times (h_7 - h_1)$$

$$w_{turbine,out} = (h_5 - h_6) + (1 - y) \times (h_6 - h_7)$$

$$w_{pump,in} = w_{pumpII} + (1 - y) \times w_{pump,I}$$

$$y = \frac{\dot{m}_6}{\dot{m}_5}$$

$$w_{pump,I} = v_1(p_2 - p_1) \qquad w_{pumpII} = v_3(p_4 - p_3)$$

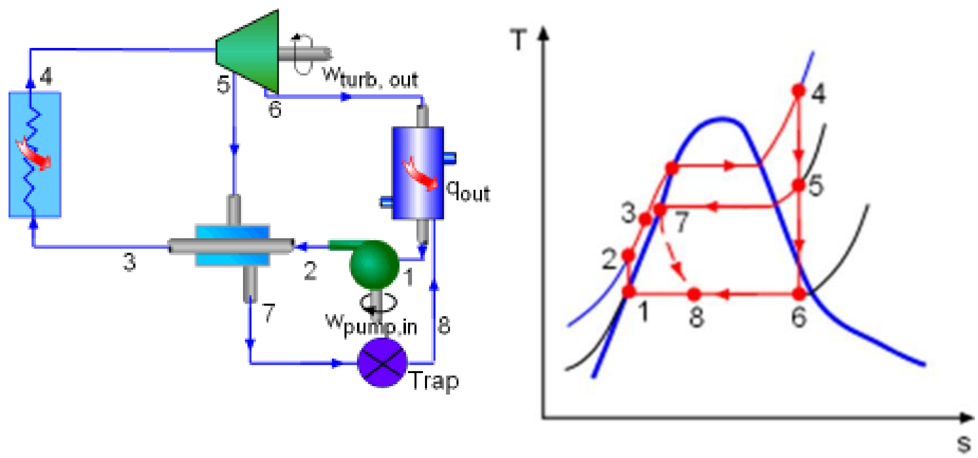
Thermal efficiency of the Rankine cycle increases as a result of regeneration since FWH raises the average temperature of the water before it enters the boiler. Many large power plants have as many as 8 FWH's.

Example (5): - A steam power plant operates on a regenerative Rankine cycle produce a power output of 300 Mw. Steam enters the turbine at 600 °C and 80 bar, and enters the condenser at 0.2 bar. Some of the steam is taken from the turbine at 20 bar to heat the feedwater in an open feedwater heater. Show the cycle on T-S diagram and determine: -

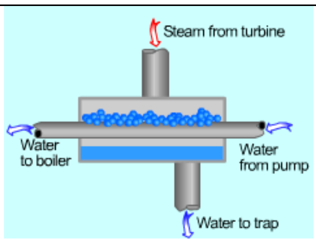
1. the mass flow rate of steam
2. the amount of heat rejected in the condenser
3. the thermal efficiency
4. the work ratio and specific steam consumption

6.1. Closed Feedwater Heaters

Closed feedwater heaters are shell-and-tube type recuperators in which feedwater temperature increases as the extracted steam condenses on the outside of the tubes carrying the feedwater. The two streams can be at different pressures since the two streams do not mix. The schematic of a steam power plant with one closed feedwater heater is shown. In an ideal regenerative Rankine cycle with a closed feedwater, steam from the boiler (state 4) expands in the turbine to an intermediate pressure (state 5). Then some of the steam is extracted at this state and sent to the feedwater heater, while the remaining steam in the turbine continues to expand to the condenser pressure (state 6).



The extracted stream (state 5) condenses in the closed feedwater while heating the feedwater from the pump. The heated feedwater (state 3) is send to the boiler and the condensate from the feedwater heater (state 7) is allowed to pass through a trap into a lower pressure heater or condenser (state 8). Another way of removing the condensate from the closed feedwater heater is pump the condensate forward to a higher-pressure point in the cycle. The T-s diagram of this cycle is shown on the left. Heat and work interactions for regenerative Rankine cycle with one closed feedwater heater is expressed per unit mass of water flowing through the boiler. They are:



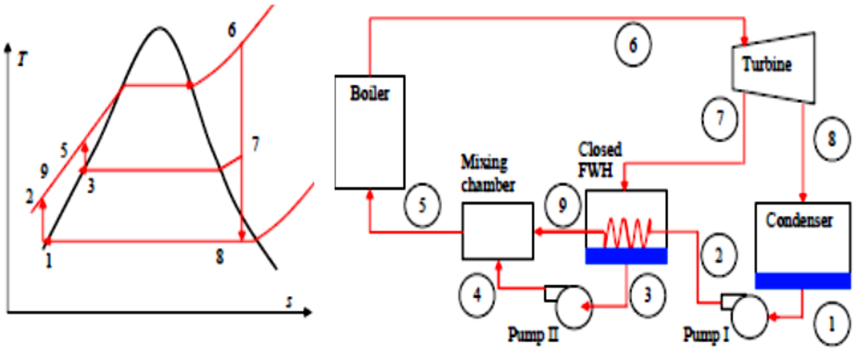


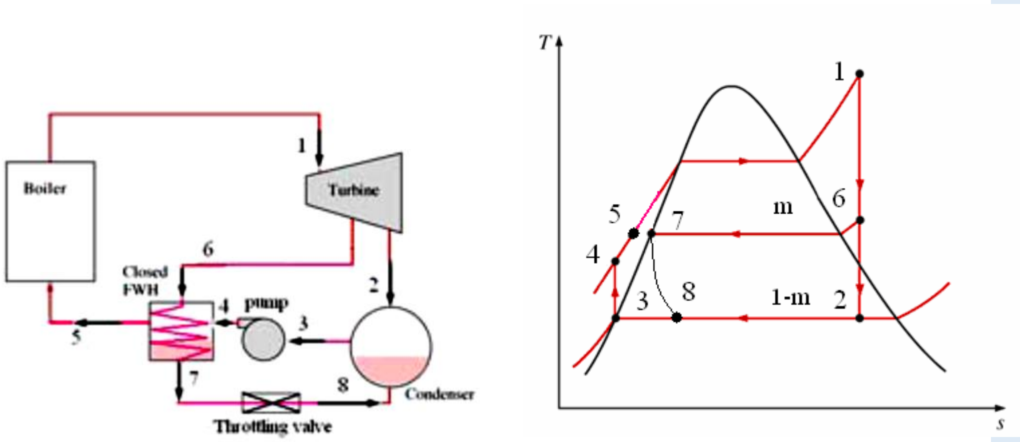
Figure 6-2 Ideal regenerative Rankine cycle with a closed FWH.

There are two type of (CFWH). They are :

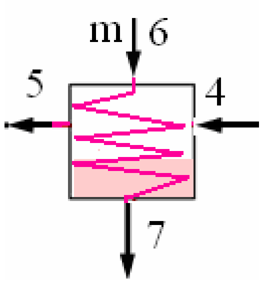
1. Cascaded backward closed feed water heater.
2. Cascaded forward ward closed feed water heater.

6.1.1. Cascaded back ward closed feed water heater:

This is the usual type used. Liquid at (p7) of high pressure is throttling to lower pressure, for example (p8).



$p_6 = p_7 = p_{bleed}$
$p_2 = p_3 = p_8$
$t_5 = t_7$
$h_7 = h_8 \approx h_5$
$h_4 = h_3 + w_{34}$



From heat balance:

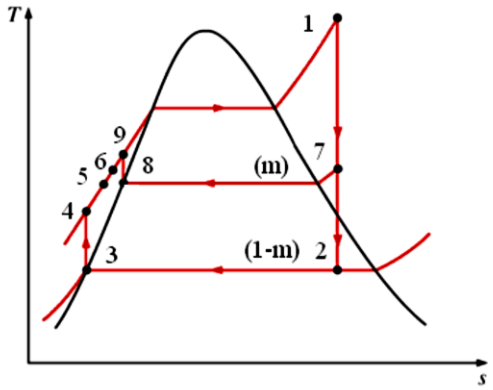
$h_5 + mh_7 = mh_6 + h$

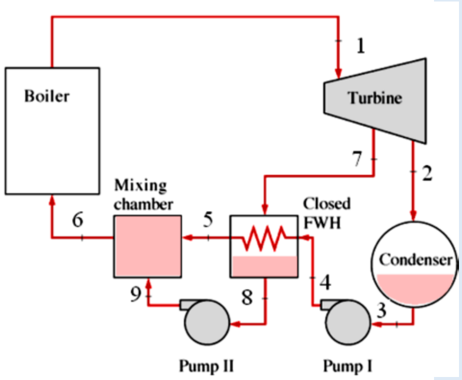
$$m = \frac{h_5 - h_4}{h_6 - h_7}$$

$w_{out} = (h_1 - h_6) + (1 - m)(h_6 - h_2)$
$w_{in} = (h_4 - h_3)$
$q_{in} = (h_1 - h_5)$
$q_{out} = (1 - m)(h_2 - h_8) + (h_8 - h_3)$

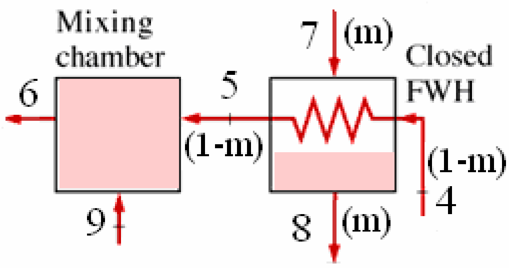
6.1.2. Cascaded forward closed feed water heater:

This type demands a mixing chamber and one extra feedwater pump.





$p_7 = p_8 = p_{bleed}$
h_7 *from* $(h - s)$ *chart*.
$h_4 = h_3 + w_{34}$



$t_5 = t_8$
$h_8 \approx h_5$
$h_9 = h_8 + w_{89}$
From heat balance:
Closed feed – water heater:
$(1 - m)h_5 + mh_8 = mh_7 + (1 - m)h_4$

$$m = \frac{h_5 - h_4}{h_7 + h_5 - h_8 - h_4}$$

Mixing camber: to evaluate (h_6):

$$h_6 = mh_9 + (1 - m)h_5$$

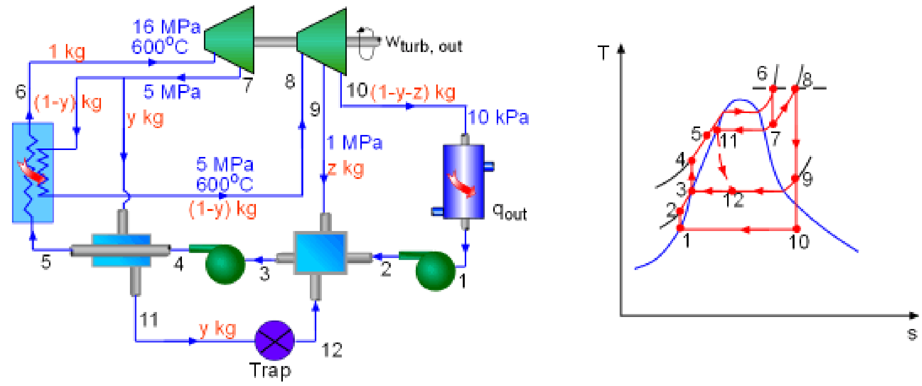
$$w_{out} = (h_1 - h_7) + (1 - m)(h_7 - h_2)$$

$$w_{in} = (1 - m)(h_4 - h_3) + m(h_9 - h_8)$$

$$q_{in} = (h_1 - h_6)$$

$$q_{out} = (1 - m)(h_2 - h_3)$$

Example 7 A steam power plant operates on an ideal reheat-regenerative Rankine cycle with one open feedwater heater, one closed feedwater heater, and one reheater. The fractions of stream extracted from turbines and the thermal efficiency of the cycle are to be determined. The schematic and the T-s diagram of the power plant are shown below Determine the fraction of steam extracted from the turbines



Schematic of the Power Plant and Its T-s Diagram

Example (6): - Repeat the solution of example 5 if a closed feedwater heater is used instead of the open feedwater heater and compare the results that you will find out?

Example (7): - A regenerative-reheat Rankine cycle produce a net power output of 100 MW. The high pressure turbine operates at 120 bar; the condenser pressure is 0.18 bar. Steam leaves the high pressure turbine at 20 bar and dry saturated. Some of the steam is extracted at this point to heat the feedwater in an open feedwater heater. The rest of the steam is reheated to temperature of 350 ºC, and thereafter expands in a low pressure turbine to the condenser pressure. Determine: -

the mass flow rate of the steam

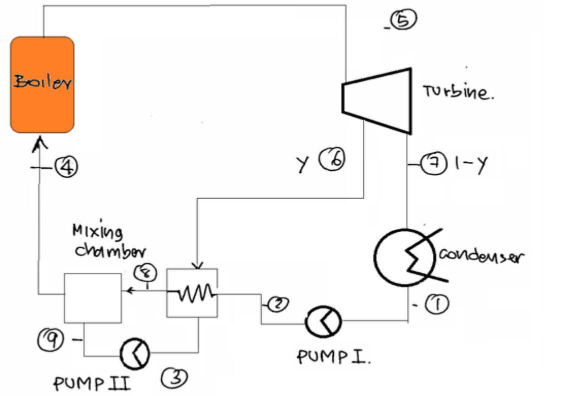
the work ratio

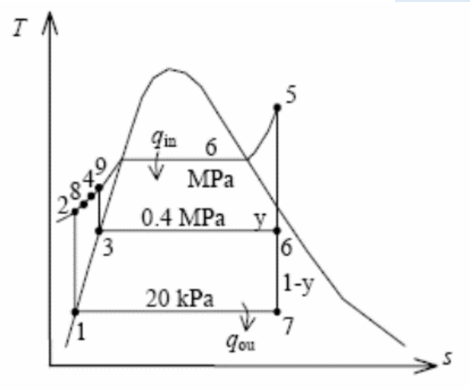
the thermal efficiency

Example (8): - A steam power plant operates on a regenerative Rankine cycle. Steam enters the turbine at 6 MPa and 450 ºC, and condensed in the condenser at 20 KPa. Steam is extracted from the turbine at 0.4 MPa to heat the feedwater in an open feedwater heater. Water leaves the feedwater heater as a saturated liquid. Show the cycle on T-S diagram and determine: -

1. the work ratio
2. the thermal efficiency

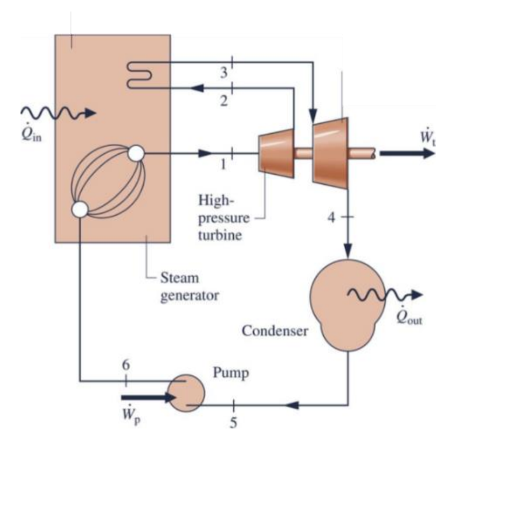
Example (9): A steam power plant operates on an ideal regenerative Rankine cycle. Steam enters the turbine at 6 MPa 450OC and is condensed in the condenser at 20 kPa. Steam is extracted from the turbine at 0.4 MPa to heat the feedwater in a closed feedwater heater. Water leaves the heater at the condensation temperature of the extracted steam and that the extracted steam leaves the heater as a saturated liquid and is pumped to the line carrying the feedwater. Determine (a) the network output per kilogram of steam flowing through the boiler and (b) the thermal efficiency of the cycle.

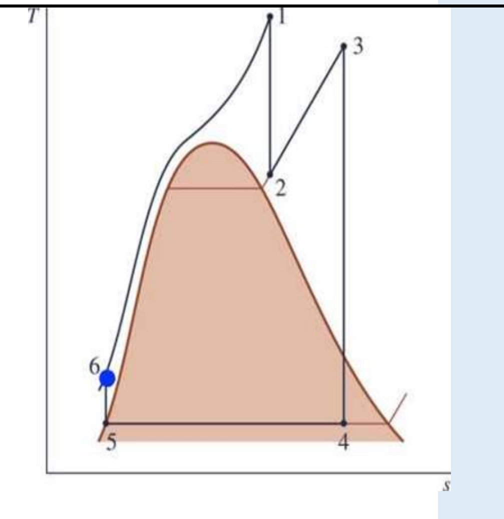




7. Supercritical Ideal Reheat Cycle

- Steady improvements over many decades in materials and fabrication methods have permitted significant increases in maximum allowed temperatures and steam generator pressures.
- These efforts are embodied in the supercritical reheat cycle.
- Supercritical Ideal Reheat Cycle
- Steam generation occurs at a pressure greater than the critical pressure of water: Process 6-1.
- No phase change occurs during process 6-1. Instead, water flowing through tubes is heated from liquid to vapor without the bubbling associated with boiling.
- Today's supercritical plants achieve thermal efficiencies up to 47%. Ultra supercritical plants capable of operating at still higher temperatures and steam generator pressures will have thermal efficiencies exceeding 50%.





Homework 1

Steam is the working fluid in a Rankine cycle. Saturated vapor enters the turbine at 8.0 MPa and saturated liquid exits the condenser at a pressure of 0.008 MPa. The net power output of the cycle is 100 MW. The turbine and the pump each have an isentropic efficiency of 85%. Determine for the cycle (a) the thermal efficiency, (b) the mass flow rate of the steam, in kg/h, (c) the mass flow rate of the condenser cooling water, in kg/h, if cooling water enters the condenser at 15 °C and exits at 35 °C.

Answers: (a) Thermal efficiency=31.4% (b) The mass flow rate of the steam= 4.449 X 105 kg/h (c) 9.39X106 kg/hr

Homework 2

A Rankine cycle operates between pressures of 80 bar and 0.1 bar. The maximum cycle temperature is 600°C. If the steam turbine and condensate pump efficiencies are 0.9 and 0.8 respectively, calculate the specific work and thermal efficiency. *Answers: Thermal efficiency= 0.368 or 36.8 %.*

Homework 3 A Rankine cycle with water superheats to 500◦C at 3 MPa in the boiler, and the condenser operates at 100◦C. All components are ideal except the turbine, which has an exit state measured to be saturated vapor at 100◦C. Find the cycle efficiency and the turbine isentropic efficiency. with (a) an ideal turbine and (b) the actual turbine. *Answers: (a)Real Efficiency=0.271 , (b) Actual Efficiency= 0.256*

Homework 4 In a Rankine cycle, steam leaves the boiler at(40 bar) and (500oC) then the steam expands through the turbine to a condenser pressure of (0.05 bar) and dryness fraction of (0.9). Neglect the pump work, draw the cycle on the (T-S) diagram and calculate:

1. The isentropic efficiency of the turbine.
2. The thermal efficiency of the cycle.
3. The specific steam consumption.

Answers (1) $\eta_{ist} = 87.8\%$ (2) $\eta_t = 87.8\%$ (3) S.S.C.=3.19 kg/(kw.hr)

	Lecture sequences:5	Fifth lecture Cogeneration	Instructor Name: Dr. Mohammed Saleh

Lecture Contents

1. **Cogeneration**
2. **Binary Vapor Cycle**

1. Cogeneration

In all the cycles discussed so far, the sole purpose was to convert a portion of the heat transferred to the working fluid to work, which is the most valuable form of energy. The remaining portion of the heat is rejected to rivers, lakes, oceans, or the atmosphere as waste heat, because its quality (or grade) is too low to be of any practical use. Wasting a large amount of heat is a price we have to pay to produce work, because electrical or mechanical work is the only form of energy on which many engineering devices (such as a fan) can operate. Many systems or devices, however, require energy input in the form of heat, called process heat. Some industries that rely heavily on process heat are chemical, pulp and paper, oil production and refining, steel making, food processing, and textile industries. Process heat in these industries is usually supplied by steam at 5 to 7 atm and 150 to 200°C (300 to 400°F).

In general cogeneration is the production of more than one useful form of energy (such as process heat and electric power) from the same energy source.

Either a steam turbine cycle or gas turbine cycle can be used as the power cycle in a cogeneration plant. The schematic of an ideal steam – turbine cogeneration shown in figure.

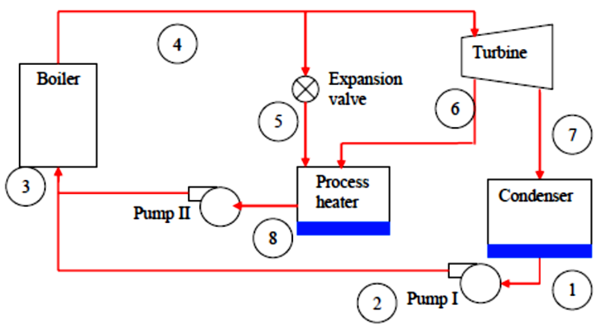


Figure 1-1 cogeneration power plant

In practical cogeneration plant and under normal operation, some steam is extracted from the turbine at some predetermined pressure P6. The rest of the steam expands to the condenser pressure P7 and then cooled at constant pressure. The heat rejected from the condenser represents the waste heat of the cycle.

The rates of heat input, heat rejected and process heat supply as well as the power produced for this cogeneration plant can be expressed as follows.

$Q_{add} = m_3 (h_4 - h_3)$

$Q_{rej} = m_7 (h_7 - h_1)$

$Q_p = m_5h_5 + m_6h_6 - m_8h_8$

$W_t = (m_4 - m_5) (h_4 - h_6) + m_7 (h_6 - h_7)$

In cogeneration plant its likely to introduce an appropriate factor to express its performance which is called as a Utilization factor εu.

Where

Q_p: is the process heat supply

W_t: is the turbine work

Q_{add}: is the heat supply in the boiler

At times of high demand for process heat, all the steam is routed to the process-heating units and non to the condenser ($m_7 = 0$), thus the waste heat is zero in this mode. If this is not sufficient, some steam leaving the boiler is throttled by an expansion or pressure-reducing valve (PRV) to the extraction pressure P_6 and is directed to the process-heating unit. Maximum process heating is realized when all steam leaving the boiler pass through the PRV ($m_5 = m_4$), and hence no power is produced in this mode. When there is no demand for process heat, all the steam passes through the turbine and then through the condenser ($m_5 = m_6 = 0$), and the cogeneration plant operate as an ordinary steam power plant.

8. Binary Vapor Cycle

Carnot cycle gives the highest thermal efficiency which is given by $\boldsymbol{\eta = 1 - \frac{T_2}{T_1}}$ To approach this cycle in an actual engine it is necessary that whole of heat must be supplied at constant temperature T1 and rejected at T2. This can be achieved only by using a vapor in the wet field but not in the superheated. The efficiency depends on temperature T1 since T2 is fixed by the natural sink to which heat is rejected. This means that T1 should be as large as possible, consistent with the vapor being saturated.

If we use steam as the working medium the temperature rise is accompanied by rise in pressure and at critical temperature of 374.15°C the pressure is as high as 225 bar which will create many difficulties in design, operation and control. It would be desirable to use some fluid other than steam which has more desirable thermodynamic properties than water. An ideal fluid for this purpose should have a very high critical temperature combined with low pressure. Mercury, diphenyl oxide and similar compounds, aluminium bromide and zinc ammonium chloride are fluids which possess the required properties in varying degrees. Mercury is the only working fluid which has been successfully used in practice. It has high critical temperature (588.4°C) and correspondingly low critical pressure (21 bar abs.). The mercury alone cannot be used as its saturation temperature at atmospheric pressure is high (357°C). Hence binary vapor power cycle two working fluids are used, one with good high temperature characteristics and another with good characteristics at the lower temperature end of the operating range. Fig. 1 shows a schematic diagram and an accompanying T-s diagram of a binary vapor cycle using water and a mercury, with each substance in both the liquid and vapor phases. In this arrangement, two ideal Rankine cycles are combined, with the heat rejection from the high-temperature cycle (the topping cycle) being used as the energy input for the low temperature cycle. This energy transfer is accomplished in an interconnecting heat exchanger, which serves as the condenser for the mercury cycle and the boiler for the water cycle. Since the increase in the specific enthalpy of the water as it passes through the heat exchanger is typically several times the magnitude of the specific enthalpy decrease of the mercury, several units of mass of mercury must circulate in the topping cycle for each unit of mass of water in the other cycle. vapor cycle is generally used to increase the overall efficiency of the plant. Two fluids (mercury and water) are used in cascade in the binary cycle for production of power.

The few more properties required for an ideal binary fluid used in high temperature limit are listed below:

1. It should have high critical temperature at reasonably low pressure.
2. It should have high heat of vaporization to keep the weight of fluid in the cycle to minimum.
3. Freezing temperature should be below room temperature.
4. It should have chemical stability through the working cycle.
5. It must be non-corrosive to the metals normally used in power plants.
6. It must have an ability to wet the metal surfaces to promote the heat transfer.
7. The vapor pressure at a desirable condensation temperature should be nearly atmospheric which will eliminate requirement of power for maintenance of vacuum in the condenser.
8. After expansion through the prime mover the vapor should be nearly saturated so that a desirable heat transfer co-efficient can be obtained which will reduce the size of the condenser required.
9. It must be available in large quantities at reasonable cost.
10. It should not be toxic and, therefore, dangerous to human life.

Although mercury does not have all the required properties, it is more favourable than any other fluid investigated. It is most stable under all operating conditions.

Although, mercury does not cause any corrosion to metals, but it is extremely dangerous to human life, therefore, elaborate precautions must be taken to prevent the escape of vapor. The major disadvantage associated with mercury is that it does not wet surface of the metal and forms a serious resistance to heat flow.

This difficulty can be considerably reduced by adding magnesium and titanium (2 parts in 100000 parts) in mercury.

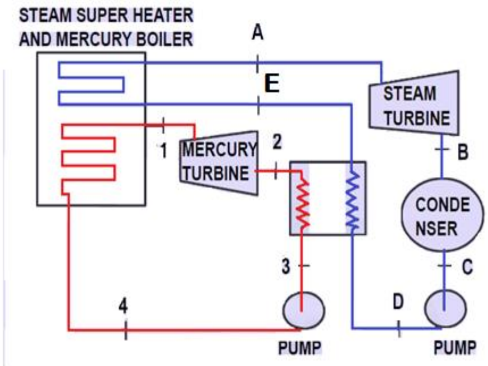
8.1. Thermal properties of mercury:

Mercury fulfils practically all the desirable thermodynamic properties stated above.

1. Its freezing point is – 3.3°C and boiling point is – 354.4°C at atmospheric pressure.
2. The pressure required when the temperature of vapor is 540°C is only 12.5 bar (app.) and, therefore, heavy construction is not required to get high initial temperature.
3. Its liquid saturation curve is very steep, approaching the isentropic of the Carnot cycle.
4. It has no corrosive or erosive effects upon metals commonly used in practice.
5. Its critical temperature is so far removed from any possible upper temperature limit with existing metals as to cause no trouble

Some undesirable properties of mercury are listed below:

1. Since the latent heat of mercury is quite low over a wide range of desirable condensation temperatures, therefore, several kg of mercury must be circulated per kg of water evaporated in binary cycle.
2. The cost is a considerable item as the quantity required is 8 to 10 times the quantity of water circulated in binary system.
3. Mercury vapor in larger quantities is poisonous, therefore, the system must be perfect and tight. Fig. 1 shows the schematic line diagram of binary vapor cycle using mercury and water as working fluids. The processes are represented on T-s diagram as shown in Fig.



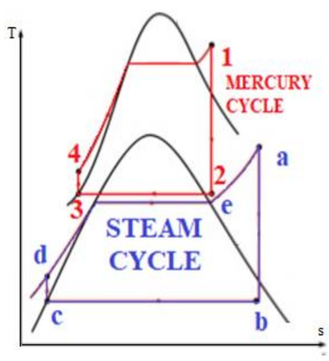


Figure8-1 Binary vapor cycle

Let m_m represent the flow rate of mercury in the mercury cycle per m_s of steam circulating in the steam cycle. Then,

$$Q_{in} = \dot{m}_m(h_1 - h_4) + \dot{m}_s(h_a - h_e)$$
$$Q_{out} = \dot{m}_s(h_b - h_c)$$
$$W_t = \dot{m}_m(h_1 - h_2) + \dot{m}_s(h_a - h_b)$$
$$W_p = \dot{m}_m(h_4 - h_3) + \dot{m}_s(h_d - h_c)$$

The cycle efficiency

$$\eta_{cycle} = \frac{Q_{in} - Q_{out}}{Q_{in}} = \frac{W_t - W_p}{Q_{in}}$$

And, the steam rate $= \frac{3600}{W_t - W_p} \quad (kg/kWh)$

The energy balance of mercury condenser steam boiler gives

$$\dot{m}_m(h_2 - h_3) = \dot{m}_s(h_e - h_d)$$
$$\frac{\dot{m}_m}{\dot{m}_s} = \frac{(h_e - h_d)}{(h_2 - h_3)} \qquad kgHg/kgH_2O$$

Example A binary vapor cycle operates on mercury and steam. Standard mercury vapor at 4.5 bar is supplied to the mercury turbine, from which it exhausts at 0.04 bar. The mercury condenser generates saturated steam at 15 bar which is expanded in a steam turbine to 0.04 bar.

Determine the overall efficiency of the cycle.

If 48000 kg/h of steam flows through the steam turbine, what is the flow through the mercury turbine?

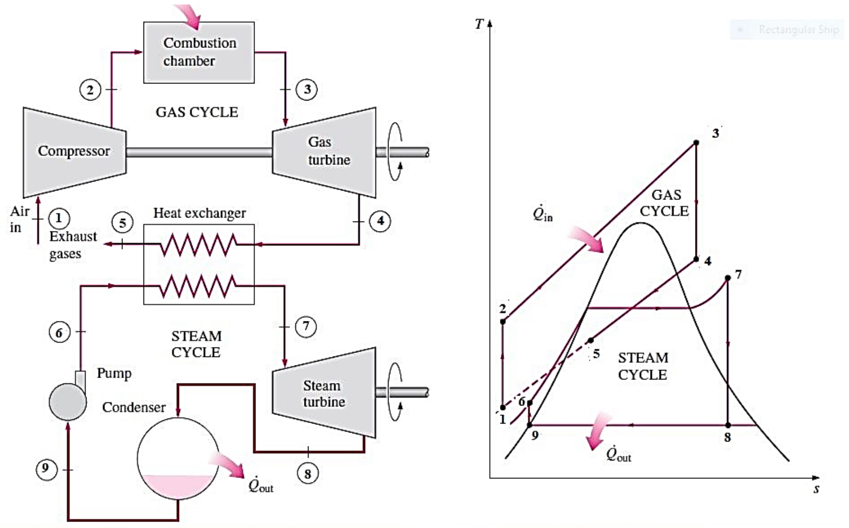
Assuming that all processes are reversible, what is the useful work done in the binary vapor cycle for the specified steam flow?

p (bar)	t (°C)	Hf (kJ/kg)	Hg (kJ/kg)	Sf (kJ/kg K)	Sg (kJ/kg K)	vf (m3/kg)	vg (m3/kg)
4.5	450	62.93	355.98	0.1352	0.5397	79.9×10^{-6}	0.068
0.04	216.9	29.98	329.85	0.0808	0.6925	76.5×10^{-6}	5.178.

Lecture Contents	Lecture sequences:6	Sixth lecture Combined Cycle Gas Turbine	Instructor Name: Dr. Mohammed Saleh
	1. Combined Cycle Gas Turbine 2. Mathematical Treatment of Bryton Cycle 3. Example 4. Problems		

1. Combined cycle gas turbine

The combined cycle has the gas turbine's high average temperature of heat addition and the vapor cycle's low average temperature of heat rejection, and thus a thermal efficiency greater than either cycle would have individually. For many applications combined cycles are economical, and they are increasingly being used worldwide for electric power generation.



With reference to Fig.2 the thermal efficiency of the combined cycle is.

Figure 1-1 A simplified diagram for a combined-cycle plant

$$\eta = \frac{w_{gas}+w_{vap}}{Q_{in}} \quad \dots 8$$

where gas $\boldsymbol{w_{gas}}$ is the net power developed by the gas turbine and $\boldsymbol{w_{vap}}$is the net power developed by the vapor cycle.

The relation for the energy transferred from the gas cycle to the vapor cycle for the system of Fig. 2 is obtained by applying the mass and energy rate balances to a control volume enclosing the heat exchanger. For steady-state operation, negligible heat transfers with the surroundings, and no significant changes in kinetic and potential energy, the result is

$$m_v(h_7 - h_6) = m_g(h_4 - h_5) \quad \dots 9$$

Where $\boldsymbol{m_v}$ and $\boldsymbol{m_g}$, are the mass flow rates of the gas and vapor, respectively.

By relations Eq. 8 and Eq.9, combined cycle performance can be analyzed using mass and energy balances.

To complete the analysis, however, the second law is required to assess the impact of irreversibilities and the true magnitudes of losses. Among the irreversibilities,

9. Mathematical treatment of Brayton cycle

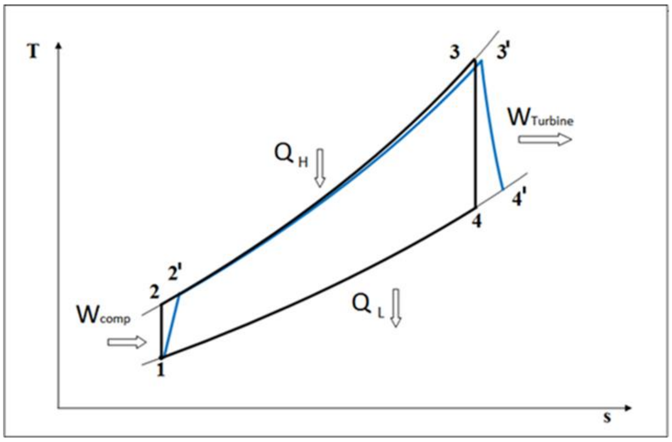


Figure 6 4 Combined gas–steam power plant

Procedure for solving gas side properties

$Data\ \ T_1, p_1, p_2,\ \ T_3\quad or\quad r = \frac{p_2}{p_1}$

$T_1\ \ table\ \ p_{r1}$

$\frac{p_2}{p_1} = \frac{p_{r2}}{p_{r1}} \Longrightarrow p_{r2}\quad from\ table\ \ find\ T_2, h_2$

$T_3\ \ table\ \ p_{r3}$

$\frac{p_3}{p_4} = \frac{p_{r3}}{p_{r4}} \Longrightarrow p_{r4}\quad from\ table\ \ find\ T_4, h_4$

$to\ \ find\ T_2{}^{\iota}\ and\ T_4{}^{\iota}\qquad from\ compressor\ and\ turbine\ efficiency$

Example

A combined gas turbine-vapor power plant has a net power output of 10MW. Air enters the compressor of the gas turbine at 100kPa, 300K, and is compressed to 1200 kPa. The isentropic efficiency of the compressor is 84%. The conditions at the inlet to the turbine are 1200 kPa and 1400 K.

Air expands through the turbine, which has an isentropic efficiency of 88%, to the pressure of 100 kPa. The air then passes through the interconnecting heat exchanger, and is finally discharged at 480 K. Steam enters the turbine of the vapor power cycle at 8 MPa, 400 o C, and expands to the condenser pressure of 8 kPa. Water enters the pump as saturated liquid at 8 kPa. The turbine and pump have isentropic efficiencies of 90 and 80%, respectively.

Determine

(a) the mass flow rates of air and steam, each in kg/s

(b) the thermal efficiency of the combined cycle

PROBLEMS

Problem 1 Consider an ideal Rankine cycle using water with a high-pressure side of the cycle at a supercritical pressure. Calculate the thermal

	efficiency of the cycle if the state entering the turbine is 25 MPa, 500°C, and the condenser pressure is 5 kPa. What is the steam quality at the turbine exit? Answer: $x4 = 0.6924$ $\eta=0.44$ Problem 2 Calculate the ideal efficiency of a binary vapor cycle. The steam cycle operates between pressure of 30 and 0.04 bar, uses a superheat temperature of 450 °C. The mercury cycle works between pressures of 14 and 0.1 bar, the mercury entering turbine in a dry saturated condition. **Answer η=0.518** Problem 3 A steam power plant operates on ideal Rankine cycle using reheater and regenerative feed water heaters. It has **one open feed** heater. Steam is supplied at 150 bar and 600°C. The condenser pressure is 0.1 bar. Some steam is extracted from the turbine at 40 bar for closed feed water heater and remaining steam is reheated at 40 bar to 600°C. Extracted steam is completely condensed in this closed feed water heater and is pumped to 150 bar before mixing with the feed water heater. Steam for the open feed water heater is bled from L.P. turbine at 5 bar. Determine: Fraction of steam extracted from the turbines at each bled heater, and Thermal efficiency of the system. Draw the line diagram of the components and represent the cycle on T-s diagram. **Answer** (i) ya=0.223 yb=0.122 (ii) η=0.472

Lecture sequences:7	Seventh lecture Boiler	Instructor Name: Dr. Mohammed Saleh

Lecture Contents

Introduction
Definition and classification
Boiler classifications
Factors Considered In Selecting Boiler

The detailed contents:

1. Introduction

The world energy consumption has doubled in the last thirty years and it keeps on increasing with about 1,5 % per year. While the earth's oil and gas reserves are expected to deplete after roughly one hundred years, the coal reserves will last for almost five hundred years into the future. But there are more reasons to why electricity generation based on steam power plant will continue to grow and why there still will be a demand for steam boilers in the future:

•The cost of the produced electricity is low

•The technology has been used for many decades and is reliable and available

•Wind and solar power are still expensive compared to steam power

•The environmental impact of coal powered steam plants have under the past decade been heavily diminished thanks to improved $\mathbf{SO_x}$ and $\mathbf{NO_x}$ reduction technology

2. Definition and classification

In a traditional context, a boiler is an enclosed container that provides a means for heat from combustion to be transferred into the working media (usually water) until it becomes heated or a gas (steam). One could simply say that a boiler is as a heat exchanger between fire and water. The boiler is the part of a steam power plant process that produces the steam and thus provides the heat. The steam or hot water under pressure can then be used for transferring the heat to a process that consumes the heat in the steam and turns it into work. A steam boiler fulfils the following statements:

- It is part of a type of heat engine or process
- Heat is generated through combustion (burning)
- It has a working fluid, a.k.a. heat carrier that transfers the generated heat away from the boiler
- The heating media and working fluid are separated by walls

In an industrial/technical context, the concept "steam boiler" (also referred to as "steam generator") includes the whole complex system for producing steam for use e. g. in a turbine or in industrial process. It includes all the different phases of heat transfer from flames to water/steam mixture (economizer, boiler, superheater, reheater and air preheater). It also includes different auxiliary systems (e. g. fuel feeding, water treatment, flue gas channels including stack) .

The heat is generated in the furnace part of the boiler, where fuel is combusted. The fuel used in a boiler contains either chemically bonded energy (like coal, waste and biofuels) or nuclear energy. A boiler must be designed to absorb the maximum amount of heat released in the process of combustion. This heat is transferred to the boiler water through radiation, conduction and convection. The relative percentage of each is dependent upon the type of boiler, the designed heat transfer surface and the fuels that power the combustion.

3. Boiler classifications

Boilers are classified in too many ways like.

3.1. According to type of fuel used:

Coal fired boilers, oil fired boilers, gas fired boilers, biomass boilers, electric boilers and waste heat recovery boilers.

3.2. According to steam Pressure: -

3.2.1. Low pressure boilers

3.2.2. Medium pressure boilers and high-pressure boilers.

3.2.3. High pressure boiler

a *have been widely used in modern steam power plants due to the following reasons: Increased thermal efficiency (40-42%0 of the plant due to higher enthalpy of steam output, which result more work output from the expansion turbine.*

b *Quick start-up from cold is possible if power from external source is available.*

c *Chance of scale formation on tube walls are very low due to high velocity of feedwater.*

d *Danger of overheating and thermal shock is minimized due to all parts being uniformly heated because of forced circulation adoption.*

3.3. According to use of boiler

Stationary and portable boilers, there are some boilers that are not stationary like Locomotive Boilers and marine boilers.

3.4. According to the furnace position

Externally fired boilers and internally fired boilers.

3.5. According to the axis of shell

Vertical and horizontal boilers.

3.6. According to the number of tubes in boilers

Single tube and *multi tube boilers*. Single tube boilers like Cornish boiler and simple vertical boiler

3.7. According to use of steam

Utility steam generator, Industrial Steam Generator (process boiler), and marine boilers.

3.7.1. Utility Steam Generator:

Utility Steam Generator: are those used by utilities for electric –power generating plants and which are our main concern. Modern utility steam generator are essentially of two basic kinds: -

- the subcritical water tube drum type (130-180 bar)
- the supercritical once-through type (240 bar)

The majority of utility steam generators purchased in the 1970's and 1980's are those of 180 bar which produce superheated steam at about 540 ºC with one or two stage reheat as shown in figure (1). They have the ability to burn coal in pulverized form or oil.

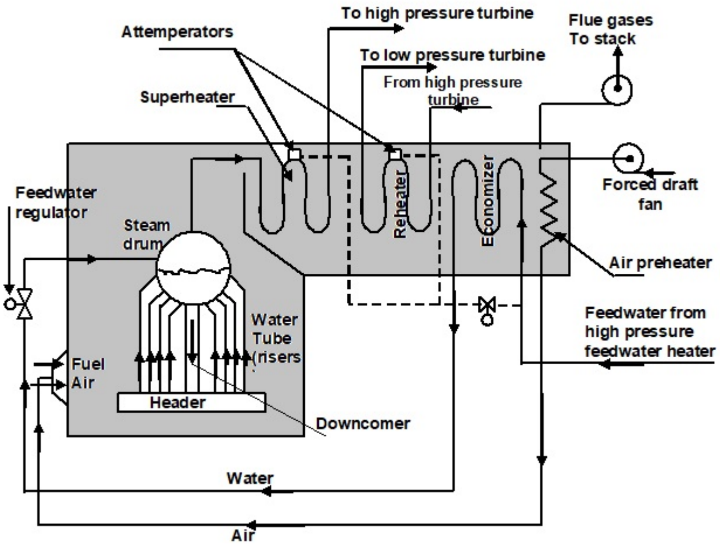


Figure (1) :- Schematic flow diagram of a modem steam generator

3.7.2. Industrial Steam Generator

Industrial Steam Generator are those used by industrial and institutional concern which are of many types. They may be water-tube of fire-tube. Industrial steam generator usually do not produce superheated steam, they operate at pressures ranging from few bars to as much as 105 bar, and steam capacities ranging from several kg/s to 125 kg/s.

3.8. According to circulation of water and steam in boilers

Natural circulation and forced circulation boilers natural circulation limit is 140 Kg/cm2 above this pressure forced circulation is adopted.

The circulation of the working fluid may be defined as the motion of the working fluid in the evaporating tubes. This motion is effected by head or pressure differences in the working fluid between the down comer and uptake (riser) tubes. The circulation may be natural or forced circulation.

3.8.1. Natural circulation

Natural circulation as shown in figure (2a), the working fluid circulates by virtue of its density differences.

3.8.2. Forced circulation

Forced circulation as shown in figure (2b), the working fluid is forced through the boiler circuit by an external pump.

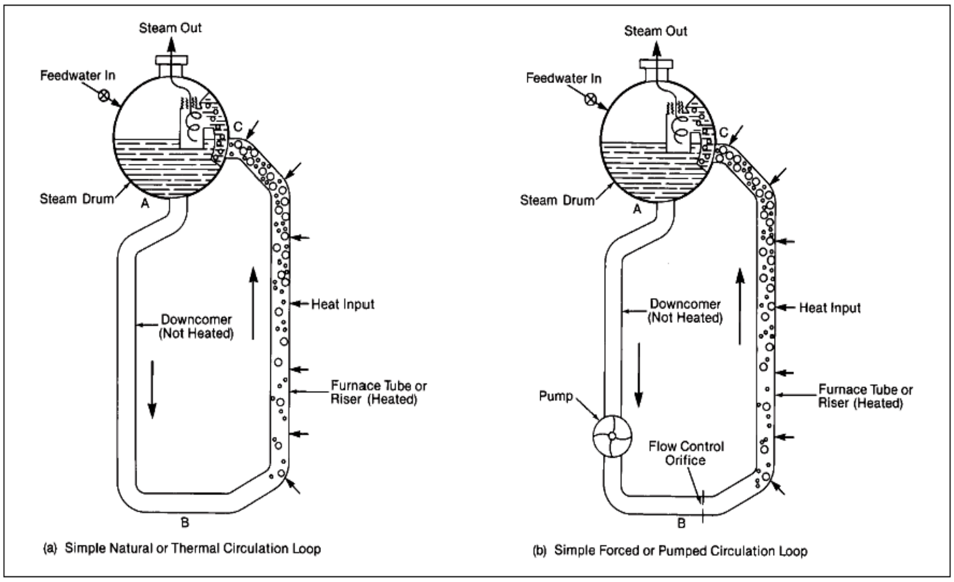


Figure 2

Circulation Ratio (C_R); - may be defined as the ratio of mass flow rate of circulating water m_w (t/h) to the rate of steam generation m_s (t/h).

$$C_r = \frac{m_w}{m_s}$$

For natural circulation C_r = 4 to 30

For forced circulation C_r = 3 to 10

The Advantages of Forced Circulation over Natural Circulation

a) steam generating rate is higher
b) Greater capacity to meet load variation
c) Quicker start-up quality from cold
d) Lower scaling problem due to high circulation velocity
e) Uniform heating to all parts which reduces the danger of overheating and thermal stresses
f) Small tube diameter and hence lighter tubes

3.9. According to tubing methods

Depending on whether the flue gas or water inside the tube, boiler can be classified as follows: -

3.9.1. Fire tube boiler

Fire tube boiler (Locomotive boiler, Cochran boiler): - fire-tube boiler have been used in various early to produce steam for industrial purpose since the late of eighteen centuries. They have no longer used in large utility power plants. Fire-tube boilers are still used in industrial plants to produce steam at upper limit of 18 bar and 6.3 kg/s. In fire-tube boiler, hot gases, instead of steam were made to pass through the tubes. Because of improved heat transfer the fire-tube boiler is become more efficient and could reach efficiency of about 70%.

3.9.2. Water tube boiler

Water tube boiler (La Mont boiler, yarrow boiler):- the modern steam generator was a water-tube boiler developed by George Babcock and Stephen Wilcox 1867, with higher steam capacities. Fire-tube boiler would need large diameter shell, with such large diameters, the shell would have to operate under such extreme pressure and temperature stresses that their thickness would have been too large. In addition, they were subjected to scale deposits and boiler explosions and become intolerably. The water-tube boiler puts the pressure instead in tubes and relatively small diameter drum that are capable of withstanding the extreme pressure of the modern steam generator. watertube boilers may be straight tube or bent tube boiler, however, bent tube boiler lend greater economy in fabrication and operation than straight tube boiler, but bent tube boiler affords greater accessibility for inspection, cleaning and maintenance due to spacious lay-out of tubes. Also have a higher steam generation rate than straight tube boiler and finally could produce drier steam than straight tube boilers.

4. Factors Considered In Selecting Boiler

a) Power required to be generated (steam quantity)
b) Operating pressure and temperature
c) Fuel-quality and type
d) Water availability and its quality
e) Probable load factor
f) Cost of operation and maintenance
g) Cost of installation

Lecture Contents	**Lecture sequences:8**	**Eight lecture Some Common Boilers**	**Instructor Name: Dr. Mohammed Saleh**

1. Benson boiler
2. La Mont boiler
3. Boiler Main Parts

1. Benson Boiler

Benson Boiler is a high pressure, drum less, supercritical, water tube steam boiler with forced circulation. This boiler was invented in the year 1922 by Mark Benson. This boiler is a super critical boiler in which the feed water is compressed to a supercritical pressure and this prevents the formation of bubbles in the water tube surface. The bubbles do not form because at supercritical pressure the density of water and steam becomes same. It was Mark Benson who first proposed the idea to compress the water at supercritical pressure before heating into boiler and due to this the latent heat of water reduces to zero. As the latent heat of water reduces to zero the water directly changes into steam without the formation of bubbles.

Operating parameters: above 350 ºC, above 221 bar, is also called the forced-circulation or universal –pressure boiler because it is applicable to all temperature and pressures, although economically it suited to large sizes and pressures in the high subcritical and supercritical range. shown in figure (4).

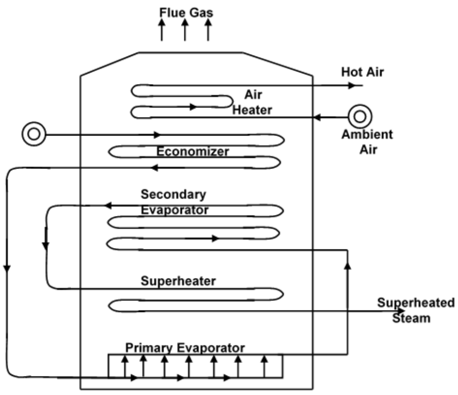


Figure (4):- Benson Boiler- A Schematic Representation

1.1.1. Air circuit

Air circuit: cold air blown by the blower is heated up in air preheater by hot flue gas by indirect contact heat transfer. The resulting is directed to the combustion chamber to be used as combustion air.

1.1.2. Water-steam circuit

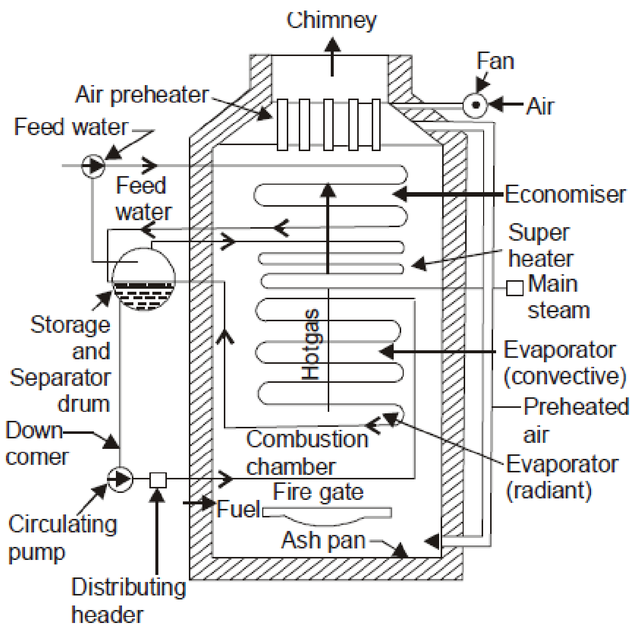
Water-steam circuit: Forced circulation is introduced to generate superheating steam in this open hydraulic system. A high pressure feed pump feeds BFW radiant evaporator, convective evaporator and superheater, thus converting feedwater into superheated steam in a once-through (no steam drum) cycle. Because of the once-through mode of operation, very high purity feedwater is a requirement.

i. Advantages of a Benson boiler

a) there is no boiler drum, which means a reduction in overall weight of the boiler and a cut in capital investment.
b) Better and more efficient protection of furnace walls as high pressure tubes have smaller diameters and are closely spaced.
c) Economic operation at partial load or over load is possible
d) Needs comparatively less floor-space than other boiler of the same capacity.
e) Minimum explosion hazard as tubes are of small diameter with very little storage capacity.

2. La Mont Boiler

Lamont boiler is a high pressure, forced circulation, water tube boiler with internally fired furnace. An external pump is used to circulate the water within small diameter water tubes of the boiler. This boiler was invented by Walter Douglas La-Mont in the year 1925. At that time this boiler was invented to use in ships. La-Mont boiler is consisting of three circuit as shown in figure (5). The boiler is adaptable for all pressures from subcritical to supercritical, capacity exceeding 50 t/h



2.1.1. Air circuit

Air circuit:- cold air is blown by a blower through the air preheater where it gets heated up in the process of heat exchanger with flue gases. Hot air is then directed to the combustion chamber to be used as combustion air.

2.1.2. Water circuit

Water circuit:- Deaerated BFW is pumped is pumped through the economizer by BFW pump and fed to the steam separating drum from which is forced through the tubes of radiant evaporator by a circulating pump. Together with steam it returns to steam drum to complete the cycle.

2.1.3. Steam circuit

Steam circuit:- the steam separated in the steam drum is saturated steam. It is superheated in the superheater coil and fed the expansion turbine to generate power to drive compressors.

3. Boiler main parts

3.1. The Steam Drum

Steam drum is a collector and separator equipment for water and steam from water wall tubes. The steam drum is provided in all modern steam generator; the most important steam drum function is separating the steam from the boiling water. According to separation concept of water and steam in steam drum, separation process can be classified in three types such as natural gravity driven separation, baffle assisted primary separation and mechanical primary separation.

3.1.1. Natural Gravity Driven Separation

In the process of natural separation, mixture of water and steam is separated due to differences in density. Steam has less density than water so steam will go to the top of drum and water will fall to bottom of drum. This separation process depends on the location out of steam and water, the speed and position of the incoming steam, the quality of steam and so on. But the natural separation process has some disadvantages such as Figure 1 below:

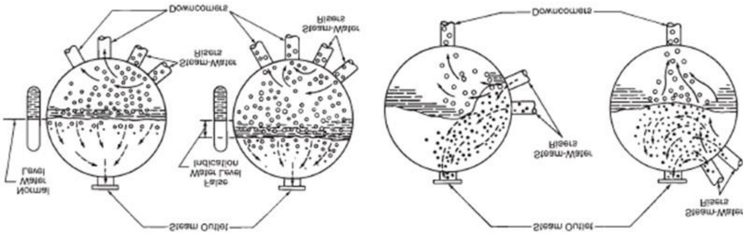


Figure 1: Natural Gravity Driven Separation in Steam Drum

In the figure shown, if the steam entered through the bottom of drum, the steam will mix with boiler water so reduce temperature of steam and increase temperature of water which will be distributed to downcomer pipe or convection wall tubes. If velocity of steam is low, steam will not be able to pass water and its quality will be reduced while if the velocity of steam is too high, some steams will go to downcomer pipe so the water level in steam drum will rise, thus disturbing the accuracy of water level gauges on drum.

If steam is entered to the centre of drum, the water level in steam drum will be uneven and some steams will enter to downcomer pipe. If the steam is entered from the top of drum, steam will affect to water level in steam drum.

3.1.2. Baffle Assisted Separation

In this separation process, a mixture of steam and water coming out of the water wall tubes will be separated by baffle with redirecting the flow into baffle, so water separate from steam and the flow of steam will be directed so it does not mix with water in the steam drum as shown in Figure 2 below.

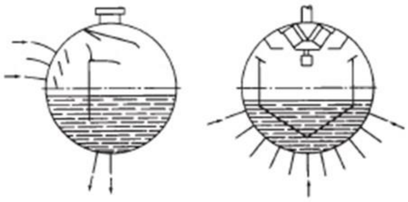


Figure 2: Baffle Assisted Separation in Steam Drum

3.1.3. Mechanical Primary Separation

The working principal of mechanical primary separation is use separation process due to centrifugal force and radial force by passing the mixture of steam and water in cyclone shaped equipment. Steam will be separated from water because centrifugal force and radial force occur when the mixture flow this cyclone. The figure below is sample of cyclone equipment such as conical cyclone, curved arm cyclone and horizontal cyclone .

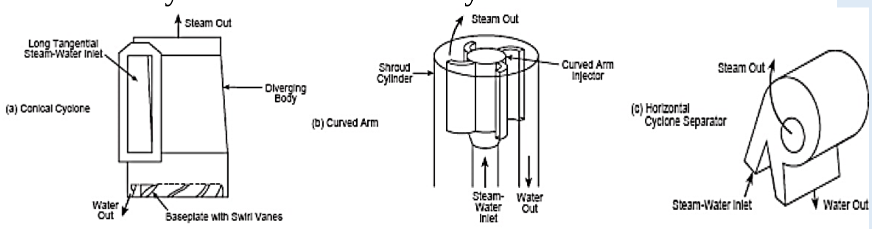
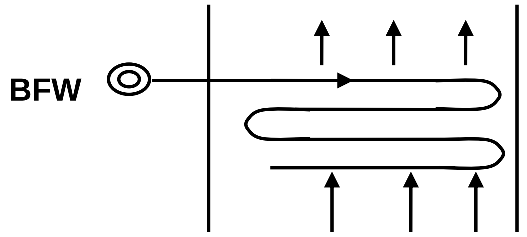


Figure 3: Type of Cyclone in Steam Drum.

3.2. ECONOMIZER

The economizer is a heat exchanger that raises the temperature of water leaving the highest-pressure feedwater to the saturation temperature corresponding to the boiler pressure. This done by hot gases leaving the last superheater or reheater, these gases at high enough temperatures to transfer heat to superheater, reheater, enters the economizer at 700 to 1000 ºF. part of their energy is used to heat the feedwater. The term " economizer" historically was used because the discharge of such high temperature gases would have caused a large loss in availability and efficiency and hence loss in economy operation.

Boiler feedwater is preheated in the economizer by indirect heat exchange with flue gas in cross or counter flow with boiler feedwater. However, boiler feedwater is not allowed to enter the economizer below a minimum temperature, for, this may cause a sharp drop in temperature of flue gases. If the flue gas temperature drops to its dew point temperature, it will give rise to condensation of sulphuric acid H_2SO_3 resulting from the reaction of oxides of Sulphur with water vapor due fuel burning (SO_3 or SO_2 + H_2O).



Earlier economizer tubes of low pressure turbine were made from cast iron with bare tube which show resistance to acid corrosion. Recently finned economizer tubes are used for efficient heat transfer. Economizers tubes are commonly 1.75 to 2.75 in outer diameter (OD) and made in vertical sections of continuous tubes, between the inlet to outlet headers. Economizer are generally placed between the superheater and air preheater

3.3. SUPERHEATER AND REHEATER

The purpose of a superheater is to produce superheated steam by first bringing the wet steam to saturation point and then raising the temperature to the degree of superheat according to the design.

Obviously the temperature of the superheated steam leaving the superheater is restricted by the operating pressure and temperature of the steam turbine in the plant. However , the greater the degree of superheat, the greater is the enthalpy drop available from superheated steam with out being wet, thereby increasing the life and efficiency of the turbo alternator.

Superheater and reheater in utility steam generators are made of tubes of 2 to 3 in OD. The smaller diameters have lower pressure stresses and withstand them better. The larger diameters have lower steam flow pressure drops and easier to align. Finning on the outside surface on the outside surface of the tubes is avoided because it increase thermal stresses and make cleaning is difficult. Modern superheater and reheater operating at about 1000 ºF are usually made of special high-strength alloy steels chosen for strength and corrosion resistance.

3.3.1. Convection Superheater

early superheater designs placed above or behind bank of water tubes to protect them from combustion flames and high temperature. The main mode of heat transfer between the combustion gases and superheater tubes, therefore, was convection and that type of superheater become known as the convection superheater.

3.3.2. Radiant Superheater

Because the need for greater heat absorption, superheater were made eventually placed nearer high temperature in view of the combustion flames. Steam flow velocities were increased to increase the overall heat transfer coefficients, and overall superheater designs were improved to overcome expected high material temperatures. This placement of superheater results in the main heat transfer between the hot gases and flame, and the tube outer walls, to accomplished by radiation. This design has come to be known as a radiant superheater. Convection superheater alone are used with low-temperature steam generators. Radiant and convection superheater and reheater are used for high temperature service. Different type of superheater are available according to its mechanical construction as shown in figure

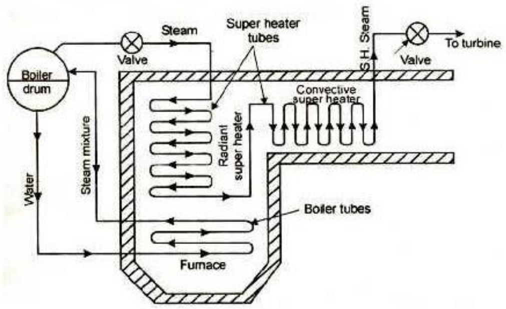


Fig Super heater (radiant and convective)

3.4. AIR PREHEATER

Like economizer, air preheater (or air heaters) utilize some of the energy left in the flue gases before exhausting them to atmosphere. They receive 600 to 800 ºF hot gases, these gases are cooled to 275 to 350 ºF to avoid gas condensation and corrosion problem to allow for proper dispersion in atmosphere.

The air is heated from forced-draft outlet temperature, at far from atmosphere to 500 to 650 ºF and sometimes higher. Preheating air saves fuel that would other wise be used for that heating. The fuel saving (an hence increase in plant efficiency) are nearly directly proportional to the air temperature rise in the preheater.

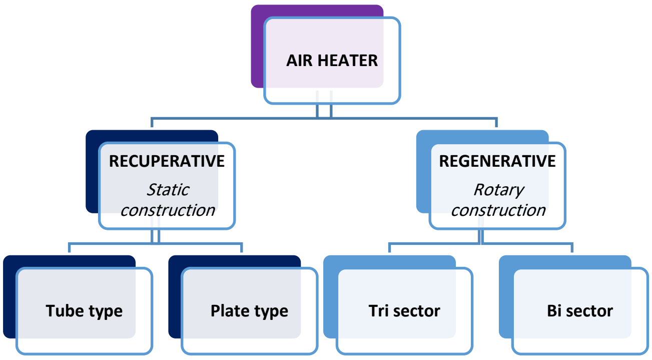
Typical fuel savings are 4% for 200 ºF air temperature rise and about 11% for a 500 ºF air temperature rise in the preheater. In addition to fuel saving, preheated air is a requirement for the operation of pulverized-coal furnace. Air in the 300 to 600 °F range is needed for drying that fuel. There are two general types of air preheater:- Recuperative and regenerative.

3.4.1. Recuperative type

In recuperative type, heating medium flue gas is on one side, air is on the other side of tube or plate, and the heat transfer is by conduction through the material, which separates the media. These are of static construction and hence there is only nominal leakage through expansion.

3.4.2. Regenerative type

In regenerative type, the heating medium flows through a closely packed matrix to raise its temperature and then air passed through the matrix to pick-up the heat. Either the matrix or the hoods rotated to achieve this and hence there is slight leakage through sealing arrangements at the moving surfaces.



Tubular air preheater (recuperative):

- Large number of steel tubes of 40 to 65 mm dia.
- Either welded or expanded into the tube plates.
- Either gas or air flow through the tube.
- Gas through the tube normally requires higher size tube and vertical flow to reduce fouling.
- Single or more passes on the gas side and multi pass cross flow on the airside usually fits in with the overall plant design.

i. Plate air preheater (recuperative):

- These comprise of parallel plates.
- Which provide alternate passage for gas and air.
- This type is simple and compact compared to that of tubular type.
- The narrow passes between plates make the cleaning tedious but with shot cleaning method it is improved.
- Replacement is a major task.

3.5. BOILER FEED PUMP

Boiler feed pump is a pump that feeds the boiler steam drum with water (clean water) via the economizer (for preheating). The pump must absolutely positive and reliable under all variable operating conditions.

There are various kind of pumps that can be used such as a direct acting pump driven by its own cylinder, or a reciprocating pump driven by a motor or belted machinery. A third type is a centrifugal pump- turbo driven or electrically driven by motor. The centrifugal pump is usually preferred as a boiler feedwater pump due to the following reasons:-

a) Delivering steady flow of BFW.
b) Supplying the largest quantity of BFW under a given load
c) Accepting loading variation most easily.
d) Trouble free and smooth operation , less floor is required and maintenance cost is low.

Lecture sequences:9	Ninth lecture Boiler Calculations	Instructor Name: Dr. Mohammed Saleh

1. Temperature heat (T-Q) Diagram
2. Procedure for determination of specific enthalpies and mass flow rates
3.Calculations of heat load
4. Boiler efficiency an equivalent evaporation

Lecture Contents

1. Temperature-heat (T-Q) diagram

The T-Q diagram is a useful tool for designing heat exchangers. It can also be used to present the heat transfer characteristics of an

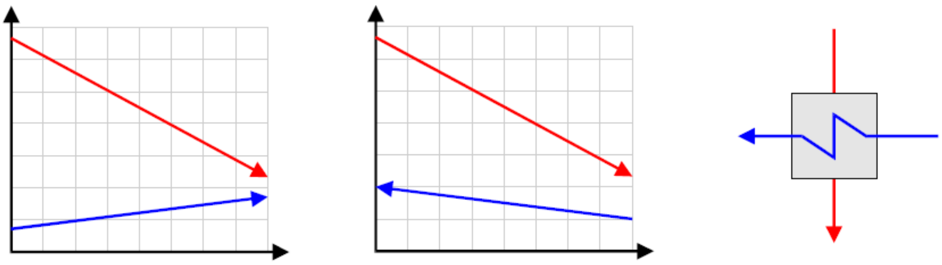


Figure 1: Examples of T-Q diagrams for a parallel flow heat exchanger (left), and a counter (or cross) flow heat exchanger (middle). The hot stream is marked with red color and the cold with blue color.

existing heat exchanger or heat exchanger network. The T-Q diagram consists of two axes: The current stream temperature on the y-axis and the amount of heat transferred on the x-axis. The hot stream transfers its heat to the cold stream, thus the flow direction of the hot stream is towards lower temperature and the flow direction of the cold stream is towards higher temperatures. For the same reason, the hot stream is always above the cold stream in the T-Q diagram (figure 1).

The T-Q diagram is applied when designing boilers; especially the heat exchanger surface arrangement can be clearly visualized with a T-Q diagram (figure 2).

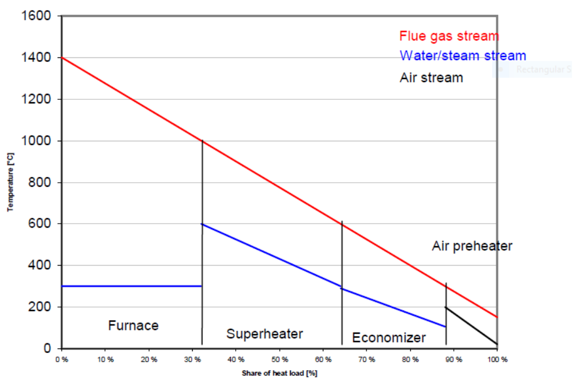


Figure 2: Example of a T-Q diagram representing the heat surfaces in a PCF boiler.

2. Procedure for determination of specific enthalpies and mass flow rates

a) The specific enthalpy of the water and steam can be determined with an h-s diagram or steam tables.

b) The total pressure loss of the superheater stages should be chosen. Thus, the pressure in steam drum (drum-type boilers) or pressure after evaporator (once-through boilers) can be calculated by adding the pressure loss over the superheater stages to the pressure of the superheated steam.

c) For removal of minerals concentrated in the steam drum, a part of the water in steam drum is removed as blowdown water from the bottom of the steam drum. Normally the mass flow rate of blowdown is 1-3 % of the mass flow rate of feedwater coming into steam drum.

d) In principle, the feedwater coming into steam drum should be saturated water. To prevent the feedwater from boiling in the transportation pipes, the temperature of the feedwater reaching the steam drum is 15-30 °C below saturation temperature.

e) The water pressure after the economizer can be assumed equal to the pressure in the steam drum and specific enthalpy after the economizer can then be read from an h-s diagram.

f) The pressure before the economizer can be calculated by adding the pressure loss in the economizer to the feedwater pressure after economizer.

g) The feedwater temperature it should be chosen in depends on the fuel type from the range of 200-250 °C. The mass flow rate before the economizer is the blowdown mass flow rate added to the mass flow rate from the steam drum to the superheater.

3. Calculations of heat load

When the steam parameters and mass flows have been determined, the heat load of the heat exchanger units can be calculated. The heat load is the heat transferred by a heat exchanger (calculated in kW).

i. Evaporator

The heat load of the evaporator part of the boiler can be calculated as:

$$Q_{EVA} = \dot{m}_{SH}\left(\acute{\acute{h}}_d - h_{ECO2}\right) + \dot{m}_{BD}\left(\acute{h}_d - h_{ECO2}\right)$$

where $\dot{m}_{SH}$ is the mass flow of steam before superheater [kg/s], $\acute{h}_d$ the specific enthalpy of saturated steam at steam drum pressure [kJ/kg], h_{ECO2} the specific enthalpy after economizer $\dot{m}_{BD}$ the mass flow of *blowdown* water from steam drum, and h′ the specific enthalpy of saturated water at steam drum pressure [kg/s].

x. Superheater

Normally superheating takes place in three or four stages in a big boiler. The heat load of the superheater is

$$\dot{Q}_{SH} = \dot{m}_{SH}\left(h_{SH} - \acute{h}_d\right)$$

The heat load calculations of the superheater with three stage superheating are:

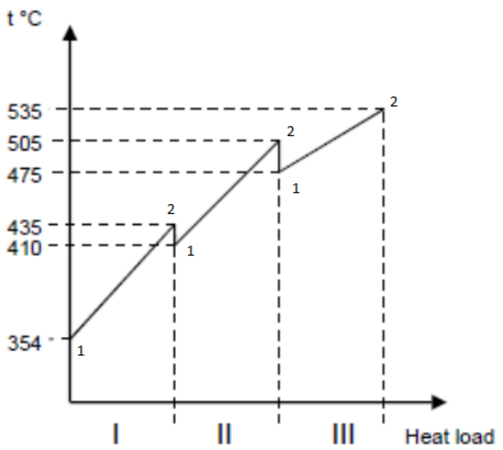
$$\dot{Q}_{SH\_I} = \dot{m}_{SH}\left(h_{SH\_I2} - \acute{h}_d\right)$$

$$\dot{Q}_{SH\_II} = \dot{m}_{SH\_II}\left(h_{SH\_II2} - h_{SH\_II1}\right)$$

$$\dot{Q}_{SH\_III} = \dot{m}_{SH\_III}\left(h_{SH\_III2} - h_{SH\_III1}\right)$$

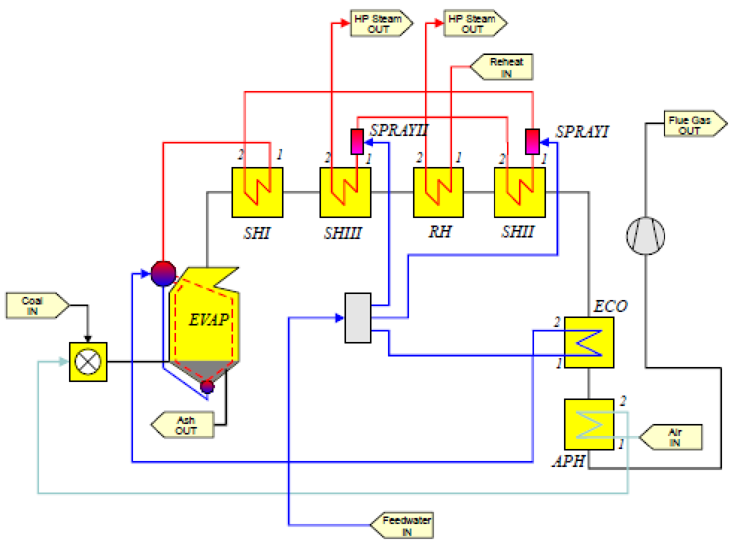
$$\dot{m}_{SH\_II} = \dot{m}_{SH} + \dot{m}_{SPRAY\_I}$$

$$\dot{m}_{SH\_III} = \dot{m}_{SH\_II} + \dot{m}_{SPRAY\_II}$$



An example of the heat load share of superheater stages.

where $\dot{m}_{SH_{II}}$ is the mass flow rate of steam after second superheater stage [kg/s], $\dot{m}_{SPRAY\_II}$ the mass flow rate of spray water to second spray water group, $\dot{m}_{SH_{III}}$ the mass flow rate of superheated steam (live steam),



Flow chart of the PCF boiler arrangement used in this heat load calculation model.

x. Reheater

The heat load of the reheater stage can be calculated as:

$$\dot{Q}_{RH} = \dot{m}_{RH}(h_{RH2} - h_{RH1})$$

where $\dot{m}_{RH}$ is the mass flow rate of steam in the reheater [kg/s], h_{RH2} the specific enthalpy of steam after the reheater [kJ/kg] , and h_{RH1} the specific enthalpy of steam before the reheater.

i. Economizer

The heat load of the economizer can be calculated as:

$$\dot{Q}_{ECO} = \dot{m}_{ECO}(h_{ECO2} - h_{ECO1})$$

where $\dot{m}_{ECO}$ is the mass flow rate of feedwater in the economizer [kg/s], h_{ECO2} the specific enthalpy of feedwater after the economizer [kJ/kg], and h_{ECO1} the specific enthalpy of feedwater before the economizer.

4. Boiler efficiency an equivalent evaporation

4.1. Determination losses in boiler and boiler efficiency

There are two main standards used for definition of boiler efficiency, of those, the German DIN 1942 standard employs the lower heating value (LHV) of a fuel and is widely used in Europe .The American ASME standard is based on higher heating value (HHV). However, this chapter calculates the efficiency according to the DIN 1942 standard[1] .

4.1.1. Major heat losses

a Heat loss with unburned combustible gases

The typical unburned combustible gases are carbon monoxide (CO) and hydrogen (H_2). In large boilers usually only carbon monoxide can be found in significant amounts in flue gases. Assuming that flue gases contain only these two gases, the losses [kW] can be calculated as:

$$\dot{Q}_{L1} = \dot{m}_{CO} h_{L,CO} + \dot{m}_{H_2} h_{L,H_2}$$

where $\dot{m}_{CO}$ is the mass flow of carbon monoxide [kg/s], $\dot{m}_{H_2}$ the mass flow of hydrogen, $h_{L,CO}$ the lower heating value (LHV) of carbon monoxide (10,12 MJ/kg), and h_{L,H_2} the lower heating value (LHV) of hydrogen (119,5 MJ/kg). If a relevant amount of some other flue gas compound can be found in the flue gases, it should be added to the equation.

Heat loss due to unburned solid fuel

Unburned fuel can exit the furnace as well as bottom ash or fly ash. The heating value of ashes can be measured in a specific laboratory test. The losses [kW] of unburned solid fuels can be calculated as:

$$\dot{Q}_{L2} = \dot{m}_{ubs} h_{L,ubs}$$

where $\dot{m}_{ubs}$ is the total mass flow of unburned solid fuel (bottom ash and fly ash in total) [kg/s], and $h_{L,ubs}$, the lower heating value (LHV) of unburned solid fuel (fly ash and bottom ash in total) [kJ/kg]. Some estimates of the losses with unburned solid fuels are presented in table1:

Table1: Estimates of losses with unburned solid fuel.

Boiler type	Heat loss per heat input of fuel
Oil fired boiler	0,2 - 0,5%
Coal fired boiler, dry ash removal	3%
Coal fired boiler, molten ash removal	about 2%
Grate boiler	4-6%

b Heat loss due to wasted heat in flue gases

Flue gases leave the furnace in high temperature and thus they carry significant amount of energy away from boiler process. To decrease flue gas losses, flue gas temperature (exit temperature) should be decreased. However, the acid dew point of flue gases restricts the flue gas temperature to about 130-150° C for sulphur containing fuels. The losses caused by the sensible heat of flue gases can be calculated as:

$$\dot{Q}_{L3} = \dot{m}_{fuel} \sum \frac{m_i}{\dot{m}_{fuel}} h_i$$

where $\dot{m}_{fuel}$ is the fuel mass flow [kg/s], m_i the mass flow of a flue gas component, and h_i the specific enthalpy of a flue gas component (e.g. CO2) [kJ/kg].

Heat loss due to wasted heat in ashes

Ash can exit the furnace either as bottom ash from bottom of the furnace or as fly ash with flue gases. The losses related to the sensible heat of ash can be calculated as:

$$\dot{Q}_{L4} = \dot{m}_{ba} C_{p,ba} \Delta T_{ba} + \dot{m}_{fa} C_{p,fa} \Delta T_{fa}$$

where $\dot{m}_{ba}$ is the mass flow of the bottom ash [kg/s], $C_{p,ba}$, the specific heat of the bottom ash [kJ/(kgK)], ΔT_{ba} the temperature difference between the bottom ash temperature and the reference temperature [°C], $\dot{m}_{fa}$ the mass flow of fly ash, $C_{p,fa}$, the specific heat of fly ash, ΔT_{fa} the temperature difference between the fly ash temperature and the reference temperature [°C]. Usually the reference temperature is 25 °C. In recovery boilers the bottom ash is removed as molten ash in temperature of about 700-800 °C. In addition, the amount of bottom ash divided by the amount of fuel is about 40 %. The loss of sensible heat of ash is therefore of great importance in recovery boilers

.

c Losses due to heat transfer (radiation) to the environment

The main form of heat transfer from boiler to boiler room is radiation. It is proportional to the outer surface area of the boiler and is usually 200-300 W/ (m^2K) for a well-insulated boiler having its outer surface temperature below 55 °C. Another possibility to determine the heat transfer losses to the environment is to use a table from the DIN 1942 standard, presented in table 2.

Table 2: Estimations of heat transfer losses by radiation

	Combustion method	Mass flow rate of steam [t/h]									
		10	20	40	60	80	100	200	400	600	800
Loss [%]	Pulverized firing	-	1,3	1,0	0,9	0,75	0,7	0,55	0,4	0,35	0,3
	Grate	1,5	1,1	0,9	0,7	-	-	-	-	-	-
	Oil/gas fired boiler	1,3	0,9	0,7	0,6	0,55	0,4	0,3	0,25	0,2	0,2

d Losses of blowdown and sootblowing

Blowdown water from the steam drum and sootblowing steam, (used to remove soot from heat exchanger surfaces within the boiler) use a part of the steam produced by the boiler. This lowers the boiler efficiency. In addition, steam is sometimes also used to atomize fuel in the burners.

The losses can be calculated as:

$$\dot{Q}_{L6} = \dot{m}_{ba}\acute{h} + \dot{m}_{sb}\, h_{sb} + \dot{m}_{atomizing}\, h_{atomizing}$$

$\dot{m}_{ba}$ is the mass flow of blowdown water [kg/s], h′ is the specific enthalpy of saturated water (blowdown water from steam drum) [kJ/kg], $\dot{m}_{sb}$ is the mass flow of sootblowing steam, h_{sb} the specific enthalpy of steam used for sootblowing (when leaving the boiler), $\dot{m}_{atomizing}$ is the mass flow of atomizing steam, and atomizing h the specific enthalpy of steam used for atomizing the fuel (when leaving the boiler) [kJ/kg].

e Internal power consumption

The power plant itself consumes a part of the electricity produced. This is due to the various auxiliary equipment’s required, like feedwater pumps, circulation pumps, and air/flue gas blowers. In forced circulation boilers, the share of electricity consumed by the circulation pump is about 0.5 % of the electricity produced by the plant. Normally the internal power consumption is about 5 % of the electricity produced by the power plant. Since the power used is electrical (and taken from the grid), the internal power consumption share is reduced from the final boiler efficiency in boiler calculations.

4.1.2. Equivalent Evaporation

Equivalent Evaporation might be more simply defined as “the quantity of water at 100°C that a boiler can convert into dry/saturated steam at 100°C from each kJ of energy that is applied to it. This defines it in terms of kg (of water/steam) per kJ of energy. However, it is sometimes defined in units of kg water per kg of fuel, and (as in the case of the graph above) kg water/steam per hour.

$$m_{eq} = \frac{m_s(h_s - h_w)}{L_{ev\,100}} \quad (1)$$

Where:-

m_{eq}: equivalent evaporated

m_s: actual mass of steam generated per unit mass of fuel burnt

h_s: specific enthalpy of steam (kJ/kg)

h_s: specific enthalpy of feedwater (kJ/kg)

$L_{ev_{100}}$: Latent heat of dry saturated steam at 100 ºC $(h_{fg})_{100}$ (**Latent heat of vaporization** is a physical property of a substance. When a material in liquid state is given energy, it changes its phase from liquid to vapor; the energy absorbed in this process is called **heat of vaporization**. The **heat of vaporization of water** is about 2,260 kJ/kg, which is equal to 40.8 kJ/mol.)

4.1.3. Evaporation Factor (f)

May be defined as the ratio of the equivalent evaporation to actual mass of steam generated per unit mass of fuel.

$$f = \frac{m_{eq}}{m_s} \qquad \text{Or} \qquad m_{eq} = \frac{m_s(h_s - h_w)}{L_{ev\,100}} = f m_s$$

$$\text{Hence} \quad f = \frac{(h_s - h_w)}{L_{ev\,100}} \quad (3)$$

4.1.4. Boiler Efficiency

It is the ratio of heat load of the generated steam to the heat supplied by the fuel over the same period.

$$\dot{Q}_s = \dot{m}_s(h_s - h_w) \quad (4)$$

$$\dot{Q}_f = m_f \dot{L}CV \quad (5)$$

Where:-

Qs: - Heat load of the generated steam (kJ/s)

Qf :- The rate of heat supplied by the fuel (kJ/s)

ms:- Rate of steam generation (kg/s)

mf :- Mass flow rate of fuel (kg/s)

LCV : Lower calorific value of fuel (kg/kJ) (Lower calorific value of a fuel portion is defined as the amount of heat evolved when a unit weight (or volume in the case of gaseous fuels) of the fuel is completely burnt and water vapor leaves with the combustion products without being condensed.)

Therefore, the boiler efficiency can be obtained as follows:-

$$\eta_{boiler} = \frac{Q_s}{Q_f} = \frac{m_s(h_s - h_w)}{m_f LCV} \quad (5)$$

$$\eta_{boiler} = \frac{Q_s}{Q_f} = \frac{m_{sf}(h_s - h_w)}{LCV} \quad (6)$$

Since $m_{sf} \frac{m_s}{m_f}$ (7)

By definition equation (7):- actual mass of steam generated per unit mass of fuel burned).

4.1.5. Economizer Efficiency

may be defined as the ratio of the heat absorbed by the boiler feedwater (BFW) in the economizer to the heat supplied by the flue gases (Exhaust gases) in the economizer.

$$\eta_{eco} = \frac{m_s(T_{in} - T_{out})}{m_{exh} * Cp_{exh} * (T_{exh} - T_{air})} \quad (8)$$

Where:-

Tin: - Temperature of boiler feedwater BFW inlet to the economizer.

Tout :- Temperature of boiler feedwater BFW outlet of the economizer.

mexh :- Mass of flue gases (exhaust gases) per unit mass of fuel

Cpexh :- Specific heat of flue gases

Texh :- Temperature of flue gases at inlet to the economizer.

Tair :- Temperature of air delivered to the boiler

Example (1):- A boiler generate 4.5 ton of superheated steam at 500 ºC and 90 bar per ton of fuel. The boiler feedwater (BFW) temperature is 45 ºC. What is the equivalent evaporation from and at 100 ºC per ton of fuel.

Example (2):- A steam boiler generate 7.5 ton of steam per ton of coal burned. Calculate the equivalent evaporation from and at 100 ºC per ton of coal from the following data:-

Steam pressure = 10 bar

Dryness fraction = 0.95

Feedwater temperature= 50 ºC

Example (3):- A boiler is working at 14 bar and evaporates 8.5 kg of water per kg of coal fired from BWF entering at 39 ºC. determine the

	equivalent evaporation from and at 100 ºC if the steam quality is 96% at the stop valve. Example (4):- A boiler produce 220 ton of dry saturated steam at a pressure of 60 bar. The feedwater temperature is 120 ºC. The used fuel is coal of lower calorific value is 17556 kJ/kg. assume 1% of the coal is burned, determine:- the equivalent evaporation per ton of coal fired the efficiency of the boiler the overall efficiency of the boiler Example (5):- A boiler consumes 224 tons of coal to produce 1864 tons of steam per day. The steam is dry, saturated at 90 bar. Calculate the boiler thermal efficiency and the equivalent evaporation per ton of coal if the calorific value of coal is 5400 kcal/kg, the specific enthalpy of water being 425 kj/kg.

Lecture Contents	Lecture sequences:10	Tenth lecture Condenser	Instructor Name: Dr. Mohammed Saleh

1. Introduction
2. Definitions
3. Power plant cooling system

1. Introduction

Thermal efficiency of a closed cycle power developing system- using steam as working fluid and working on Carnot cycle is given by an expression $\eta_{car} = \frac{T_1 - T_2}{T_1}$.

This expression of efficiency shows that the efficiency increases with an increase in temperature T_1 and decrease in temperature T_2. The maximum temperature T_1 of the steam supplied to a steam prime mover is limited by material considerations. The temperature T_2 (temperature at which heat is rejected) can be reduced to the atmospheric temperature if the exhaust of the steam takes place below atmospheric pressure. If the exhaust is at atmospheric pressure, the heat rejection is at 100°C.

Low exhaust pressure is necessary to obtain low exhaust temperature. However, the steam cannot be exhausted to the atmosphere if it is expanded in the engine or turbine to a pressure lower than the atmospheric pressure. Under this condition, the steam is exhausted into a vessel known as condenser where the pressure is maintained below the atmosphere by continuously condensing the steam by means of circulating cold water at atmospheric temperature.

2. Definition

A steam condenser is a closed vessel in to which the steam is exhausted, and condensed to water at a pressure less than atmosphere after doing work in an engine cylinder or turbine.

A steam condenser has the following two object:

a *The primary object is to maintain a low pressure (below atmospheric pressure) so as to obtain maximum possible energy from steam and thus to secure high efficiency. The exhaust pressure in the condenser is maintained nearly 7 to 8 kPa which corresponds to condensate temperature of nearly 40 0C.*

b *The secondary object is to*

c *Supply pure feed water to the hot well, from where it is pumped back to boiler.*

d *Enables removal of air and other non-condensable gases from steam. Hence improved heat transfer .*

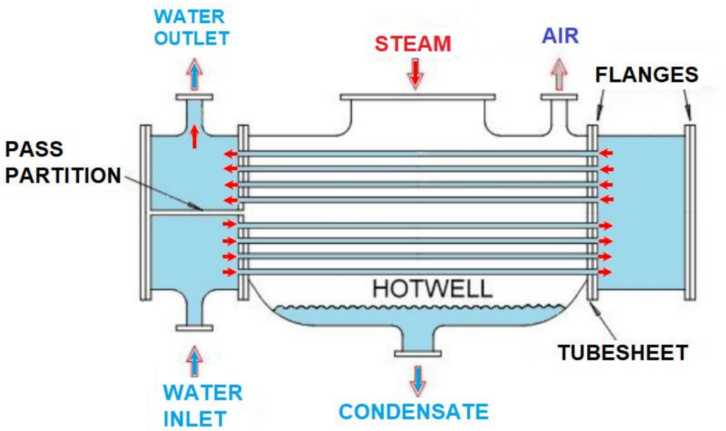


Figure 23 condenser

3. Power plant cooling system

3.1. Types of cooling systems

The choice between evaporative and dry cooling systems is basically an economic one in regions of inadequate water supplies.

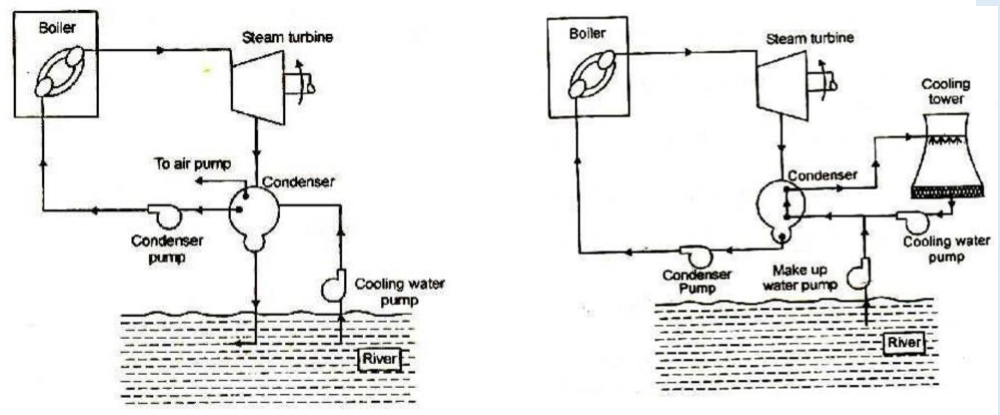
a *Open cycle cooling systems*

Some power plants have an open cycle (once through) cooling water system where water is taken from a body of water, such as a river, lake, or ocean, pumped through the plant condenser and discharged back to the source.

b *Closed cycle cooling systems*

Inland plants away from large water bodies prefer to use closed cycle wet cooling system with wet cooling towers. Power plants in remote dry areas without economic water supplies use closed cycle dry cooling systems that do not require water for cooling.

c *Hybrid cooling systems are used in particular circumstances.*



(a) Open cycle condensing system

Figure: (b) Closed cycle condensing system

Figure 3 open and closed cycle cooling system

The type of cooling system used is therefore heavily influenced by the location of the plant and on the availability of water suitable for cooling purposes. The selection process is also influenced by the cooling system's environmental impacts.

3.2. Elements of a steam condensing plant

The main elements of a steam condensing plants are:

- A condenser in which the exhaust steam is condensed
- Supply of cooling water for condensing exhaust steam
- A pump to circulate the cooling water in case of a surface condenser
- A pump called the wet air pump to remove the condensed steam (condensate) the air, and uncondensed water vapor and gases from the condenser (separate pump may be used to remove air and condensed steam)
- A hot well where the condensed steam can be discharged and from which the boiler feed water is taken
- An arrangement (cooling pond or cooling tower) for cooling the circulation water when a surface condenser is used and the supply of water is limited

3.3. Types of Steam Condensers

The steam condensers are broadly classified into:The Spray Condenser

Direct-contact condenser, as the name implies, condense the steam by mixing it directly with cooling water. In the spray condenser, this is done by spraying the water into steam. Thus turbine exhaust steam at point 2 in figure 3 mixes with cooling water at point 5 to produce nearly saturated condensate at point 3, which is pumped to point 4. Part of the condensate, equal to the turbine exhaust flow, is sent back to the plant as feedwater. The rest is cooled, usually in a dry cooling tower to point 5. The cooled water at 5 is sprayed into turbine exhaust, and the process is repeated.

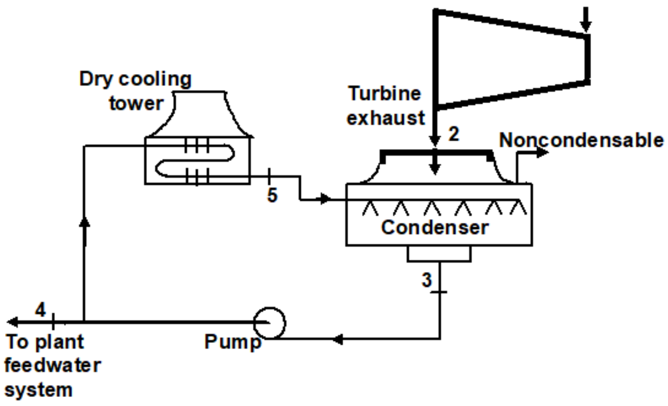


Figure 4 spray condenser

A mass balance on the system gives

$$\dot{m}_2 = \dot{m}_4 \quad (1)$$

And $\dot{m}_2 + \dot{m}_5 = \dot{m}_3$ (2)

and energy balance can be written as:-

$$\dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_5 h_5 \quad (3)$$

and the ratio of circulating cooling water to steam flow is given by:-

$$\frac{\dot{m}_5}{\dot{m}_2} = \frac{h_2 - h_3}{h_3 - h_5} \quad (4)$$

Thus circulating water flow is much greater than steam flow according to equation 4.

3.3.1. Jet Condensers or Mixing Type Condensers.

In jet condensers, there is direct contact between the exhaust steam and cooling water. The temperature of the condensate is same as that of the cooling water leaving the condenser. Heat exchange occurs by direct conduction between the steam and water. If the cooling water is not pure and free from harmful impurities then the condensate cannot be reused as feed water to the boilers. Due to loss of condensate and high power requirement by the pump these condensers are rarely used in modern steam power plants.

Jet condensers are of the following types:

a Low-level jet condensers: These are of the following two types

- Parallel flow type: The steam and cooling water flow in the same direction.

- Counter flow type: The steam and cooling water flow in the opposite directions.

b *High-level jet condensers, and*

c *Ejector jet condensers.*

Low-level jet condenser is placed at low levels such that vacuum inside the condenser draws the cooling water into it from the cooling water source. Parallel flow and counter flow low-level jet condensers are shown in Figure 4. In counter flow jet condenser the water and steam flows in opposite directions but in parallel flow both flow in the same direction. In both the cases, the cooling water enters at the top of the condenser and passes through the perforated trays so that it breaks into sprays and increases the heat transfer rate by providing more contact surface area. When the steam comes into contact with cooling water it gets condensed. The extraction of air is done from the top of the condensers. The vacuum created in the condenser is sufficient to draw the cold water from the cooling pond. The pressure p_v causing the water flow from the cooling pond (or cold tank) to the condenser top is given by

$$p_v = (pa - pc),$$

where pa is the atmospheric pressure and pc is the condenser pressure. The condensate is extracted by the extraction pump and is discharged to the hot well figure 4. The excess amount of condensate from hot well flows into the cooling pond by an overflow pipe and the remaining water is pumped to the boiler as feed water. These condensers have the disadvantage of flooding the turbine if water extraction pump fails due to any reason.

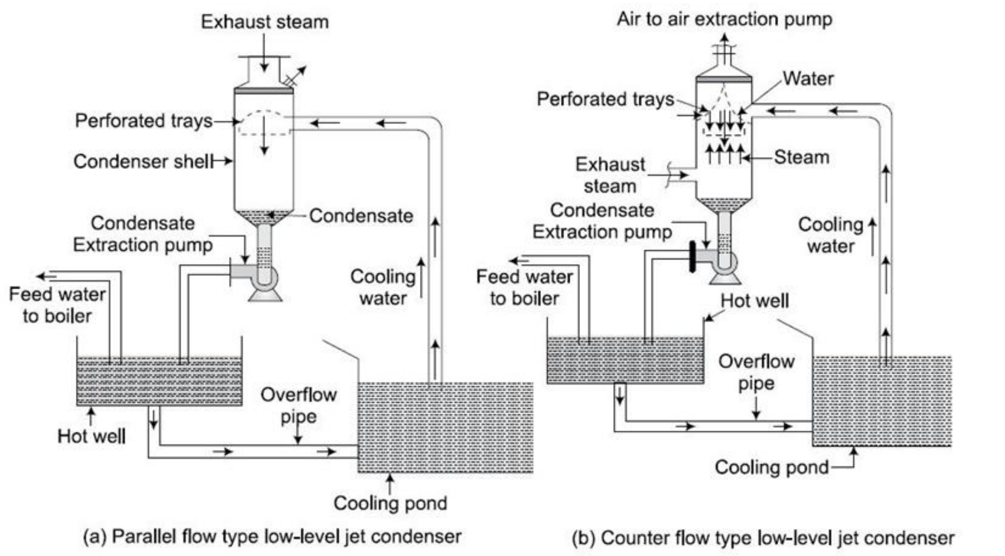


Figure 26 parallel and counter flow type jet condenser

high-level jet condenser is also called barometric condenser because the condenser shell is placed above the hot well by more than barometric height of water column of 10.363 m as shown in figure 5. A long tailpipe, more than 10.363 m in length is attached between the bottom of the condenser and the hot well. The pressure at the bottom of the pipe is equal to atmospheric pressure, whereas at its top in the condenser shell vacuum pressure is maintained.

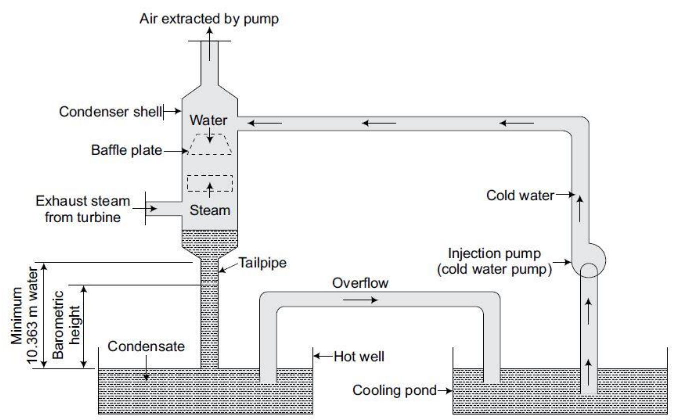


Figure 27 high-level jet condenser

It avoids the rise of water in the tail pipe and water extraction pump is also not required. The condensate and water from the condenser go down to the hot well under the gravity and maintain a water leg in the tail pipe depending upon the vacuum in the condenser. As the height of the shell is large so, an injection pump is required to pump water to the top of the shell. A schematic view of high jet condenser is shown in Figure 4. The working and other details of this condenser are similar to low-level counter flow jet condenser. Its drawbacks are high costs and loss of vacuum between the turbine and the condenser. It is used where sufficient head required for tailpipe is available.

3.3.2. Surface Condensers or Non-mixing Type Condensers.

In surface condensers, there is no direct contact between the exhaust steam and the cooling water. The steam surrounds the tubes fitted in the condenser shell and the cooling water circulates through these tubes. The steam gets condensed due to the heat transfer to cooling water by conduction and convection. The condensate collected from these condensers is reused as feed water in the boiler. Thus, these condensers are most suitable for modern steam power plants and chemical industries. These are generally used where a large quantity of inferior water is available and better quality of feed water is to be supplied to the boiler. So, these condensers are universally used in marine engines where seawater is used for cooling purposes. The only drawback of these condensers is its high initial cost but is recovered by the saving in running cost.

The surface condensers may be classified according to:

- **Down flow type**: In down flow surface condenser, the steam enters from the top as shown in Figure 6. The exhaust steam is forced to flow downwards over the water tubes due to suction of the extraction pump at the bottom. The suction pipe of the dry air pump is provided near the bottom and is covered by a baffle so that the condensed steam does not enter into it. As the steam flow perpendicular to the direction of flow of cooling water, it is also called cross flow surface condenser.
- **Central flow type**: In this type of surface condenser, the suction pipe of the air extraction pump is placed in the center of the tube nest as shown in Figure 6. The exhaust steam from turbine enters from the top and flows radially inwards over the tubes. The condensate is collected at the bottom.

The advantage of central flow type surface condenser over the down flow type is that the steam flows over the whole periphery of the water tubes as the steam flows radially inwards.

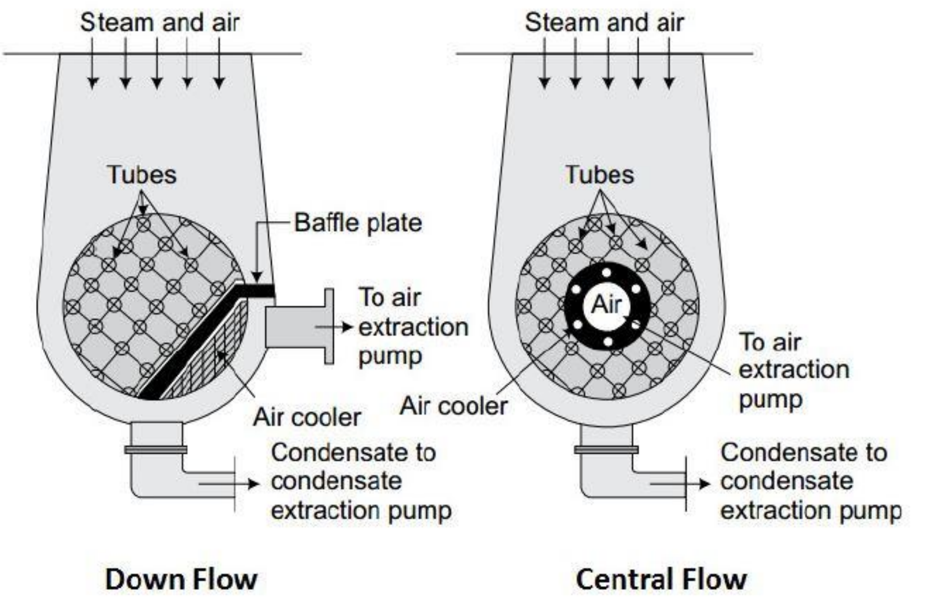


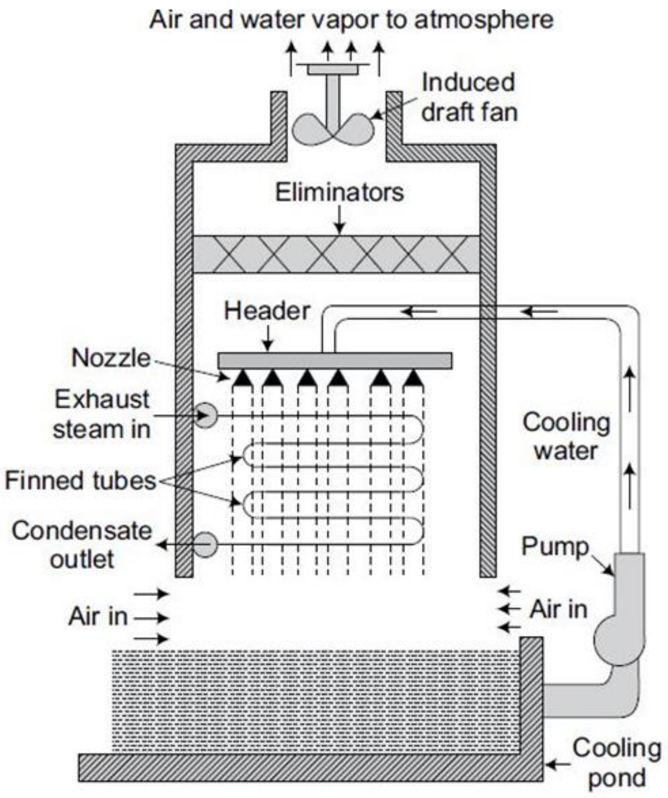
Figure 28 Surface condensers

- **Inverted flow type**. In the inverted flow type surface condenser the air suction pump is provided at the top. So, the steam entering from the bottom of the condenser flows upwards. The condensed steam collects in the bottom section from where it is extracted with the help of a condensate extraction pump.

3.3.3. Evaporative Condenser

A schematic arrangement of the evaporative condenser is shown in Figure7.These are used where there is scarcity of water. The exhaust steam from the turbine enters a coiled finned pipe. The water from the cooling pond is pumped by means of a pump to a horizontal header which is provided with spray nozzles. The sprayed water forms thin film over the pipe surface and gets evaporated in passing over the pipe under a small partial pressure and thus cools the steam inside the pipes. The air is drawn over the surface of finned pipe with the help of induced draft fan to increase the evaporation of cooling water, which further increases the condensation of steam in pipes. Eliminators are provided to prevent the exit of water vapors with the leaving heated air. The cooling water gets collected into the cooling pond. In the cooling pond, the water lost due to evaporation is replenished by the addition of required amount of cold make up water.

Figure 8 evaporative condenser



The arrangement of this type of condenser is simple, cheap, and requires small quantity of cooling water thus capacity of water circulating pump is small. The vacuum maintained in this type of condenser is not as high as in the case of surface condensers. These condensers are used in small power plants and are extensively used in refrigeration plant units.

3.4. Advantages and Disadvantages of Condensers

3.4.1. Jet Condensers

The following are the advantages and disadvantages of jet condensers.

Advantages

Due to more intimate mixing of steam and cooling water it requires less quantity of circulating water for the condensation of steam.

1. Due to direct mixing it requires less building space.
2. The arrangement of jet condenser is simple in construction and low in cost. Its maintenance cost is also low.
3. Low-level jet condenser does not require cooling water pump. In barometric and ejector condensers there is no need of condensate extraction pump.

Disadvantages

1. There is wastage of condensate.
2. If the condensate is to be used as feed water then the cooling water should be pure and free from any harmful impurities.
3. In the barometric condenser use of long pipe increase the cost of the condenser.
4. In the low-level jet condenser if the condensate extraction pump fails then there is greater possibility of flooding of the engine.
5. In the case of barometric condenser a vacuum loss of about 1 to 1.5 cm of Hg occurs due to leakage in the long exhaust pipe line.
6. The air extraction pump needs high power which may be about double the power required by a surface condenser.

3.4.2. Surface Condensers

The following are the advantages and disadvantages of surface condensers.

Advantages

1. A high vacuum can be achieved (as much as 73.5 cm of Hg) and thus gives greater plant efficiency.
2. Since the cooling water and steam do not mix, the condensate is recovered and can be used as feed water to the boiler. Due to this advantage, these condensers are used in all steam power plants.

3. Since the cooling water and steam do not mix, any kind of cooling water can be used. This results in considerable reduction in the cost of water softening plant.
4. The chances of vacuum loss are minimized.
5. It requires much less power to run the air extraction pump and for water pumping.
6. It ideally suits high capacity plants.
7. It requires less quantity of makeup water (about 4% to 5%).

Disadvantages

1. The system is bulky and requires large floor area.
2. It requires high capital cost and maintenance cost.
3. It requires more cooling water

4. Deaeration

Deaeration is the removal of noncondensable gases (air) from the system. In steam power plants, it is important to remove the noncondensable gases from the system. The noncondensables are mostly air that leaks from the atmosphere into that portion of the cycle that operate below atmospheric pressure, such as condenser. It also include other gases caused by the decomposition of water into oxygen and hydrogen. The presence of noncondensable gases in large quantities has undesirable effects on equipment for several reasons as follows:-

1. They raise the total pressure of the system because the total pressure is the sum of the partial pressures of the constituent. However, an increase in condenser pressure would decrease the plant efficiency.
2. They results in a severe decrease in the condensing heat-transfer coefficient and hence in condenser effectiveness.
3. The presence of some noncondensable results in various chemical activities. Oxygen causes corrosion, most severely in the steam generator. Hydrogen, methane, and ammonia are also combustible.

Lecture sequences:11	Eleventh lecture Condenser	Instructor Name: Dr. Mohammed Saleh

1. Condensation Heat Transfer
2. Heat Exchanger
3. Vacuum Efficiency
4. Condenser Efficiency

Lecture Contents

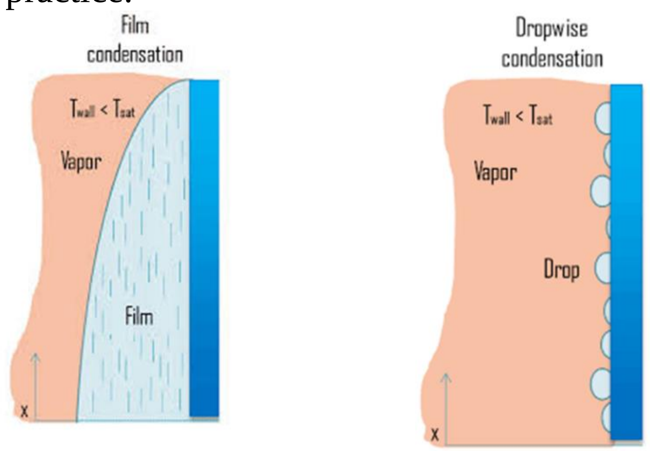
1. Condensation Heat Transfer

Condensation occurs when the temperature of a vapor is reduced below its saturation temperature T_{sat}. This is usually done by bringing the vapor into contact with a solid surface whose temperature Ts is below the saturation temperature T_{sat} of the vapor.

Two type of condensation can be observed:-

1. Film condensation
2. Dropwise condensation

Film condensation:- in this type, the condensate wets the surface and forms a liquid film on the surface that slides down under the influence of gravity. The thickness of the liquid film increase in the flow direction as more vapor condenses on the film. This is how condensation normally occurs in practice.



a-film condensation b- Dropwise condensation

Figure 9 condensation type

Dropwise condensation:- in Dropwise condensation, the condensed vapor forms droplets on the surface instead of a continuous film, and the surface is covered by countless droplets of varying diameter. In this type, there is no liquid film to resist heat transfer because the droplets slide down when they reach a certain size, clearing the surface and exposing it to vapor. As a result , heat transfer rates that are more than 10 times larger than those associated with film condensation. Therefore , Dropwise condensation is the proffered mode of condensation of heat transfer applications, however, Dropwise condensation would achieved did not last long and converted to film condensation after some time.

2. Heat Exchanger

The simplest type of heat exchanger consist of two concentric pipes of different diameter as shown in figure below, called the double heat exchanger.

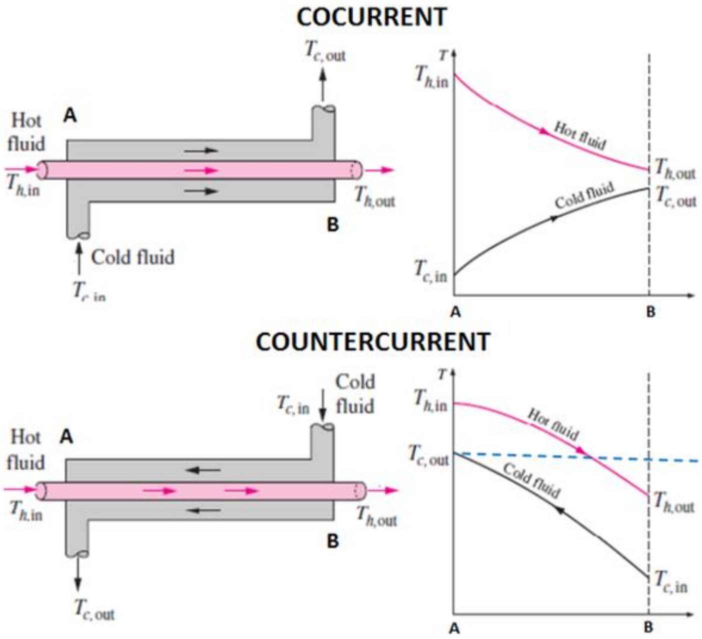


Figure 31 flow type in heat exchanger

In a heat exchanger, heat is first transferred from the hot fluid to the wall by convection, then through the wall by conduction, and from the wall to the cold fluid again by convection.

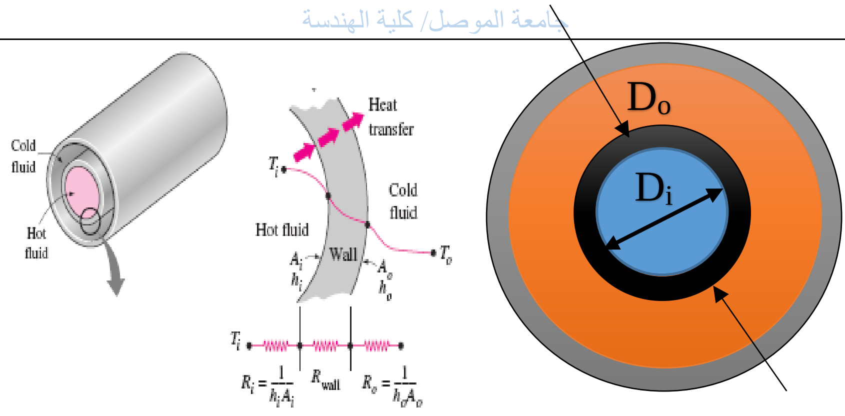


Figure 11 thermal resistance

The total thermal resistance becomes-

$$R = R_i + R_{wall} + R_0$$

$$R = \frac{1}{h_i A_i} + \frac{\ln(\frac{D_o}{D_i})}{2\Pi KL} + \frac{1}{h_o A_o}$$

$$Q_{Cond} = \frac{T_2 - T_1}{R_{wall}}$$

$$Q_{Conv} = hA($$

Where: $A_i = \pi D_i L$ and $A_0 = \pi D_0 L$

The rate of heat transfer between two fluids can be obtained as follows:-

$$Q = U A \Delta T_m \quad \text{(KJ/s)}$$

Where :- U is the over all heat transfer coefficient W/ m2.K

ΔT_m : is the logarithmic mean temperature differences

$$\Delta T_m = \frac{\Delta T_1 - \Delta T_2}{\ln(\frac{\Delta T_1}{\Delta T_2})}$$

From the first law of thermodynamics requires that the rate of heat transfer from the hot fluid be equal to the rate of heat transfer to the cold one

$$Q = m_c Cp_c\,(T_{c,out} - T_{c,in})$$

And

$$Q = m_h Cp_h(T_{h,out} - T_{h,in})$$

The heat capacity rate C_h and C_c of the hot and cold fluid represent the rate of heat transfer needed to change the temperature of the fluid stream by 1ºC as it flows through the heat exchange.

$$C_c = m_c\, Cp_c \qquad and \qquad C_h = m_h\, Cp_h$$

Note that in a heat exchanger, the fluid with a large heat capacity rate will experience a small temperature change, and the fluid with a small heat capacity rate will experience a large temperature change.

Two special types of heat exchanger commonly used in practice are condenser and boiler. One of the fluids in a condenser or a boiler undergoes a phase change process, and the rate of heat transfer is expressed as :-

$$Q = m\, h_{fg} \quad \text{(kW)}$$

Where:-

m :- is the rate of evaporation or condensation of fluid (kg/s)

h_{fg}:- is the latent heat of evaporation of the fluid at specified temperature or pressure (kJ/kg)

In actual condensation process a modified latent of heat of vaporization may be used:-

$$h'_{fg} = h_{fg} + 0.68CpL\,(Tsat - Ts)$$

where:-

$$h'_{fg} = modified\ latent\ of\ heat\ of\ vaporization\ (kJ/kg)$$

$$C_{pL} = is\ the\ specific\ heat\ of\ the\ liquid\ at\ the\ average\ film\ temperature\ (kJ/kg.K)$$

In case of superheated steam at $T_{sup,}$ the vapor must be cooled first to Tsat before it condense. The amount of released as a unit mass of superheated steam at temperature of $T_{sup,}$ is cooled to $T_{sat,}$ is given as:-

$$Q = C_{psup}(T_{sup} - T_{sat})$$

Where C_{psup} is the specific heat at average temperature of $[(T_{sup} + T_{sat})/2]$.

The modified latent of heat is :-

$$h'_{fg} = h_{fg} *+ 0.68C_{pL}\,(Tsat - Ts) + C_{psup}(T_{sup} - T_{sat})$$

with these consideration, the rate of heat transfer can be expressed as:-

$$Q = h\, A_s\,(T_{sat} - T_s) = m\, h_{fg}$$

Where A_s is the heat transfer area of the condenser.

3. Vacuum Efficiency

In a steam condenser, we have a mixture of steam and air, and the total pressure, which exists in the condenser, is the sum of the partial pressures exerted by the steam and air. With no air present in the condenser, the total absolute pressure in the condenser would be equal to partial pressure of steam corresponding to the temperature of condenser, and maximum vacuum would be obtained in the condenser. The ratio of the actual vacuum obtained at the steam inlet to the condenser, to this maximum vacuum (or Ideal vacuum) which could be obtained in a perfect condensing plant (with no air present) is called the vacuum efficiency.

$$Actual\ vacuum\ = barometric\ pressure - actual\ pressure$$

$$Ideal\ vacuum$$

$$= barometric\ pressure$$

$$- Absolute\ pressure\ corresponding$$

$$to\ temperature\ of condensation$$

$$\eta_v = \frac{actual\ vacuum}{ideal\ vacuum}$$

4. Condenser Efficiency

The ideal condenser should remove only the latent heat. So thermal efficiency of a condenser is stated as the ratio of the difference between the outlet and inlet temperatures of cooling water, to the difference between the saturation temperature corresponding to the absolute pressure in the condenser and inlet temperature of the cooling water. The maximum temperature of the outgoing cooling water is the condensate temperature ideally but it is less than practically. Therefore, the condenser efficiency is defined as the ratio of actual rise in temperature of cooling water to the maximum rise in temperature.

$$condenser\ efficiency = \frac{t_2 - t_1}{t_3 - t_1}$$

Where

t_1 = inlet temperature of cooling water

t_2 = outlet temperature of cooling water

t_3 = saturation temperature corresponding to condenser pressure

Example1. The vacuum in a surface condenser is found to be 707.5 mm of Hg with barometer reading 760 mm of Hg. The cooling water enters the condenser 1at 15°C and leaves at 36°C. Find the condenser efficiency.

Example 2: Steam enters a condenser at 32.88°C and with barometer standing at 760 mm of Hg, a vacuum of 685 mm of Hg was produced. Determine the vacuum efficiency.

Example3. A certain surface condenser condense 20 t/h of exhaust steam from turbo- alternator. The dryness fraction of the steam is 0.85. The cooling water inlet and outlet temperature is 33 ºC and 42 ºC respectively. The condensate temperature at the exit is 49 ºC, determine the flow rate of cooling water.

Example (3):- A surface condenser operates at a vacuum of 699.2 mmHg when the barometric head is 760 mm of Hg. It receives steam at a rate 10 t/h of a quality of 90%. If the cooling water inlet and outlet temperature is 33 ºC and 40 ºC respectively Calculate:-

Condenser efficiency

Cooling water flow rate

The vacuum efficiency if the mean condensation temperature is 36 ºC

Example (4):- A surface condenser condenses steam at a rate of 20 t/h, which leaves the condenser at the corresponding saturation temperature. The condenser operates at a vacuum of 680 mmHg, determine-

condenser efficiency

flow rate of cooling water

number of condenser tubes

Given :- $T_{w,in} = 33$ ºC, $T_{w,in} = 43$ ºC, mean velocity of cooling water is 2.5 m/s , internal diameter of condenser tubes is 19.6 mm, barometric pressure 760 mmHg, quality of steam 95%

Example (5):- The following parameters were recorded for a surface condenser:-

Condenser vacuum =690 mmHg

Barometric pressure = 760 mmHg

Mean condenser temperature = 37 ºC

Condenser exit temperature = 30 ºC

Rise in temperature of cooling water =10 ºC

Rate of steam condensation = 25 t/h

Rate of cooling water =1200 t/h

Determine:-

1- The mass of air present per unit volume of the condenser
2- The dryness fraction of steam at the inlet to condenser
3- The vacuum efficiency of the condense