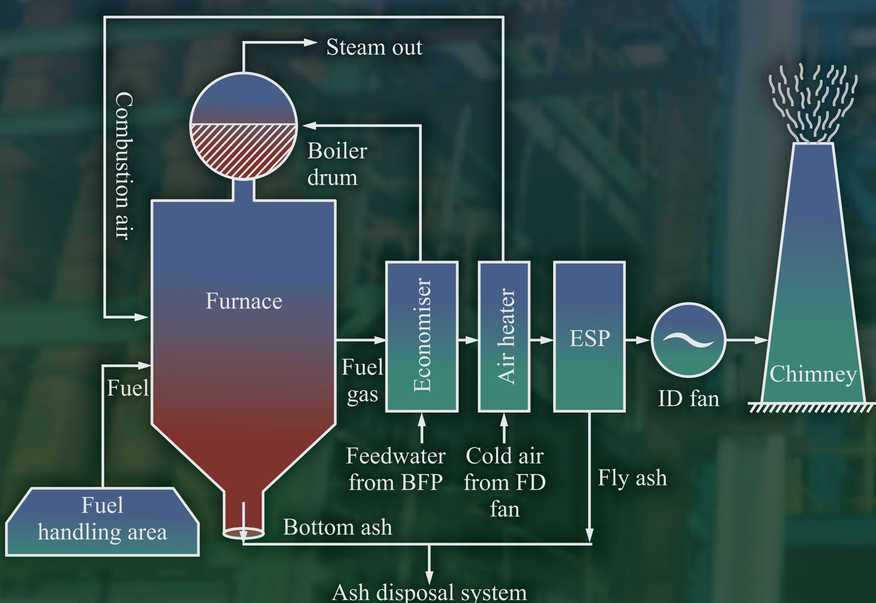
Eastern Economy Edition

Third Edition

Practical Boiler Operation Engineering and Power Plant



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CHAPTER

1 Fundamentals

1.1 INTRODUCTION

Before discussing in detail about boiler and power plant, some fundamental knowledge of mechanical engineering is essential. Some such important points are discussed in this chapter which are essential for a boiler operation engineer in his day to day job.

1.2 LAW OF CONSERVATION OF ENERGY

This law states that energy can neither be created nor destroyed; it can only be transformed from one form to another.

Energy is the capacity to do work. It is available in various forms like mechanical energy, electrical energy, chemical energy, heat energy, light energy, kinetic energy, potential energy etc.

In a boiler, chemical energy available in fuel is converted into heat energy during combustion. This heat energy is utilised to convert water to steam. Heat energy is converted to kinetic energy in steam. Kinetic energy of steam is used in steam turbine to convert into mechanical energy. Turbine drives a generator to generate electricity. In generator, mechanical energy is converted into electrical energy.

1.3 TEMPERATURE

Temperature of an object is the average energy of its molecules. Molecules move faster when they have more energy. So, the temperature is also related to the average speed of the molecules. *Temperature* of a body means the warmth or coldness felt during contact with that body. It is measured by a thermometer in quantitative way.

Most materials expand when heated. Some materials like mercury expand linearly with temperature. Some other principles normally used to measure temperature are given below:

- Change of length such as length of a mercury column
- Change of volume such as volume of a fixed mass of gas at constant pressure
- Change of pressure such as pressure of a fixed mass of gas at constant volume
- Change in electric resistance as in a thermistor
- Flow of electricity due to Seebeck effect as in a thermocouple
- Radiation as in radiation pyrometers

There are three well known scales used to measure temperature. These are as follows:

- Centigrade or Celsius scale
- Fahrenheit scale
- Kelvin scale

Centigrade or Celsius scale: This scale was developed by Anders Celsius (1701–1744). Celsius divided the difference in temperature between freezing and boiling points of water into 100 units. The point at which water frizzes under atmospheric pressure is considered as 0 °C and that at which water boils is considered as 100 °C. The scale is divided into 100 equal units. One unit is °C called as *degree centigrade* or *degree celsius*. This scale is widely used by the engineers in India.

Fahrenheit scale: Daniel Gabriel Fahrenheit (1686–1736) introduced this scale in 1724. As per this scale, freezing point of water is 32 °F and boiling point of water is 212 °F. The difference between these two points is divided into 180 equal units. Each unit is called as degree *Fahrenheit* or °F. The normal human body temperature is 98.6 °F.

Kelvin scale: Lord William Kelvin (1824–1907) introduced Kelvin (K) scale in 1854. The Kelvin scale is based on the principle of absolute zero. The zero point on Kelvin scale is the lowest possible theoretical temperature that exists in the universe, i.e., –273.15 °C or 0 K. As the temperature goes down, the average energy and the speed of the molecule decreases. There is a temperature at which the molecule stops moving. That temperature is called *absolute zero*.

The freezing point of water is 273.15 K. Boiling point of water is 373.15 K. Each division in the scale is called *Kelvin*. Neither the term *degree* nor the symbol (°) is used. As there is no negative numbers on the Kelvin scale, it is very convenient to use Kelvin scale to measure extremely low temperatures for scientific research.

A comparison of the above three scales is shown in Figure 1.1.

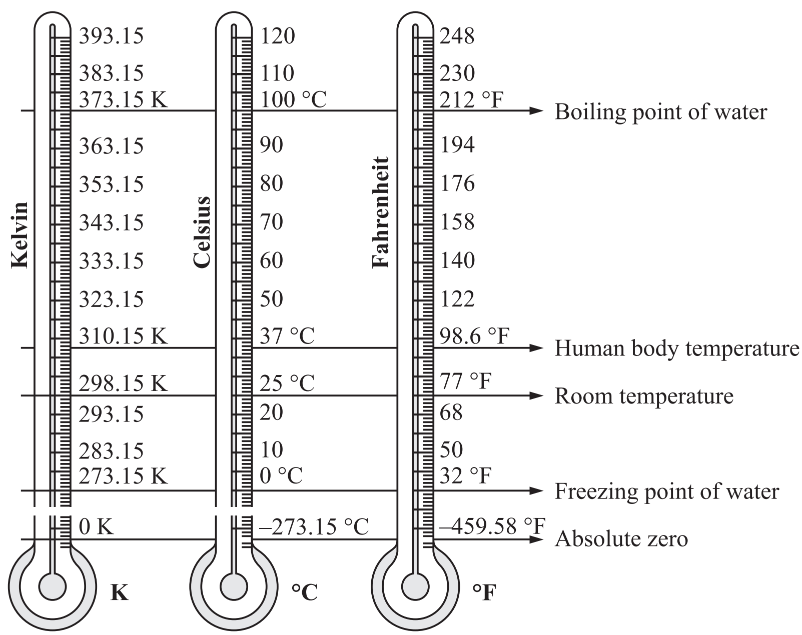


Figure 1.1 Comparison of different temperature scales.

The temperature measured in one scale can easily be converted to another by using simple formulae given in Table 1.1.

Table 1.1 Conversion of Degree Celsius, Degree Fahrenheit and Degree Kelvin into each other

From	To		
	°C	°F	K
°C	C	(C × 1.8) + 32	C+ 273.15
°F	(F – 32)/1.8	F	(F – 32) 5/9 + 273.15
K	K – 273.15	(K – 273.15) 9/5 + 32	K

1.3.1 Absolute Temperature

It is the theoretical lowest temperature possible in the universe. *Absolute temperature* is the theoretical temperature at which all the molecular motions stop and substances possess no thermal energy. Temperature of any substance cannot fall below this temperature. For calculation, absolute zero temperature is taken as –273 °C or 0 K.

1.4 PRESSURE

Pressure is defined as the force per unit area exerted by a body on its surface in a direction normal to the surface. It is caused by the collision of molecules of a substance with the boundaries of the system. As molecules hit the walls, they exert force and try to push the wall outward.

The unit of pressure depends upon the unit of force and the unit of area. Different units of pressure are used in power plant. Some of them are given below:

- kilogramme per square centimetre (kg/cm^2)
- kilogramme per square metre (kg/m^2)
- Newton per square centimetre (N/m^2)
- Pound per square inch (psi)
- Millimetre of mercury column (mmHg)
- Millimetre of water column (mmwc or mmH_2O)
- Atmospheric absolute (ata)
- Barometric (bar)
- kilopascal (kPa)

Also, there are many more pressure units. But only some important units are mentioned here. The relation between all these units is given at end of the book.

1.4.1 Gauge Pressure and Absolute Pressure

Pressure gauges are mounted at different pipelines and systems of a power plant. In practice, pressure gauge shows the difference between the actual pressure of the system and the atmospheric pressure. The reading of pressure gauge is known as gauge pressure. The actual pressure or absolute pressure of the system (Figure 1.2) can be obtained by adding gauge pressure with atmospheric pressure.

$$\text{Absolute pressure} = \text{Gauge pressure} + \text{Atmospheric pressure}$$

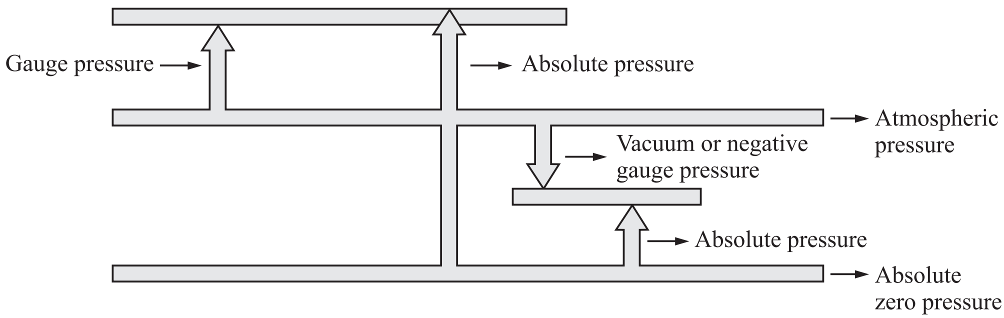


Figure 1.2 Absolute pressure and gauge pressure.

The value of atmospheric pressure is taken as 1.0332 kg/cm^2 or 1.0132 bar absolute at sea level. If the height of the place is more than the sea level, then the atmospheric pressure of that place is less. At the sea level, the height of mercury column is 760 mm with the density of mercury taken as 13.5951 g/cm^3.

1.5 HEAT

Heat is the amount of energy in a system. It is transferred from higher temperature objects to lower temperature object through radiation, conduction or convection. *Heat* of an object is the total kinetic energy of its molecules (and the temperature of an object is the measurement of average energy of its molecules). Heat is denoted by Q and its SI unit is joule (J).

Heat is measured by the quantity required to raise the temperature of a known mass of water through some known temperature. Following three units are used to measure the amount of heat:

- Calorie
- Centigrade heat unit (CHU)
- British thermal unit (BTU)

Calorie: It is the amount of heat required to raise the temperature of one gram of water by one degree Celsius. Its larger unit is kilocalorie (kcal) which may be defined as the quantity of heat required to raise the temperature of one kilogramme of water through one degree Celsius.

$$1 \text{ kcal} = 1000 \text{ cal}$$

Centigrade heat unit (CHU): It is the amount of heat required to raise the temperature of one pound of water by one degree Celsius.

$$1 \text{ pound} = 453.6 \text{ g}$$

So, $1 \text{ CHU} = 453.6 \text{ cal}$

British thermal unit (BTU): It is the amount of heat required to raise the temperature of one pound of water through one degree Fahrenheit.

In SI unit, unit of heat is joule (J) or kilojoule (kJ). When *m* kilogramme of substance is heated up to T Kelvin and specific heat is *C* kilojoule per kilogramme degree Celsius, then the amount of heat (in kilojoules) required is given by

$$H = mCT$$

$$1 \text{ kcal} = 4.1868 \text{ kJ}$$

1.5.1 Specific Heat

Specific heat of any substance is defined as the amount of heat required to raise the temperature of a unit mass of a substance by one degree Celsius. It is normally denoted by *C*.

Heat required to raise the temperature of one kilogramme of water by one degree Celsius is one kilocalorie. So, the specific heat of water is one.

Specific heat of some substances which are required by a boiler engineer is given in Table 1.2.

Table 1.2 Specific Heat of Some Substances

Substance	Specific Heat (kcal/kg)
Steel	0.117
Coal	0.241
Coke	0.200
Water	1.00
Steam	0.500
Air	0.237
Oxygen	0.221
Flue gas	0.23

1.6 WORK

When force is applied on a body, the body moves and work is done. *Work* is the product of force applied on a body and the displacement of the body in the direction of applied force. If *F* newtons force acts on a body and produces a displacement of *X* metres in the direction of force, then the work done is given by

$$W = F \times X$$

Depending upon the units of force and displacement, the unit of work is decided. In MKS system, when force is one kilogramme and displacement is one metre, the unit of work is kilogram metre (kgm). In SI unit, the unit of work is newton metre (Nm).

1.7 POWER

Power is the rate of doing work. It is defined as the work done per unit time.

$$\text{Power} = \frac{\text{Work done}}{\text{Time taken}}$$

$$P = \frac{dW}{dT}$$

In metric system, the unit of power is metric horsepower. This is 4500 kgm/min.

In SI system, the unit of power is watt (W).

$$1 \text{ W} = 1 \text{ Nm/s}$$

or

$$1 \text{ W} = 1 \text{ J/s}$$

Bigger unit of power is kilowatt.

$$1 \text{ kW} = 1000 \text{ W}$$

1.8 ENERGY

Energy is the ability or capacity to do work. Different forms of energy like heat energy, light energy, chemical energy, electrical energy, atomic energy, etc. are available.

1.9 ENTHALPY

Enthalpy is a thermodynamic function of a system equivalent to the sum of the internal energy of the system plus the product of its volume and the pressure exerted on it by its surroundings. Symbolically, enthalpy H is the sum of the internal energy E and the product of the pressure P and the volume V of the system.

$$H = E + PV$$

1.10 LAWS OF THERMODYNAMICS

Thermodynamics is a branch of science concerned with heat and its conversion to mechanical energy. Following three laws are important in thermodynamics:

- Zeroth law of thermodynamics
- First law of thermodynamics
- Second law of thermodynamics

Zeroth Law of Thermodynamics

Zeroth law of thermodynamics speaks about thermal equilibrium. According to this law, if systems A and B are in thermodynamic equilibrium and systems B and C are in thermodynamic equilibrium, then systems A and C are also in thermodynamic equilibrium.

First Law of Thermodynamics

First law of thermodynamics is the law of conservation of energy. It states that energy cannot be created or destroyed. It is converted from one form to another. For example, from heat to work, from heat to light, from chemical to heat, etc.

Alternately, this law states that a definite amount of heat energy is required to produce a definite amount of mechanical energy and vice versa.

According to this law,

$$W \propto H \qquad \text{or} \qquad W = JH$$

where J is a constant called as joule mechanical equivalent of heat. It is defined as the amount of work done by the unit quantity of heat.

Total heat energy supplied is the sum of the external work done and the change in the internal energy.

$$H = E + W$$

where

H = heat supplied
W = work done
E = change in internal energy

Potential energy and kinetic energy are macroscopic forms of energy. These are visualised in terms of position and velocity of the substance. In addition to these macroscopic forms of energy, a substance poses several microscopic forms of energy due to rotation, vibration, translation and interaction among molecules of a substance. The sum of all these microscopic form of energy is called as *internal energy*.

Second Law of Thermodynamics

This law can be stated in the following two ways:

Kelvin and Planck statement: This is called as the first form of second law of thermodynamics or *Kelvin–Plank statement of second law*. According to this, it is impossible to convert all the heat supplied to an engine to get an equivalent amount of work. Some portion of the heat supplied is rejected.

So, the heat converted into work is always less than the heat supplied to engine. The ratio of the heat converted into work to the heat supplied to engine is known as thermal efficiency of the engine. So, thermal efficiency of any engine is always less than unity.

Clausius statement: According to this, without any external energy, heat cannot flow from cold object to hot object. Heat can flow from higher temperature to lower temperature. But some external energy is required in case of reverse situation, i.e., when heat flows from lower temperature to higher temperature.

Second law of thermodynamics also speaks about a useful state variable called as *entropy*, denoted by S. The change in entropy dS is equal to the heat transfer dH divided by temperature T.

$$dS = \frac{dH}{T}$$

1.11 SPECIFIC HEAT OF GAS

As discussed in previous section, *specific heat* of any substance is defined as the amount of heat required to raise the temperature of unit mass of that substance by one degree Celsius. It is important to note that all solids and liquids have one specific heat. But a gas can have a number of specific heats depending upon the condition under which it is heated.

The idea about following two types of specific heat of gas is helpful for a boiler engineer:

Specific heat at constant volume C_V: It is the amount of heat required to raise the temperature of a unit mass of a gas through one degree Celsius when the volume of the gas is kept constant.

If m kilogramme of gas is heated from initial temperature of T_1 degree Celsius to T_2 degree Celsius at constant volume, then the heat required is given by

$$H = mC_V(T_2 - T_1)$$

Specific heat at constant pressure C_P: It is the amount of heat required to raise the temperature of a unit mass of a gas through one degree Celsius when pressure is kept constant.

If m kilogramme of gas is heated from initial temperature of T_1 degree Celsius to T_2 degree Celsius at constant pressure, then the heat required is given by

$$H = mC_P(T_2 - T_1)$$

For a particular gas, C_P and C_V are assumed to remain constant.

C_P is always greater than C_V. As C_P and C_V remain constant for a particular gas, so their ratio also remains constant and is more than unity.

$$\gamma = \frac{C_P}{C_V}$$

1.12 THERMODYNAMIC PROCESS OF PERFECT GAS

When flow of energy takes place, various properties of gas like pressure, volume, temperature, specific energy, specific enthalpy also change. With the change in properties of a system, state of the system also changes. The path on which state of the system changes is called as thermodynamic process.

One example of a thermodynamic process is increasing temperature of a fluid while maintaining constant pressure. Another example is increasing pressure of a confined gas while maintaining a constant temperature.

There are different process like cyclic processes, reversible process, and irreversible process.

Cyclic process: In *cyclic process*, a system moves from a given initial state, goes through a number of different changes in state (going through various processes) and finally, returns to its initial state. Therefore, at the end of a cycle, all the properties have the same value they had at the beginning.

Reversible process: A *reversible process of* a system is a process that once taken place, can be reversed, leaving no change in either system or surrounding. But practically, there is no truly reversible process.

Irreversible process: An *irreversible process* is a process in which both the system and the surrounding cannot return to their original condition.

Apart from these processes, following are some important processes which help a boiler engineer in his practical field. Methods of heating and expanding of gas may be applied in case of superheated steam also.

1.12.1 Constant Volume or Isochoric Process

In this process, gas is heated at a constant volume. Temperature and pressure increase when heat is added to the system. As there is no change in the volume of the gas, so total heat supplied is stored in the gas as internal energy.

If m kilogramme of gas is heated at constant volume from initial temperature of T_1 degree Celsius to final temperature of T_2 degree Celsius, then the heat supplied which is equal to increase in the internal energy of gas is given by

$$H = mC_V(T_2 - T_1)$$

where C_V is the specific heat of the gas at constant volume.

$$H = E + W$$

In this case, work done is zero. So, the heat supplied is equal to

$$H = E = mC_V(T_2 - T_1)$$

This process is shown in the P–V and T–S diagram. P–V diagram [Figure 1.3(a)] shows the change in volume and pressure, whereas T–S diagram [Figure 1.3(b)] shows change in entropy and temperature of the gas. P–V and T–S diagrams are used to visualise the process in thermodynamic cycle and help to understand the changes in system parameter.

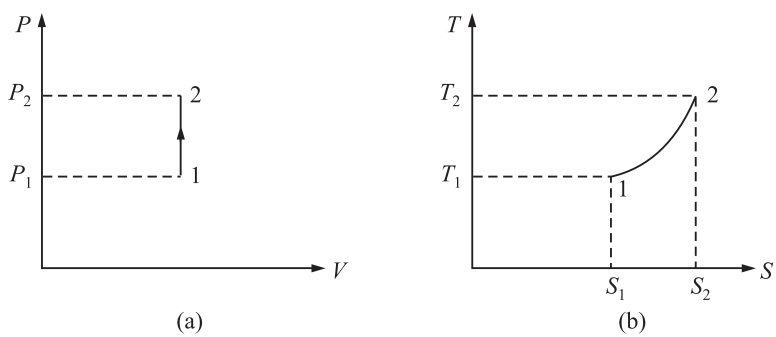


Figure 1.3 Constant volume process (a) P–V diagram and (b) T–S diagram.

1.12.2 Constant Pressure or Isobaric Process

When a gas is heated at constant pressure, its temperature as well as volume increases. As the volume and temperature increase, heat supplied is utilised for doing some external work and increasing internal energy.

If m kilogramme of gas is heated at constant pressure from initial temperature of T_1 degree Celsius to T_2 degree Celsius, then the heat supplied is given by

$$H = E + W$$
$$H = mC_P(T_2 - T_1)$$

where, C_P is the specific heat of gas at constant pressure.

This process is shown in P–V and T–S diagram (Figure 1.4).

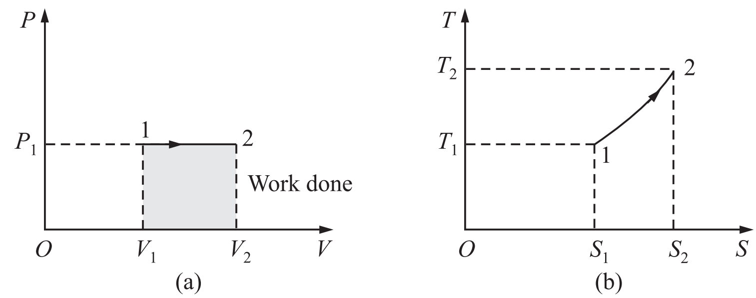


Figure 1.4 Constant pressure process (a) P–V diagram and (b) T–S diagram.

Work W done during this process is the shaded area below line 1–2.

So,
$$W = \text{Area of } 12V_2V_1$$
$$= \text{Area of } P_12V_2O - \text{Area of } P_11V_1\text{O}$$
$$= P_1V_2 - P_1V_1 = P_1(V_2 - V_1)$$

1.12.3 Constant Temperature or Isothermal Process

In this process, heat is supplied to a gas in such a way that its temperature remains constant and the volume of the gas increases. The expansion of the gas is called as isothermal expansion. When heat is taken out at constant temperature, volume of the gas decreases. As there is no change in the temperature of the gas, change in internal energy is zero. All the heat supplied is used for doing external work. In this process, PV is constant.

This process is shown in P–V and T–S diagrams (Figure 1.5).

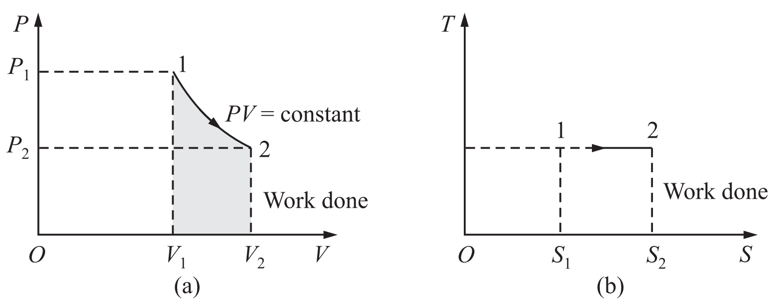


Figure 1.5 Isothermal process (a) P–V diagram and (b) T–S diagram.

Work done in this process is equal to heat supplied, as there is no change in internal energy.

1.12.4 Adiabatic Process or Isentropic Process

In this process, the system neither receives nor rejects any heat. The expansion and contraction of the gas depend upon the change in internal energy of the gas. As the internal energy changes in this process, so the temperature of the gas also changes. External work is done in this process.

In this process,

$$PV^{\gamma} = \text{Constant}$$

where, γ is the ratio of specific heats.

This process is shown in the *P–V* and *T–S* diagram (Figure 1.6).

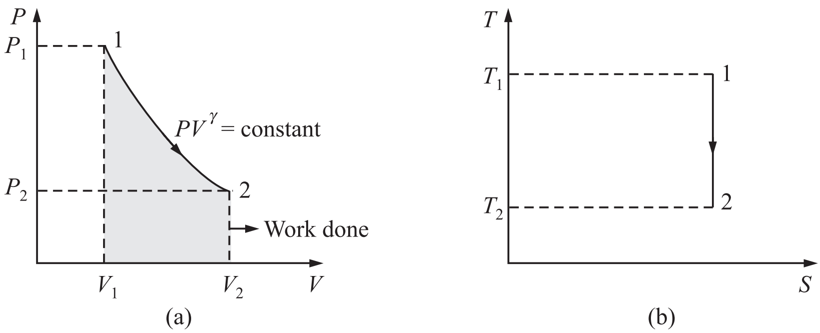


Figure 1.6 Adiabatic process (a) *P–V* diagram and (b) *T–S* diagram.

We know,

$$H = E + W$$

As there is no heat supplied, so $H = 0$

or

$$E = -W$$

1.12.5 Free Expansion Process

In this process, the gas is allowed to expand suddenly into a vacuum chamber through an orifice of large dimension. No heat is added or no external work is done and no internal energy is developed. So, in this case,

$$H = 0 \quad \text{and} \quad W = 0$$

1.12.6 Throttling Process

In this case, the gas is expanded through an aperture of small dimension like a slightly opened valve. There is also no work done, no heat is supplied and no change takes place in internal energy.

1.13 THERMODYNAMIC CYCLE

As discussed earlier, any change in the system like compression, expansion, heating and cooling, etc. can be represented on a *P–V* diagram. When any working fluid of a system undergoes a number of operations or processes in a certain order and finally, returns to the initial state, then a thermodynamic cycle takes place. In the *P–V* diagram, each operation has its own curve and finally, they form a closed figure. The work done during one cycle is given by the enclosed area of the *P–V* diagram.

There are a number of cycles in the field of mechanical engineering. But only about those cycles are discussed here which are useful for a boiler engineer.

1.13.1 Carnot Cycle with Steam as Working Fluid

Sadi Carnot, a French scientist and engineer in 1800, proposed an ideal cycle. In a heat engine, heat is always rejected. Work done is the difference between the heat absorbed and the heat rejected. The maximum efficiency is limited by temperature difference. The most efficient theoretical thermodynamic cycle which is possible between any two temperatures is given by *Carnot cycle* (Figure 1.7).

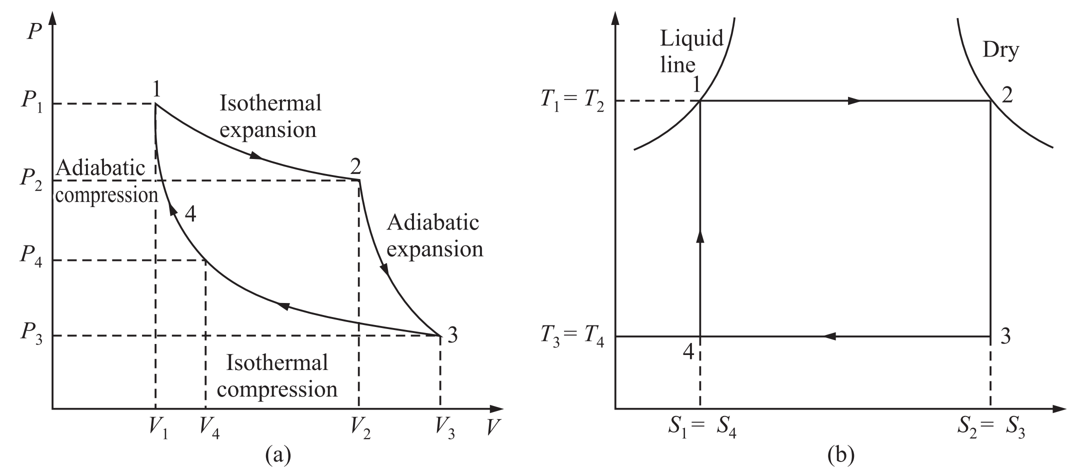


Figure 1.7 Carnot cycle (a) *P–V* diagram and (b) *T–S* diagram.

Carnot cycle is a four step process having two *isothermal processes* and two *adiabatic processes* (i.e., without heat transfer). In the isothermal steps, there is no change in internal energy and the heat supplied is equal to the work done. In two adiabatic processes, the heat is not exchanged. It is impossible to build such a system. This is an idealised process. The importance of the cycle is that it gives an idea about the highest efficiency of any cyclic process between two temperatures.

The four steps of Carnot cycle are explained below:

Isothermal expansion (1–2): The first process performed is an isothermal expansion. Volume and pressure of the fluid change from V_1 to V_2 and P_1 to P_2 respectively. This process is represented by curve 1–2.

Adiabatic expansion (2–3): The second process is an adiabatic expansion. During this process, the fluid is allowed to expand till point 3. At this point the volume, temperature and pressure are dropped to V_3, T_3 and P_3. This process is represented by curve 2–3.

Isothermal compression (3–4): The third process is again an isothermal compression. The fluid is compressed till point 4. This process is shown in curve 3–4.

Adiabatic compression (4–1): The fourth process performed on the fluid is an adiabatic compression. So, the fluid is compressed adiabatically from point 4 to point 1. Pressure and temperature return back to their original state as before starting of the cycle. This process is represented by curve 4–1.

Work done during the cycle = $(S_2 - S_1)(T_1 - T_3)$

Efficiency of Carnot cycle = $1 - T_3/T_1$

Carnot cycle is a theoretical cycle. No engine can be made on this cycle.

1.13.2 Rankine Cycle

Rankine cycle was proposed by Scottish engineer W. J. M. Rankine (1820–70). This cycle is mostly used at thermal power plants for power generation by steam turbine.

There are four processes in the Rankine cycle. During each process, the state of the working fluid changes. These states are identified by number in *P–V* and *T–S* diagrams of a Rankine cycle (Figure 1.8) using dry or superheated steam. Dashed lines are shown for Rankine cycle using superheated steam.

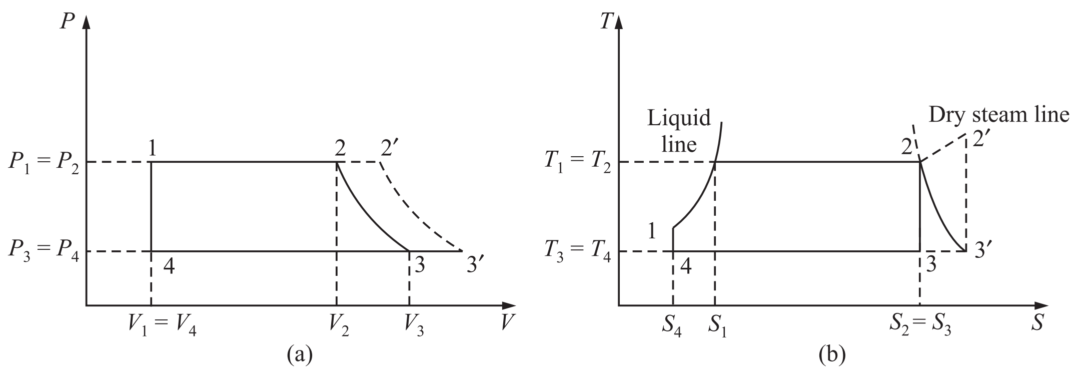


Figure 1.8 Rankine cycle (a) *P–V* diagram and (b) *T–S* diagram.

Process 4-1: First, the working fluid (feed water) is pumped from low pressure to high pressure by a boiler feed pump into the boiler. Pumping requires power input (for example, mechanical or electrical).

Process 1–2: The high pressure liquid (feedwater) enters a boiler where it is heated at constant pressure by an external heat source to convert it into superheated vapour. Heat is obtained by burning fuel.

Process 2–3: The superheated vapour expands in a turbine to generate power. Ideally, this expansion is adiabatic. Temperature and pressure of the vapour decrease upto the condenser pressure.

Process 3–4: The vapour then enters a condenser where it is cooled to make saturated liquid. This liquid then reenters to the boiler through pump and the cycle repeats.

The above discussed cycle is an ideal cycle. In practice, an actual rankine cycle is different from the ideal cycle. The actual cycle is 4–1′–2–3′, whereas the ideal cycle is 4–1–2–3, as shown in Figure 1.8 and 1.9.

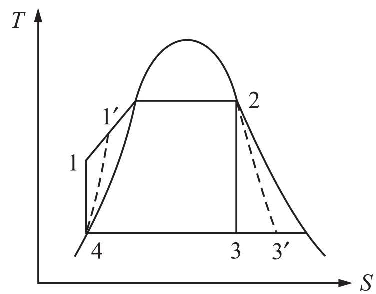


Figure 1.9 Actual Rankine cycle.

An actual rankine cycle differs from the ideal rankine cycle for the following reasons:

Turbine losses: During the expansion of steam in the turbine, there is always a heat loss to the surroundings and the expansion does not exactly follow 2–3. Instead, it follows a path 2–3′.

Pump losses: There is always a loss in the pump. So, the process follows 4–1′ instead of actual path 4–1.

Condenser losses: Sometime, the fluid cools below the saturation temperature at condenser. This is called as subcooling. So, more heat is required to bring the liquid upto the saturation temperature.

We know that carnot cycle can develop maximum power with certain high and low temperature limits than any other cycle. It is not practicable to get an efficiency equal to that of a carnot cycle. But, it is always expected to gain an efficiency close to that of a carnot cycle. In thermodynamic cycle, a small gain in overall efficiency is an important achievement.

Following two methods are adopted to increase the efficiency of rankine cycle:

- By reheating the exhaust steam and using it again at turbine (reheat cycle)
- By extracting some steam from the turbine and using it for feedwater heating (regenerative cycle)

These thermodynamic cycles are called as *modified rankine cycle*.

Reheat Rankine Cycle

Increasing boiler pressure increases the thermal efficiency. But steam becomes wet at the exhaust end. Wet steam causes erosion of turbine blades. In reheat Rankine cycle, this problem is avoided. Steam is extracted from high pressure turbine and then, it is reheated in the boiler again and sent back to the low pressure turbine for further expansion. Thus, excessive moisture in the low pressure stages of the turbine is avoided. There are two turbines working in series.

As shown in Figure 1.10, steam after expanding at high pressure turbine from 3–4 is extracted and further heat is added to it at boiler. This is represented by 4–5. This reheated steam enters the low pressure turbine and further gets expanded till the condenser pressure is achieved. This process is represented by 5–6.

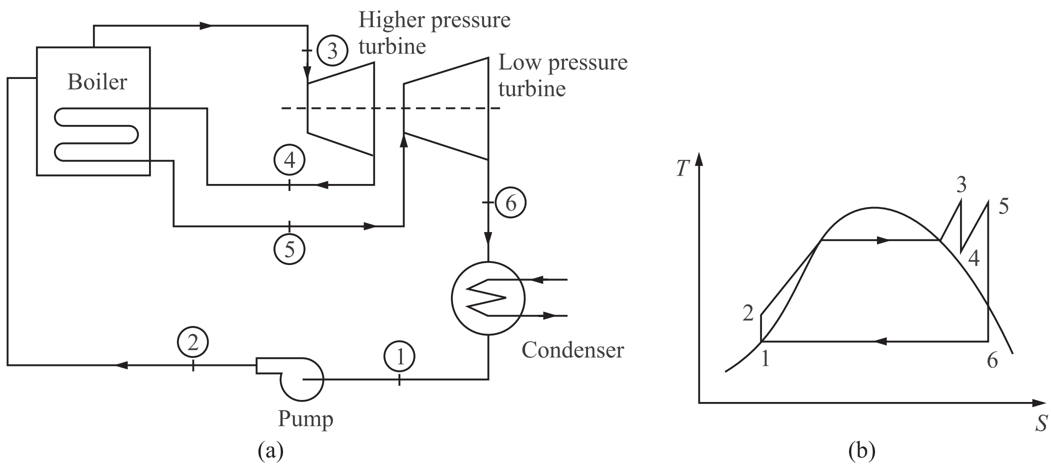


Figure 1.10 Reheat Rankine cycle (a) Flow diagram of reheat Rankine cycle and (b) *T–S* diagram of reheat Rankine cycle.

Benefits of reheat: The benefits of reheat are given below:

- Boiler pressure can be increased without increase of moisture content at turbine exhaust.
- Average temperature of the steam entering the turbine is increased, so the thermal efficiency of the cycle increases.

Regenerative Rankine Cycle

In regenerative Rankine cycle (Figure 1.11), considerable amount of energy input is required at boiler to heat the high pressure feedwater from its normal temperature to the saturation temperature. To reduce this energy, the feedwater is preheated before it enters the boiler. Preheating of feed water is done by regeneration method. The device in which feed water is heated is called as feedwater heater. Some steam is extracted from various stages of the turbine and used to preheat the feedwater.

Benefits of regeneration: The benefits of regeneration are given below:

- Energy loss within the condenser is less, since less steam is condensed.
- Temperature of feedwater entering the boiler increases. So, the efficiency of the cycle also increases.

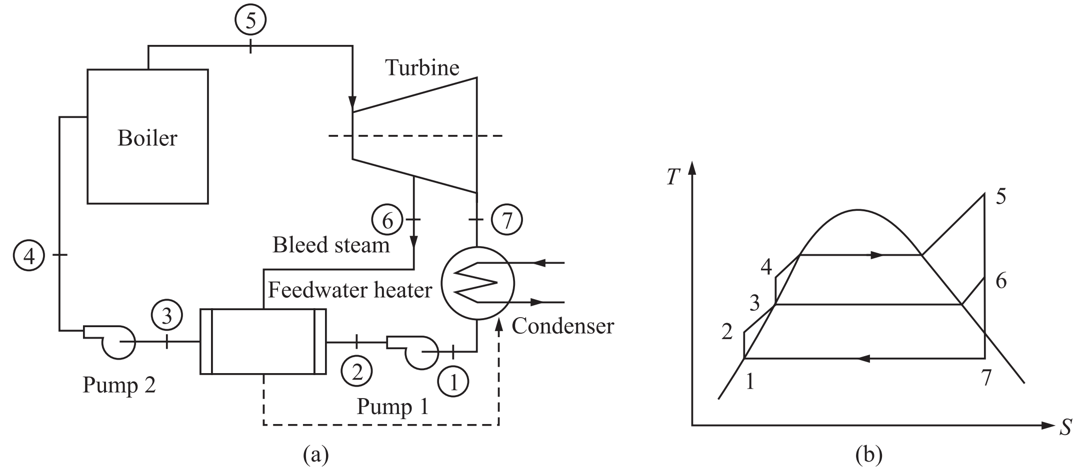


Figure 1.11 Regeneratiive Rankine cycle (a) Flow diagram of regenerative Rankine cycle and (b) *T–S* diagram of regenerative Rankine cycle.

Regeneration is achieved by open or close feedwater heaters. In closed system, the bled steam from the turbine is not directly mixed with the feed water and therefore, the two streams can be at different pressures. In practical steam power plants, various combinations of open and closed feedwater heaters are used. Deaerator is an open heater and low pressure/high pressure heaters are closed feedwater heaters.

Combined Reheat and Regenerative Rankine Cycle

In practice, the combination of reheat and regenerative Rankine cycle is used in thermal power plants. Single or double stage reheat along with a series of high pressure and low pressure feedwater heaters are used in practical power plant. The combined reheat and regenerative cycle is shown in Figure 1.12.

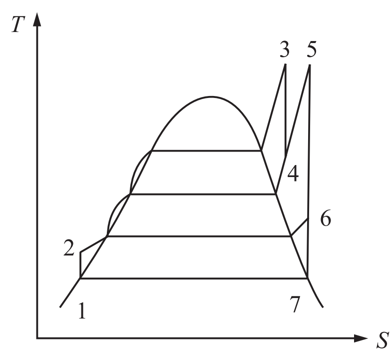


Figure 1.12 Benefits of combination of reheat and regenerative cycle: This arrangement increases the thermal efficiency of the plant.

Details about the reheat and regenerative heater arrangement are discussed later.

Effect of Design Parameters on Rankine Cycle

Power plant is required to be designed for the highest efficiency as far as possible and steam parameters are selected accordingly. Rankine efficiency increases with the increase in steam pressure and temperature. Regenerative or reheat cycle is selected depending upon the capacity of the plant and other conditions. The effects of parameters on Rankine cycle efficiency are discussed below:

Effect of inlet steam pressure: If the turbine inlet steam pressure is increased, then Rankine cycle efficiency also increases. It can be seen from Figure 1.13. Cycle area changes from 1–2–3–4 to 1–2′–3′–4′. After the expansion at turbine, steam condition shifts towards the left, i.e., from 4 to 4′. The steam becomes more moist. So, the inlet pressure should be selected in such a way so that minimum heat rate is achieved with allowable exhaust steam condition for a particular inlet steam temperature. Excessive moist steam can damage the turbine blades. Otherwise, to avoid excessive moist steam, reheat cycle can be considered.

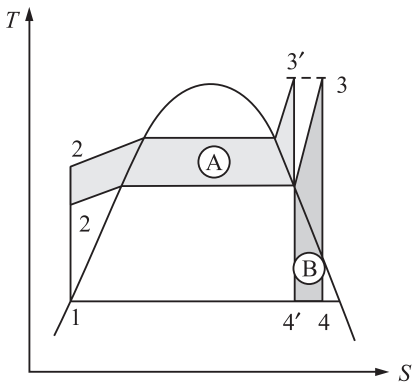


Figure 1.13 Effect of inlet steam pressure on Rankine cycle.

Increase in work done is given by the difference of area *A* and area *B*, as shown in Figure 1.13.

Effect of inlet steam temperature: On increasing the turbine inlet steam temperature, the efficiency of Rankine cycle increases. This can be seen from Figure 1.14. Cycle area changes from 1–2–3–4 to 1–2–3′–4′.

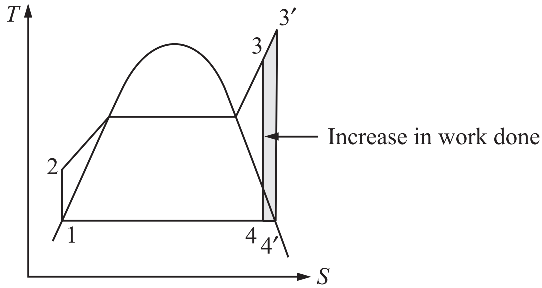


Figure 1.14 Effect of the inlet steam temperature on Rankine cycle.

It is clear that area 3–3′–4′–4 is added to the previous area 1–2–3–4. So, the net work done increases. For high temperature use, costly alloy steel is required and also, due to metallurgical limitations, temperature of the steam cannot be increased beyond certain limits.

Effect of exhaust pressure: If the turbine exhaust pressure decreases from 4 to 4′, then the cycle efficiency increases, as shown in Figure 1.15. More work is done by the steam and the area of the cycle changes from 1–2–3–4 to 1′–2′–3–4′.

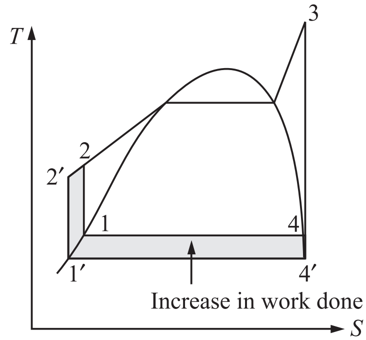


Figure 1.15 Effect of exhaust pressure on Rankine cycle.

It can be seen from Figure 1.15 that area 1′–2–4–4′ is added to the earlier area 1–2–3–4. The condenser vacuum is to be maintained as low as possible. Air ingress in the vacuum system or scaling of condenser tube can increase the condenser pressure.

1.13.3 Brayton Cycle

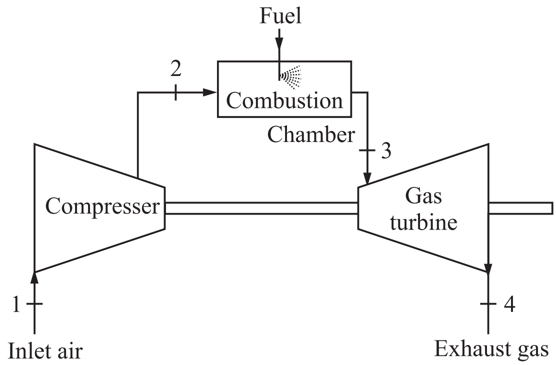
The Brayton cycle or Joule cycle is a thermodynamic cycle related to the gas turbine. Gas turbines are used for power generation. Mostly, the combined cycle technology is used worldwide for efficient way of power generation. Details about the combined cycle are discussed later.

Brayton cycle consists of following three components:

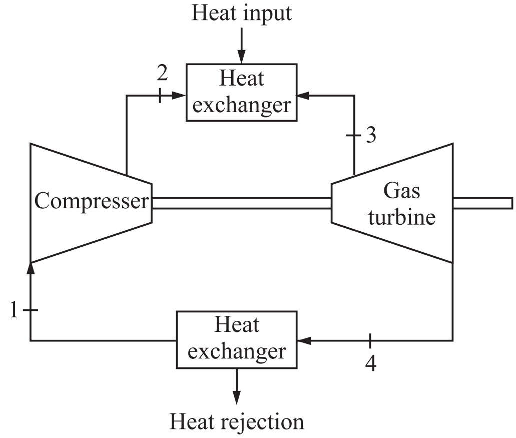
- A compressor
- A Combustion chamber
- An expansion turbine

Usually, the gas turbine is operated on open cycle [Figure 1.16(a)]. Fresh atmospheric air enters the compressor where it is compressed. This compressed air then enters the combustion chamber where fuel is burnt and heat is added at constant pressure. After that, the hot compressed air enters the turbine where it is expanded to atmospheric pressure. After expanding, the exhaust gas is discharged to the atmosphere. A part of the power developed in the turbine is to be supplied to the compressor power requirements and the remaining is available to drive the turbine.

In close cycle operation [Figure 1.16(b)], both the compression and expansion processes remain same as open cycle but the combustion process is replaced with the heat addition at constant pressure by the external source and the exhaust process is replaced with the heat rejection at atmospheric and constant air pressure.



(a) Open cycle operation



(b) Closed cycle operation

Figure 1.16 Brayton cycle arrangement (a) Open cycle operation and (b) Closed cycle operation.

The above process can be summarised as below:

- 1–2 adiabatic compression at compressor
- 2–3 constant pressure heat addition
- 3–4 adiabatic expansion in the turbine
- 4–1 constant pressure heat rejection

These four processes are shown in *P*–*V* and *T*–*S* diagrams given in Figure 1.17.

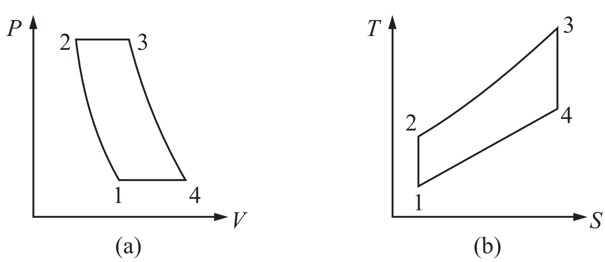


Figure 1.17 Brayton cycle (a) *P*–*V* diagram and (b) *T*–*S* diagram.