## Course Title:

# Fundamental of Thermodynamics and Heat Transfer

## Lecture 13 (Week 13):

# Thermodynamic Cycles

## Lecturer: Assoc. Prof. Dr. Lila Raj Koirala

## Learning Objective of Lecture:

To impart a great deal of knowledge to undergraduate students on the following topics:

- ✓ Thermodynamic Cycles
- ✓ Classification of Thermodynamic Cycles
- ✓ Air Standard Brayton Cycle
- ✓ Rankine Cycle
- ✓ Internal Combustion Cycles
- ✓ Operation of Four Stroke Engines

## 6.0. Thermodynamic Cycles

As mentioned earlier, a thermodynamic cycle or a cyclic process is a combination of a series of individual thermodynamic processes that starts at some initial state and returns to the same initial state, i.e., initial and final states are identical. Most of the devices which are used for energy conversion operate on cyclic processes. These devices are used, in one hand, to produce work output by supplying heat from the burning of fossil fuels in a combustion chamber or within engine itself and in other hand, to provide heating or cooling effect by supplying work input usually through electrical power. In the followings, the working principles of different idealized practical cycles are described with the analysis of their performances (efficiencies).

### 6.1. Classification of Thermodynamic Cycles

Practical cycles can be categorized in different types based on different features. Some of these features are described below:

**(a) Based on Working Principle**
Based on working principle, cycles are categorized as a closed cycle and an open cycle.

**Closed Cycle:**
A cycle in which the working substance is continuously circulated in the cycle and does not need replenishment is called a closed cycle. Most of the steam power cycles and refrigeration cycles are closed type.

**Open Cycle:**
A cycle in which the working substance may be thrown into environment after completion of each cycle and a fresh charge of the working substance enters the cycle again for next cycle is known as an open cycle. Open cycles are more possible when air is the working substance. Most of the internal combustion engines and gas turbines work on open cycle where cycle exhausts are emitted into atmosphere and cycle starts again with a fresh charge of air.

**(b) Based on Working Substance**
Based on working substance, cycles are categorized as a gas cycle and a vapor cycle.

**Gas Cycle:**
If the working substance remains in gaseous state or there is no phase change during the execution of the cycle, then such a cycle is known as a gas cycle. Some common examples of gas cycles are Brayton cycle, Otto cycle, Diesel cycle, etc.

**Vapor cycle**:
If the working substance undergoes phase change (from liquid to vapor or vapor to liquid) during the execution of the cycle, then such a cycle is called a vapor cycle. Most common example of vapor power cycle is Rankine cycle.

### (c) Based on Power or Work

Based on power or work, cycles are categorized as a power cycle and a refrigeration cycle.

**Power Cycle:**
If a cycle produces power or delivers work to the surroundings during the execution of the cycle, then such a cycle is known as a power cycle. Power cycle operates a heat engine. Hence, network is always positive for a power cycle. Some common examples of power cycles are Brayton cycle, Otto cycle, Diesel cycle, Rankine cycle, etc.

**Refrigeration Cycle:**
A cycle is said to be a refrigeration cycle, if power or work should be supplied to execute the cycle. Refrigeration cycle operates a heat pump and refrigerator. Hence, network is always negative for a refrigeration cycle. Most common example of refrigeration cycle is Vapor compression refrigeration cycle.

### (d) Based on Combustion Location

This categorization is applicable only for power cycles. Based on combustion location, cycles are categorized as internal combustion cycle and external combustion cycle.

**Internal Combustion Cycle:**
If the combustion or burning of fossil fuel takes place inside any one component of the system (within engine itself), then such a cycle is known as an internal combustion cycle. In internal combustion cycles, the working substance and fuel come in physical contact with each other. Some common examples of internal combustion cycles are Otto cycle and Diesel cycle.

**External Combustion Cycle:**
If the combustion or burning of fossil fuel takes place outside the system e.g. in a combustion chamber, then such a cycle is called an external combustion cycle. In external combustion cycles, the working substance and fuel do not come in physical contact with each other. Some common examples of external combustion cycles are Brayton cycle and Rankine cycle.

Internal combustion cycles are further divided into following two categories:

### (a) Based on Ignition Method

Based on the method of ignition adopted, internal combustion cycles are categorized as spark ignition (SI) and compression ignition (CI) cycles.

**Spark Ignition (SI) Cycle:**
If the compressed working substance (mixture of air and fuel) of the cycle is ignited by an electric spark so that the combustion takes place and energy is liberated by the spontaneous exothermic chemical reaction, then such a cycle is called a spark ignition (SI) cycle. This type of combustion is called constant volume combustion. The common example of spark ignition cycle is Otto cycle or petrol cycle.

**Compression Ignition (CI) Cycle:**
If the air is compressed to a high pressure and temperature that is above the auto-ignition temperature of the fuel and the fuel injected after compression process ignites quickly resulting the combustion, then such a cycle is called a compression ignition (CI) cycle. Such combustion is known as constant pressure combustion. The common example of compression ignition cycle is Diesel cycle.

### (b) Based on Working Stroke

Based on the number of working strokes needed to complete a cycle, internal combustion cycles are categorized as four stroke and two stroke cycles.

**Four Stroke Cycle:**
If the cycle is completed in two revolutions of the crankshaft or four strokes of piston, then the cycle is called the four stroke cycle, e.g. a four stroke engine cycle such as four stroke petrol or Diesel engine.

**Two Stroke Cycle:**
If the cycle is completed in one revolution of the crankshaft or two strokes of piston, then the cycle is called the two stroke cycle, e.g. a two stroke engine cycle such as two stroke petrol or Diesel engine.

## 6.1.1. Common Features of Power Cycles

In practice, simple idealized thermodynamic cycles are usually composed of four thermodynamic processes. Although any number (two or more than two) of thermodynamic processes may be used to complete a cycle. However, when idealized practical cycles are modeled, thermodynamic processes where one property of a state is kept constant are often used as shown in table (6.1). Thus, all practical power cycles consist the following four thermodynamic processes in series: compression, heat addition, expansion and heat rejection. For ideal analysis of all power cycles, expansion and compression processes are assumed to be isentropic processes. Hence, they are differentiated only with respect to the conditions at which heat is added to the system and heat is rejected by the system. The table (6.1) illustrates the comparison between different power cycles with respect to different thermodynamic processes that they undergo with one constant property.

Table 6.1: Comparison between different power cycles [1]

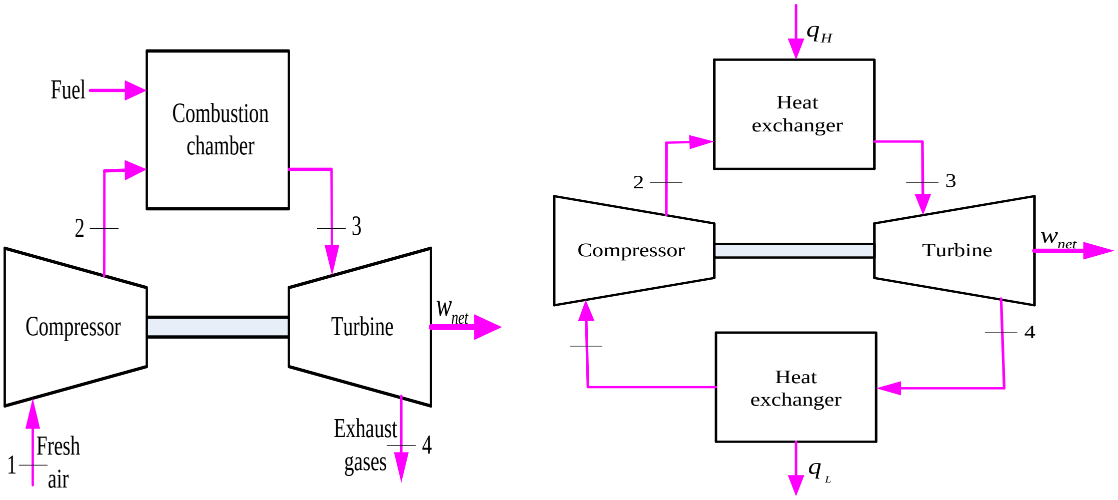
| **Processes** | **Power cycles** | | | | |
|---|---|---|---|---|---|
| | **Carnot** | **Otto** | **Diesel** | **Brayton** | **Rankine** |
| **Compression** | Isentropic | Isentropic | Isentropic | Isentropic | Isentropic |
| **Heat Addition** | Isothermal | Isochoric | Isobaric | Isobaric | Isobaric |
| **Expansion** | Isentropic | Isentropic | Isentropic | Isentropic | Isentropic |
| **Heat Rejection** | Isothermal | Isochoric | Isochoric | Isobaric | Isobaric |

## 6.2. Air Standard Brayton Cycle

The Brayton cycle which is also known as Joule cycle was first developed by an American engineer George Brayton for use in piston engine with fuel injection around 1870. However, nowadays it is widely used in open cycle as well as closed cycle gas turbine engines only. Gas turbines usually operate on an *open cycle*. In an open gas turbine cycle, fresh air at atmospheric conditions is drawn into the compressor and the exhaust gases leaving the gas turbine after execution of the cycle are thrown out (not re-circulated) to the atmosphere again, as shown in figure 6.1(a).

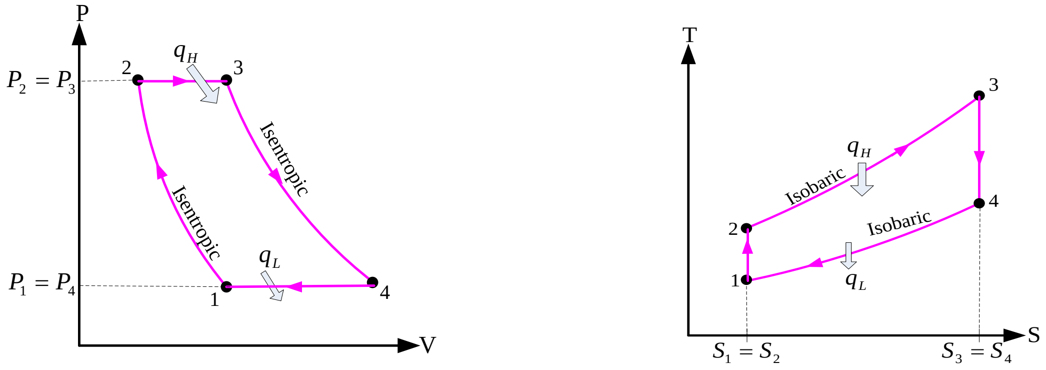
The open gas-turbine cycle can be modeled as a *closed cycle* by utilizing the air-standard assumptions mentioned earlier. In a closed gas turbine cycle, air as the working substance is drawn into the compressor and the exhaust gases leaving the gas turbine are passed to a heat exchanger where they reject the heat to the atmospheric air, attaining the initial conditions and are re-circulated for next cycle as shown in figure 6.1(b). Such an ideal cycle in which the working substance (air) undergoes in a closed loop is known as the ideal *Brayton cycle*. Hence, Brayton cycle is an ideal power cycle consisting of a gas turbine which consists of two isentropic and two isobaric processes as described below.

The schematic arrangement of the different components or devices of an ideal Brayton cycle are shown in figures 6.1 (a) and (b). The *P-v, T-s* and *P-h* plots for an ideal Brayton cycle are given in figures 6.2 (a) (b) and (c) respectively.

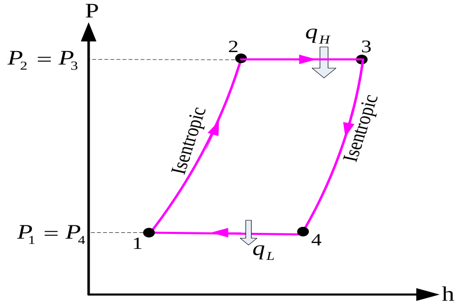


(a) An open cycle (b) A closed cycle

Figure 6.1: Different components of an ideal Brayton cycle [2]



(a) *P-V* diagram (b) *T-S* diagram



(c) *P-h* diagram

Figure 6.2. $P - V$, $T - S$ and *P-h* diagrams for an ideal Brayton cycle

### (i) Isentropic Compression (Process $1 - 2$)

Air at low pressure and low temperature is supplied to the compressor where it is compressed and delivered to a heat exchanger. The compression process occurring in the compressor is assumed to be isentropic. Hence, during this isentropic compression process the pressure, temperature as well as enthalpy of the working substance increase and its volume decreases while entropy of the system remains constant.

**(ii) Isobaric Heat Addition (Process $2-3$)**

The working substance air at state 2 is passed through a heat exchanger where heat is supplied to it from an external source and the air is heated under constant pressure. Hence, during this isobaric heat addition process the volume, temperature, enthalpy and entropy of the air increase.

**(iii) Isentropic Expansion (Process $3-4$)**

The air at high temperature and high pressure leaving the heat exchanger is supplied to the turbine. The turbine produces work by consuming high energy carried by the air at the turbine inlet (state 3). The expansion process occurring in the turbine is assumed to be isentropic. Hence, during this isentropic expansion process the pressure, temperature as well as enthalpy of the air decreases and its volume further increases whereas entropy of the system remains constant.

**(iv) Isobaric Heat Rejection (Process $4-1$)**

The air at state 4 from the turbine exit is passed through a heat exchanger where it rejects heat to the low temperature sink such that its initial state 1 is restored to complete the cycle. This heat rejection process occurs at constant pressure during which the volume, temperature, enthalpy and entropy of the air decrease.

## Calculation of Thermal Efficiency of Brayton Cycle

All four processes of the ideal Brayton cycle explained above are executed in steady flow devices. Hence, they should be analyzed as steady flow processes. When the changes in kinetic and potential energies are neglected, work produced by adiabatic turbine per kg of air is then given by

$$w_T = w_{34} = h_3 - h_4 = c_P(T_3 - T_4) \qquad \text{………} (6.1)$$

Similarly, work consumed by the adiabatic compressor per kg of air can be expressed as

$$w_C = w_{12} = h_2 - h_1 = c_P(T_2 - T_1) \qquad \text{………} (6.2)$$

During steady state operation of the cycle, some part of the work produced by the turbine is utilized to run the compressor. The ratio of the compressor work to the turbine work is known as *back work ratio*. Hence, the net work delivered to the surroundings is determined as

$$w_{net} = w_T - w_c = c_P[(T_3 - T_4) - (T_2 - T_1)] \qquad \text{………} (6.3)$$

Heat supplied to the air in the high temperature heat exchanger as flow device is calculated as

$$q_H = q_{23} = h_3 - h_2 = c_P(T_3 - T_2) \qquad \text{………. (6.4)}$$

Thermal efficiency of the ideal Brayton cycle is then derived as

$$\eta_B = \frac{w_{net}}{q_H} = \frac{c_P[(T_3 - T_4) - (T_2 - T_1)]}{c_P(T_3 - T_2)} = \frac{[(T_3 - T_2) - (T_4 - T_1)]}{(T_3 - T_2)} \qquad \text{...……..(6.5)}$$

Equation (6.5) can also be expressed as

$$\eta_B = 1 - \frac{T_4 - T_1}{T_3 - T_2} \qquad \text{…..…… (6.6)}$$

Equation (6.6) requires the temperatures of each state to determine the efficiency of the cycle. It can be further simplified to reduce the number of required variables. For this, applying pressure - temperature relationship for isentropic compression process $1 - 2$ and isentropic expansion process $3 - 4$,

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \qquad \text{…..…..... (6.7)}$$

and $$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}} \qquad \text{…...…. (6.8)}$$

Putting $P_3 = P_2$ from the isobaric heat addition process 2 – 3 and $P_4 = P_1$ from the isobaric heat rejection process 4 – 1 in equation (6.8), we get

$$\frac{T_3}{T_4} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \qquad \text{…....…. (6.9)}$$

Equating equations (6.7) and (6.9) gives

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} \quad \text{or,} \quad \frac{T_4}{T_3} = \frac{T_1}{T_2} \qquad \text{…......…. (6.10)}$$

Now, by using $T_4 = \frac{T_1}{T_2} T_3$ from equation (6.10), the following expression reduces to

$$\frac{T_4 - T_1}{T_3 - T_2} = \frac{T_1}{T_2} \frac{(T_3 - T_2)}{(T_3 - T_2)} = \frac{T_1}{T_2} \qquad \text{…..……. (6.11)}$$

Combining equations (6.6), (6.10) and (6.11) yields

$$\eta_B = 1 - \frac{T_1}{T_2} = 1 - \frac{T_4}{T_3} \qquad \text{……….} (6.12)$$

Now, from the equation (6.12) the thermal efficiency of the cycle can be determined by knowing only the temperatures of two states namely either of states 3 and 4 or of states 1 and 2. This equation can be further simplified by substituting equations (6.7) and (6.9) into equation (6.12), then thermal efficiency of an ideal Brayton cycle can be expressed in terms of pressure ratio as

$$\eta_B = 1 - \left(\frac{P_1}{P_2}\right)^{\frac{\gamma-1}{\gamma}} = 1 - \left(\frac{1}{r_P}\right)^{\frac{\gamma-1}{\gamma}} \qquad \text{……….} (6.13)$$

where $r_P = P_2/P_1$ is called pressure ratio. The pressure ratio for maximum net work developed by the cycle can be derived by putting derivation of net work with respect to pressure ratio equal to zero as

$$r_P = \left(\frac{T_3}{T_1}\right)^{\frac{\gamma}{2(\gamma-1)}} \qquad \text{……….}(6.14)$$

Equation (6.13) shows that the thermal efficiency of an ideal Brayton cycle depends on the pressure ratio $r_P$ of the gas turbine and the specific heat ratio $\gamma$ of the working substance. The thermal efficiency of the cycle increases when both of these parameters are increased, which is also the case for actual gas turbines. Although high pressure ratio is desirable for high thermal efficiency but in reality high pressure ratio causes high temperature and there is a limitation to which actual turbine blades can withstand maximum temperature or pressure. This then limits the pressure ratio that can be used in the cycle. In an actual gas turbine cycle (Brayton cycle) pressure ratio is usually between 11 to 16 [1]. The thermal efficiency of the Brayton cycle can be improved by using multistage compression with intercooling, multistage expansion with reheating and regeneration.

A plot of thermal efficiency of an ideal Brayton cycle versus the pressure ratio is shown infigure 6.3 for $\gamma = 1.4$, which is the specific heat ratio value of air at room temperature. The curve tends to become flat at higher pressure ratios which implies that though the thermal efficiency is increasing, the rate of increase starts diminishing at higher pressures.

The two major application areas of gas turbine engines with working substance air are aircraft propulsion and electric power generation. When the open cycle turbine engine is used for aircraft propulsion, the gas turbine produces just enough power to drive the compressor and a small generator to power the auxiliary equipment. The high velocity exhaust gases are responsible for producing the necessary thrust to propel the aircraft. Gas turbines are also used as a closed cycle in stationary power plants to generate electricity. The gas turbine cycle with working substance helium can also be executed as a closed cycle for use in nuclear power plants.

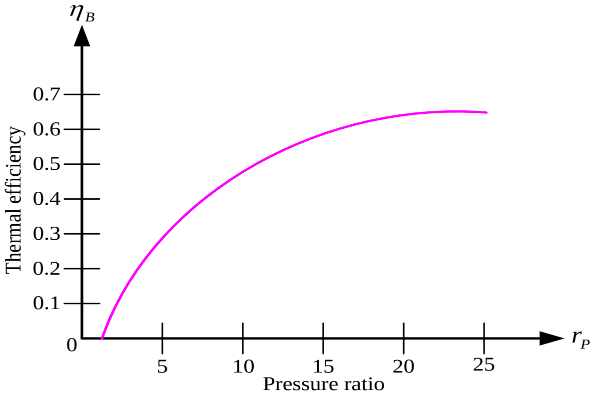


Figure 6.3: Variation of thermal efficiency of an ideal Brayton cycle with pressure ratio [3]

## 6.3. Rankine Cycle

Rankine cycle is an ideal power cycle consisting of a steam turbine. Hence, the Rankine cycle is the common cycle used in all steam power plants. This cycle was developed by a Scottish professor William Rankine to make use of water as working substance which changes its phase from liquid to vapor and vapor to liquid during the execution of the cycle. Therefore, this cycle is also known as a vapor power cycle. The schematic diagram of the arrangement of an ideal Rankine cycle with four basic components (devices) such as boiler, steam turbine, condenser and pump is shown in figure 6.4. The ideal Rankine cycle consists of four different processes namely two isentropic processes and two isobaric processes as described below. The various processes involved in Rankine cycle are shown on *P-v*, *T-s* and *P-h* diagrams in the figures 6.5 (a), (b) and (c) respectively.

### (i) Isentropic Pumping Process (Process $1 - 2$)

Water enters the pump at state 1 as saturated liquid and is compressed isentropically to the operating pressure of the boiler (state 2). The water temperature increases somewhat due to a slight decrease in the specific volume of water but the specific volume can be taken as almost constant as the liquid water is an incompressible substance. Thus, during this isentropic pumping process the working substance remains in liquid state as sub-cooled or compressed liquid at state 2. The pressure increases due to compression in pumping while entropy remains constant. The enthalpy can be taken as almost constant due to very small change in the temperature during this process.

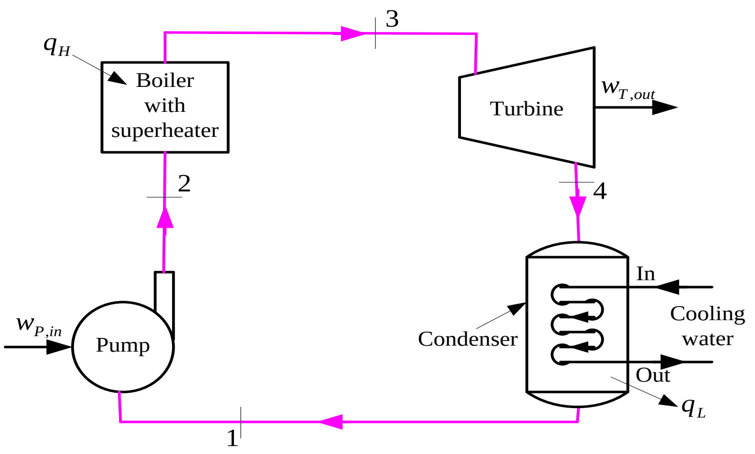
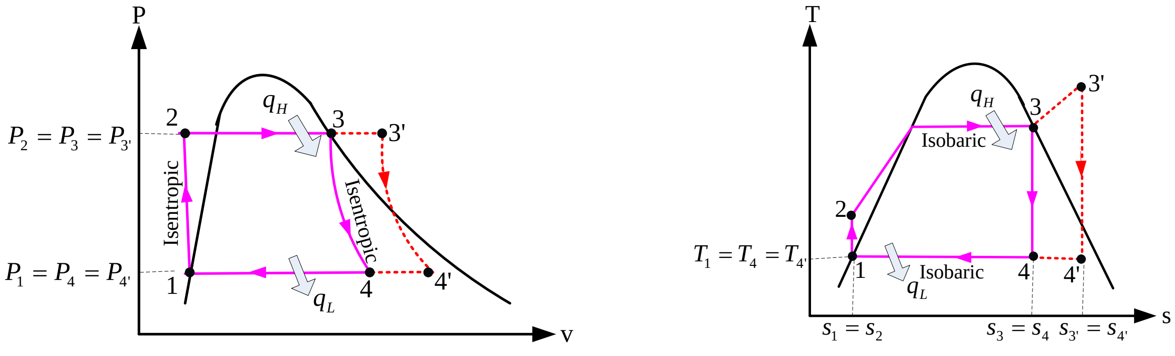


Figure 6.4: Schematic diagram of the arrangement of an ideal Rankine cycle with different components

### (ii) Isobaric Heat Addition (Process 2 – 3)

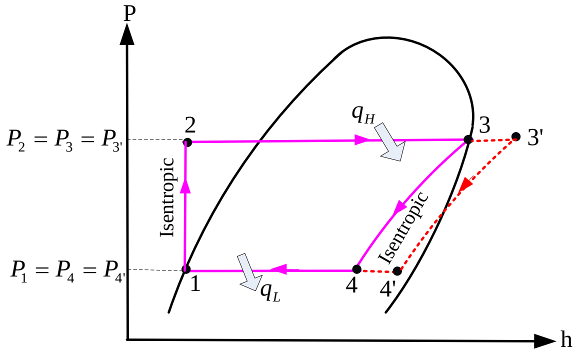
Water enters the boiler as a sub-cooled or compressed liquid at state 2 and leaves as a saturated vapor at state 3 or generally as a slightly superheated vapor at state 3'. The boiler is basically a large heat exchanger where the heat originating from combustion gases or other external sources is transferred to the water at constant pressure. The boiler together with the super heater is often called the steam generator where the steam is superheated.

Since the heat addition process in the boiler occurs at constant pressure, the temperature of the compressed liquid water increases until it becomes a saturated liquid and remains constant along two phase mixture region and again increases if it is further heated to convert into a superheated vapor. Hence, during the constant pressure heating process the specific volume, enthalpy and entropy of the steam increase.



(a) *P-v* diagram

(b) *T-s* diagram



*(c) P-h* diagram

Figure 6.5: $P - v$, $T - s$ and $P$ - $h$ diagrams for an ideal Rankine cycle with saturated vapor (state 3) and superheated vapor (state 3') at boiler outlet

### (iii) Isentropic Expansion (Process $3 - 4$)

The saturated vapor at state 3 or superheated vapor at state 3' enters the turbine, where it expands isentropically and produces work by rotating the shaft connected to an electric generator. The pressure and the temperature of steam decrease during this process to the values at state 4 or 4' (saturated liquid vapor mixture), where it enters the condenser. Hence, during an isentropic expansion process the enthalpy of the steam decrease and its specific volume increases whereas entropy of the system remains constant.

### (iv) Isobaric Heat Rejection (Process $4 - 1$)

Steam at the state 4 or 4' is usually a saturated liquid vapor mixture with a high quality. Steam is condensed at constant pressure in the condenser which is basically a large heat exchanger by rejecting heat to a cooling medium such as the water from a lake, a river, or the atmospheric air. Steam leaves the condenser as saturated liquid and enters the pump to complete the cycle.

During this process the specific volume, enthalpy and entropy of the steam decrease while its temperature remains constant since the isobaric heat rejection process occurs in two phase mixture region where the pressure and temperature are dependent.

## Calculation of Thermal Efficiency of Rankine Cycle

All four devices used in the Rankine cycle (the pump, boiler, turbine, and condenser) are steady flow devices. Hence, all four processes that comprise the Rankine cycle can be analyzed as steady flow processes. The kinetic and potential energy changes of the steam are usually small relative to the work and heat transfer terms and are therefore usually neglected.

The boiler and the condenser are flow applications and therefore do not involve any work. The pump and the turbine are assumed to be isentropic work applications. Then the conservation of energy relation for each device can be expressed as follows:

By using steady flow energy equation, work produced by the turbine per unit mass of steam is derived as

$$w_T = w_{34} = h_3 - h_4 \qquad \text{........ (6.15)}$$

Similarly, work consumed by the pump per unit mass of steam is given by

$$w_P = w_{12} = h_2 - h_1 \qquad \text{……… (6.16)}$$

Since the pumping process 1 – 2 is an isentropic process and the working substance is liquid water which can be taken as an incompressible substance, the enthalpy difference can be expressed as the function of the specific volume and pressure difference. Then equation (6.16) becomes

$$w_P = w_{12} = h_2 - h_1 = v_1(P_2 - P_1) \qquad \text{………..(6.17)}$$

During steady state operation of the cycle, some part of the work produced by the turbine is utilized to run the pump. Hence, the net work delivered to the surroundings is derived as

$$w_{net} = w_T - w_P = [(h_3 - h_4) - (h_2 - h_1)] \qquad \text{........ (6.18)}$$

Heat supplied to the steam in the boiler is given by

$$q_H = q_{23} = h_3 - h_2 \qquad \text{……… (6.19)}$$

The thermal efficiency of the Rankine cycle is then determined from

$$\eta_R = \frac{w_{net}}{q_H} = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2} \qquad \text{……… (6.20)}$$

Equation (6.21) can be rewritten in the following equivalent form

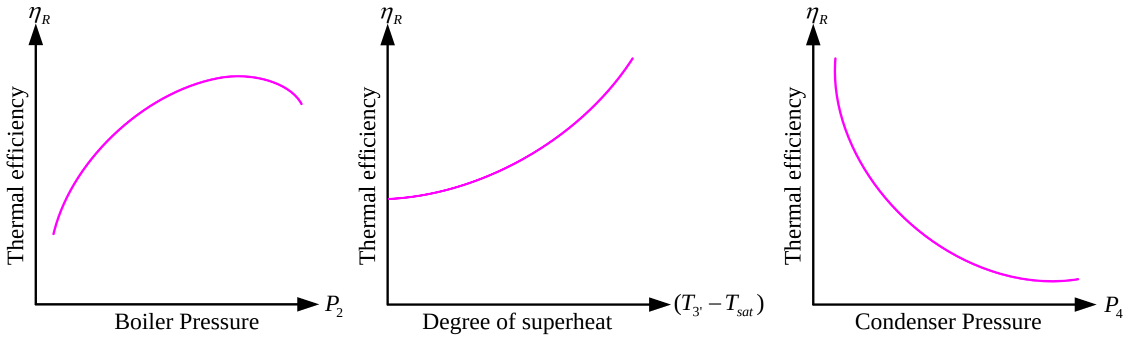
$$\eta_R = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_1) - (h_2 - h_1)} = \frac{(h_3 - h_4) - v_1(P_2 - P_1)}{(h_3 - h_1) - v_1(P_2 - P_1)}$$

The compression process in the pump is being carried out with liquid only for which the specific volume is small. Consequently, the pump work is quite small compared to the turbine work (usually around 1% of turbine work) and can therefore be neglected. Then, the thermal efficiency of Rankine cycle approximately becomes

$$\eta_R = \frac{(h_3 - h_4)}{(h_3 - h_1)} \qquad \ldots\ldots\ldots\ (6.21)$$

Rankine cycles or steam power plants are being used to produce most electric power in the world, and even small increases in its thermal efficiency can lead large savings from the fuel requirements. Therefore, every effort is made to improve the efficiency of the cycle on which steam power plants operate.

There are some methods to increase the thermal efficiency of the ideal Rankine cycle. However, the basic idea behind all the methods being used to increase the thermal efficiency of a power cycle is the same, i.e., “increasing the temperature at which heat is transferred to the working substance in the boiler or decreasing the temperature at which heat is rejected from the working substance in the condenser”. There are three ways of accomplishing this task for the ideal Rankine cycle e.g. increasing the boiler pressure, superheating the steam to high temperature (increasing the degree of superheat) and lowering the condenser pressure as shown in figure 6.6 (a), (b) and (c) respectively [4].



(a) (b) (c)

Figure 6.6. Variation of thermal efficiency of an ideal Rankine cycle with different operating conditions [4]

## 6.4. Internal Combustion Cycles (Engines)

An internal combustion engine (basically a piston–cylinder device) is one of the power producing devices that has proved to be very versatile and to have a wide range of applications, for examples, in automobiles, light aircraft, ships, and electric power generators etc.

The basic components of an internal combustion engine are shown in figure 6.7 The piston reciprocates in the cylinder between two fixed positions called the *Top Dead Center* (TDC), the position of the piston when it forms the smallest volume in the cylinder after compression of air, and the *Bottom Dead Center* (BDC), the position of the piston when it forms the largest volume in the cylinder after expansion of air. The distance between the TDC and the BDC is the largest distance that the piston can travel in one direction, and it is called the *stroke* of the engine. The diameter of the piston is called the *bore***.** The air in diesel cycle or air–fuel mixture in petrol cycle is drawn into the cylinder through the *intake valve***,** and the combustion products are expelled from the cylinder through the *exhaust valve*.

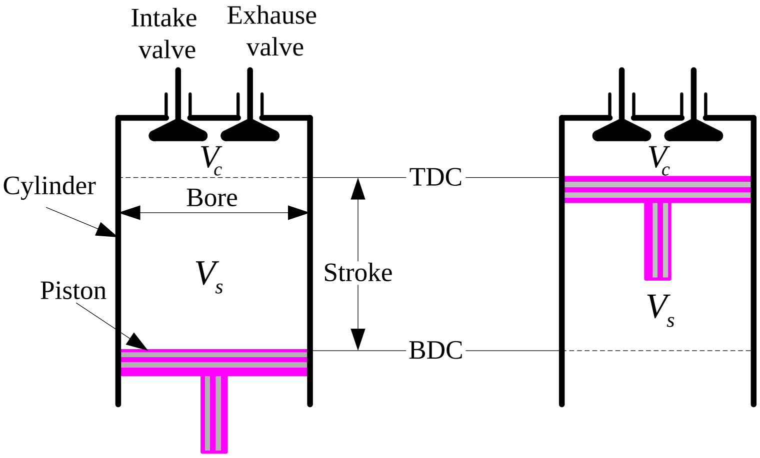


Figure 6.7. Nomenclature of an internal combustion engine with stroke and clearance volumes[2]

The minimum volume occupied by the working substance when the piston is at TDC is called the *clearance volume* ($V_c$). The volume displaced by the piston as it moves between TDC and BDC is called the *displacement volume* or *stroke volume* ($V_s$).

The ratio of the maximum volume (sum of clearance volume and stroke volume) occupied by the working substance to the minimum volume (clearance volume) is called the *compression ratio*, $r_c$ of the engine:

$$r_c = \frac{V_{max}}{V_{min}} = \frac{V_c + V_s}{V_c} \qquad \text{… … … (6.22)}$$

Another term frequently used in conjunction with reciprocating engines is the *Mean Effective Pressure (MEP)*. It is a hypothetical constant pressure that, if it acted on the piston during the entire power stroke, would produce the same amount of net work as that produced during the actual cycle with varying pressure as shown in figure 6.8, i.e.,

$$W_{net} = \text{MEP x Piston area x Stroke} = \text{MEP x Displacement volume}$$

$$Or, \qquad MEP = \frac{W_{net}}{V_{max} - V_{min}} = \frac{w_{net}}{v_{max} - v_{min}} \qquad \text{… … … (6.23)}$$

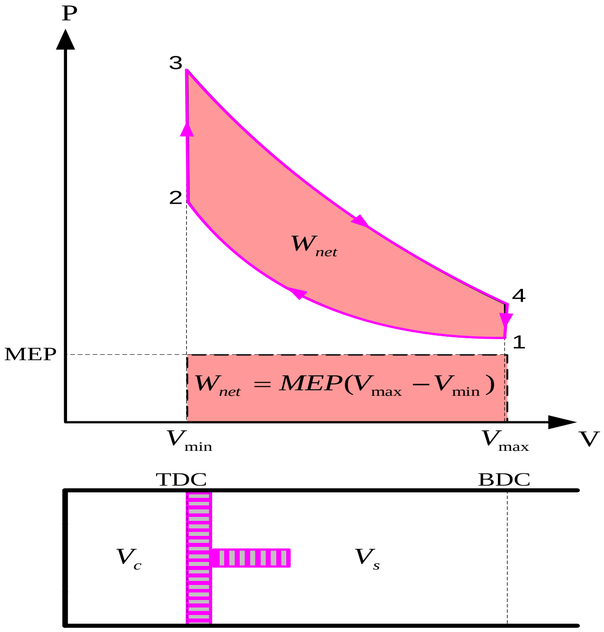


Figure 6.8. P-V diagram showing the net work output of a cycle alternately determined by using MEP as indicated by shaded areas [2].

The mean effective pressure (MEP) can be used as a parameter to compare the performances of reciprocating engines of equal size. The engine with a larger value of MEP delivers more net work per cycle and thus performs better.

Depending on how the combustion process in the cylinder is initiated, internal combustion engines are classified as *Spark-Ignition (SI) Engines* or *Compression-Ignition (CI) Engines*. In SI engines, the combustion of the air - fuel mixture is initiated by a spark plug. In CI engines, the air - fuel mixture is self-ignited as a result of compressing the mixture above its self-ignition temperature. The *Otto cycle, e.g. petrol cycle* and *diesel cycle* are the ideal cycles for the SI and CI internal combustion engines respectively.

### 6.4.1. Operation of Four Stroke Engine

In most spark-ignition (petrol) and compression-ignition (diesel) engines, the piston executes four complete strokes within the cylinder, and the crankshaft completes two revolutions for each thermodynamic cycle with only one power stroke. These engines are called *four-stroke internal combustion engines*. In the four stroke engine piston is connected to the crank through the connecting rod. The crank of the engine is connected to the wheel of the vehicle through a flywheel. When the piston moves upward and downward between Top Dead Center (TDC) and Bottom Dead Center (BDC), the crank rotates in a circular slot and thereby drives the wheel of the vehicle. This operating cycle for petrol engine as well as for diesel engine completes through four thermodynamic processes in series namely intake or suction stroke, compression stroke, expansion (power) stroke and exhaust stroke as described below. A schematic diagram of each stroke for the operation of a four-stroke engine is given in figure 6.9.

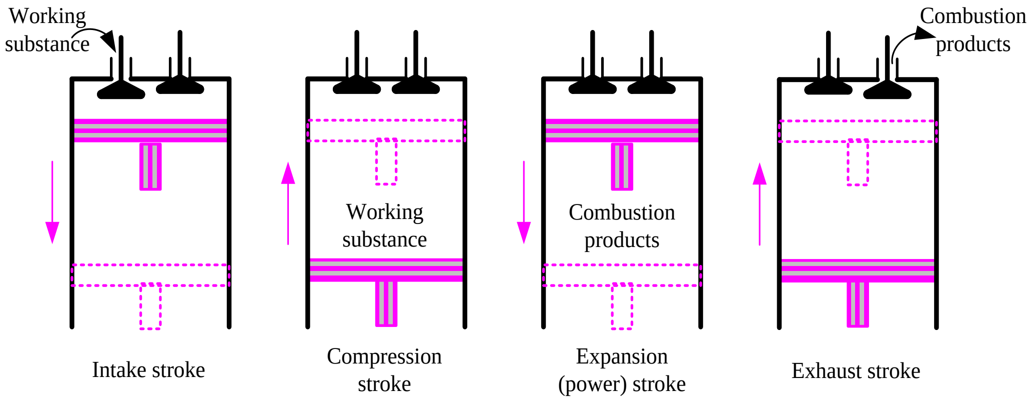


Figure 6.9. Operation of a four stroke engine [2]

**Intake or Suction Stroke:** Initially the piston is at TDC position, the intake valve is open and the exhaust valve is closed. During the intake or suction stroke, the piston moves downwards from TDC to BDC position and the fresh mass of working substance enters into the engine cylinder through the intake valve. The working substance is a mixture of air and petrol in the petrol engine and only air in the diesel engine. The flow of working substance into the cylinder is possible because the pressure inside the cylinder is reduced to a value below the atmospheric pressure.

**Compression Stroke:** At the end of the intake stroke both the intake and the exhaust valves are closed and the piston moves upwards from BDC to TDC position. During this movement of the piston the working substance inside the cylinder is compressed to the clearance volume. Due to the compression the volume decreases, pressure and temperature of the working substance inside the cylinder continuously increases.

**Expansion (power) Stroke:** When the piston reaches TDC position at the end of the compression stroke, a spark plug located in the cylinder head produces an electric spark and the working substance (mixture of air and petrol) at high pressure and temperature gets ignited in the petrol engine whereas in diesel engine a fuel nozzle injects the diesel into the cylinder containing the high temperature compressed working substance (only air). The temperature of air at this state is greater than self-ignition temperature of the diesel and therefore, diesel gets self-burnt. Due to the impact of combustion, with both valves closed, the combustion products at increased pressure and temperature expand, the piston moves downwards from TDC to BDC position and work is done by the system. During the expansion, the volume of the combustion products increases and pressure and temperature decreases.

**Exhaust Stroke:** The intake valve remains closed but the exhaust valve opens when the piston reaches BDC position at the end of the power stroke and the cylinder contains the combustion products. The pressure drops to slightly above atmospheric pressure at constant volume. The piston moves upwards from BDC to TDC position and this movement of the piston pushes the combustion products into the atmosphere through exhaust valve.

The exhaust stroke completes the cycle and the engine cylinder is ready to suck the fresh charge of working substance inside the cylinder once again and the cycle is repeated.

## Lecture Highlights

- *Cyclic process:* it is defined as a repeated series of operations occurring in a certain order. Most of the devices which are used for continuous energy conversion operate on cyclic processes. These devices are used either to produce work output by supplying heat from the combustion of fuel (e.g. heat engine) or to provide heating or cooling effect with the aid of work input usually through electrical power (e.g. heat pump, refrigerator).
- *Classification of practical cycles:*
  - According to the working principle: Closed and open cycle.
  - According to the power: Power and refrigeration cycle.
  - According to the working substance: Gas and vapor cycle.
  - According to the combustion location: Internal combustion and external combustion cycle.
- *Differences between closed cycle and open cycle are:*

| Closed cycle | Open cycle |
|---|---|
| 1. In a closed cycle the working substance is continuously circulated in the cycle.<br>2. The working substance does not need the replenishment for next cycle.<br>3. For example, most of the steam power cycles and refrigeration cycles are closed type. | 1. In an open cycle the working substance may be thrown into environment after completion of each cycle.<br>2. A fresh charge of the working substance enters the cycle again for next cycle.<br>3. For example, most of the internal combustion engines and gas turbines work on open cycle. |

- *Differences between power cycle and refrigeration cycle are:*

| Power cycle | Refrigeration cycle |
|---|---|
| 1. It produces power or delivers work to the surroundings when the cycle is executed.<br>2. It operates the heat engine.<br>3. Net work is always positive.<br>4. For examples: Otto, Diesel, Brayton, Rankine cycles. | 1. It needs power which should be supplied from surroundings to execute the cycle.<br>2. Heat operates the heat pump and refrigerator.<br>3. Net work is always negative.<br>4. Examples: Vapor compression refrigeration cycle. |

- *Differences between power cycle and refrigeration cycle are:*

| Gas cycle | Vapor cycle |
|---|---|
| 1. In this cycle, the working substance remains in gaseous state throughout the cycle.<br>2. For examples: Otto, Diesel, Brayton cycles etc. | 1. Working substance can undergo phase change (from liquid to vapor or from vapor to liquid) throughout the cycle.<br>2. For examples: Rankine cycle, vapor compression refrigeration cycle. |

- *Differences between power cycle and refrigeration cycle are:*

| Internal combustion cycle | External combustion cycle |
|---|---|
| 1. The combustion takes place inside the power producing unit of the cycle.<br>2. For examples: Otto cycle and Diesel cycle | 1. The combustion takes place outside the power producing unit of the cycle.<br>2. For examples: Brayton and Rankine cycle. |

- *Comparison between different power cycles:*

| **Processes** | **Power cycles** | | | | |
|---|---|---|---|---|---|
| | **Carnot** | **Otto** | **Diesel** | **Brayton** | **Rankine** |
| **Compression** | Isentropic | Isentropic | Isentropic | Isentropic | Isentropic |
| **Heat Addition** | Isothermal | Isochoric | Isobaric | Isobaric | Isobaric |
| **Expansion** | Isentropic | Isentropic | Isentropic | Isentropic | Isentropic |
| **Heat Rejection** | Isothermal | Isochoric | Isochoric | Isobaric | Isobaric |

- *Mean effective pressure (MEP):* It is the constant pressure which acting on piston through one stroke would do the same amount of work as it done by the varying pressure during the cycle. It is one of the parameters used for the comparison of different internal combustion cycles and it is given by

$$MEP = \frac{Work\ done}{Stroke\ volume} = \frac{W}{V_1 - V_2} = \frac{w}{v_1 - v_2}$$

- *Brayton cycle:* It is a power cycle which consists of a gas turbine. It comprises of:
  - two isentropic processes, namely an isentropic compression process and isentropic expansion process and
  - two isobaric processes, namely an isobaric heat addition process and an isobaric heat rejection process.

- *Efficiency of a Brayton cycle* is given by

$$\eta_B = \frac{w_{net}}{q_H} = \frac{w_T - w_c}{q_H} = 1 - \left(\frac{1}{r_p}\right)^{\frac{\gamma-1}{\gamma}}$$

  where $r_p = \frac{P_2}{P_1}$ is called pressure ratio. The pressure ratio for maximum net work developed by the cycle can be derived as: $r_p = \left(\frac{T_3}{T_1}\right)^{\frac{\gamma}{2(\gamma-1)}}$

  Efficiency of Brayton cycle increases with increase in pressure ratio. But high pressure ratio causes high temperature and there is limitation to which an actual turbine blade can withstand maximum temperature and pressure. Hence, the pressure ratio is usually between 10 and 16.
- *Back work:* It is the amount of work consumed by the compressor that is produced by the turbine.
- *Back work ratio:* It is defined as the ratio of compressor work to the turbine work.
- *Rankine cycle:* It is a power cycle which consists of a steam turbine. It comprises of
  - two isentropic processes, namely an isentropic pumping process and an isentropic expansion process and
  - two isobaric processes, namely an isobaric heat addition process and an isobaric heat rejection process.
- *Efficiency of a Rankine cycle* is given by

$$\eta_R = \frac{w_{net}}{q_H} = \frac{w_T - w_p}{q_H} = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_2)}$$

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