Course Title:

Fundamental of Thermodynamics and Heat Transfer

Lecture 14 (Week 14):

Thermodynamic Cycles

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Learning Objective of Lecture:

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

- ✓ Air Standard Analysis
- ✓ Air Standard Otto Cycle
- ✓ Air Standard Diesel Cycle
- ✓ Vapor Compression Refrigeration Cycle

6.5. Air Standard Analysis: Air Standard Otto Cycle and Diesel Cycle

Spark-ignition (petrol) engines, compression-ignition (diesel) engines, and conventional gas turbines are popular examples of power producing devices that operate on gas cycles. In all gas power cycles, the working fluid remains a gas throughout the entire cycle. In all these cycles, energy is provided by burning a fuel within the system boundaries. That is why they are called internal combustion cycles. Because of this combustion process, the composition of the working fluid changes from air-fuel mixture to combustion products during the course of the cycle. However, considering that air is predominantly nitrogen that undergoes hardly any chemical reactions in the combustion chamber, the working fluid can be closely approximated as air at all times. Further, during the normal operation of the internal combustion cycles, the mass of the fuel per unit mass of air, i.e., fuel-air mass ratio, is very small (generally 0.08 to 0.025) and therefore, the properties of the fuel-air mixture or combustion products before and after combustion approximates closely to those of pure air. Hence, a simplified analysis of internal combustion cycles can be done by considering only air as its working substance. Such an idealized analysis of the cycle considering only air as the working substance is known as an air standard analysis. Performance of a cycle resulting from the air standard analysis is called an air standard efficiency.

The actual gas power cycles are rather complex. To reduce the analysis to a manageable level, some approximations are used that are commonly known as the air-standard assumptions and are listed below:

(a) The working fluid is air, which continuously circulates in a closed loop with a fixed mass and always behaves as an ideal gas.
(b) The expansion and compression processes are isentropic.
(c) The combustion process is replaced by a heat-addition process from an external source.
(d) The exhaust process is replaced by a heat-rejection process to an external sink that restores the working fluid to its initial state.
(e) The properties of air (c_P, c_V, R) remains constant.

A cycle for which the air-standard assumptions are applicable is frequently referred to as an *air-standard cycle*. The air standard cycle provides considerable simplification in the cycle analysis without significantly deviating from the actual cycle. This simplified model enables us to study qualitatively the influence of major parameters on the performance of the actual engines.

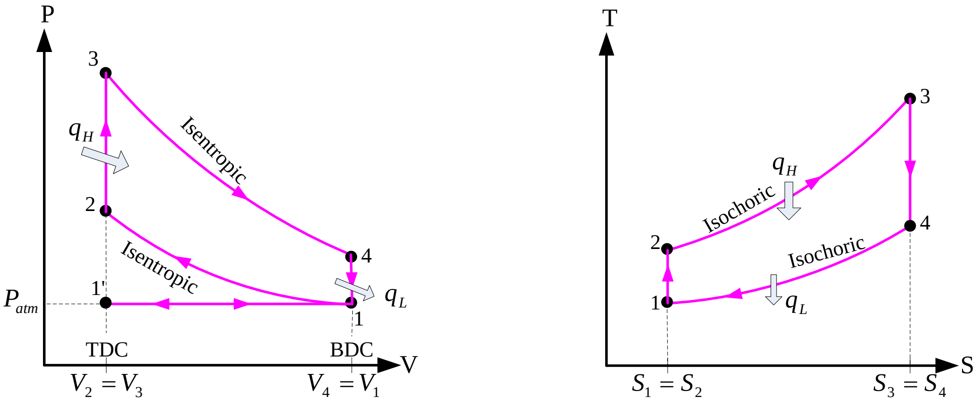
In fact, working on an open cycle is the characteristic of all internal combustion engines. Air standard internal combustion cycles are the idealized models for the operation of petrol and diesel engines.

6.5.1. Air Standard Otto Cycle

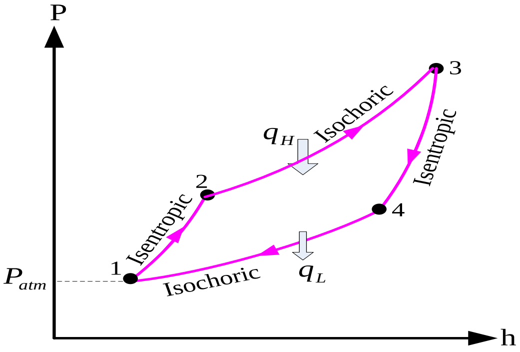
The thermodynamic analysis of the actual four-stroke or two-stroke cycles described above is not a simple task. However, the analysis can be simplified significantly if the air-standard assumptions are utilized. The resulting cycle, which closely approximates the actual operating conditions of the actual cycle, is known as the *air standard* or *ideal cycle***.** Hence, *air standard Otto cycle* is an ideal cycle for the operation of a four stroke spark-ignition or petrol engine. This cycle is named as Otto cycle because it was conceived by a German scientist Nikolous Otto in 1876. It is also called constant volume cycle. It consists of two isentropic and two isochoric processes that are discussed briefly below and an ideal Otto cycle plotted on *P-V*, *T-S* and *P – h* diagrams is shown in figure 6.10.

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

The piston is at the BDC position at the beginning of the compression, and when the piston moves upwards from BDC to TDC position, the working substance (air-fuel mixture) inside the cylinder is compressed isentropically from initial state 1 to state 2 through compression ratio, $r_c = V_1/V_2$. During this isentropic compression process the pressure, temperature and enthalpy of the system increase, its volume decreases while entropy remains constant.



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



(c) *P-h* diagram

Figure 6.10. $P-V$, $T-S$ and P – h diagrams for an air standard Otto cycle

(ii) Isochoric Heat Addition (Process $2-3$)

At the end of the compression stroke, spark plug provides an electric spark and the working substance (mixture of air and petrol) ignites instantaneously. Therefore, heat addition for an ideal Otto cycle is considered as an isochoric process. During this heat addition process the pressure, temperature, enthalpy and entropy of the system increase.

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

The increased high pressure due to the impact of combustion exerts a greater amount of force on the piston and pushes it towards the BDC from TDC position and the process is assumed to be an isentropic expansion. The expansion of working substance takes place isentropically and work is done by the system. The volume ratio V_4/V_3 is called the expansion ratio, r_e. Hence, during this isentropic expansion process the volume of the system increases whereas the pressure, temperature and enthalpy decrease while entropy remains constant.

(iv) Isochoric Heat Rejection (Process $4-1$)

Heat is rejected by the system to the surroundings (external sink) through the combustion product (exhaust gas) via exhaust valve. This process is replaced by an equivalent constant volume heat rejection process and it is so controlled that finally the working substance comes to its initial state 1 to complete the cycle. Hence, during this isochoric heat rejection process the temperature, enthalpy and entropy of the system decrease.

Calculation of Thermal Efficiency of an Air Standard Otto Cycle

The thermal efficiency of an ideal Otto cycle (internal combustion cycle) under the air standard assumptions can be determined as

$$\eta_O = \frac{w_{net}}{q_H} = \frac{q_H - q_L}{q_H} = 1 - \frac{q_L}{q_H} \qquad \text{………. (6.24)}$$

where q_H and q_L are the heat added to the working substance and heat rejected from the working substance per kg of air per cycle respectively.

The Otto cycle is executed in a closed system, and neglecting the changes in kinetic and potential energies, the energy balance for any of the processes is given by first law of thermodynamics *(du = q-w)*. Since both heat transfer processes take place at constant volume, no work is involved during the heat addition and rejection processes. Therefore, heat added to and heat rejected from the working substance during the cycle can be expressed as

$$q_H = q_{23} = u_3 - u_2 = c_V(T_3 - T_2) \qquad \text{………. (6.25)}$$

$$and \qquad q_L = q_{41} = u_4 - u_1 = c_V(T_4 - T_1) \qquad \text{………. (6.26)}$$

Putting equations (6.25) and (6.26) in equation (6.24), we get

$$\eta_O = 1 - \frac{T_4 - T_1}{T_3 - T_2} \qquad \text{……. (6.27)}$$

As per equation (6.27) it requires temperatures of each state to determine the thermal efficiency of the cycle. Equation (6.27) can be further simplified to reduce the number of required variables. For this, applying temperature – volume relationship for isentropic compression process $1 - 2$ and isentropic expansion process $3 - 4$,

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma - 1} \qquad \text{………. (6.28)}$$

$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma - 1} \qquad \text{………. (6.29)}$$

Putting $V_3 = V_2$ for isochoric heat addition process 2 - 3 and $V_4 = V_1$ for isochoric heat rejection process 4 - 1 in equation (6.29), we get

$$\frac{T_3}{T_4} = \left(\frac{V_1}{V_2}\right)^{\gamma - 1} \qquad \text{………. (6.30)}$$

Equating equations (6.28) and (6.30),

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} \quad \text{or,} \quad \frac{T_4}{T_3} = \frac{T_1}{T_2} \qquad \text{.. ……. (6.31)}$$

Now, using $T_4 = \frac{T_1}{T_2}\, T_3$ from equation (6.31), the following expression reduces to

$$\frac{T_4 - T_1}{T_3 - T_2} = \frac{T_1}{T_2}\frac{(T_3 - T_2)}{(T_3 - T_2)} = \frac{T_1}{T_2} \qquad \text{……. (6.32)}$$

Putting equation (6.32) with equation (6.31) in equation (6.27), we get

$$\eta_O = 1 - \frac{T_1}{T_2} = 1 - \frac{T_4}{T_3} \qquad \text{………. (6.33)}$$

Now, from the equation (6.33) 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 (6.28) and (6.30) into equation (6.33), thereby expressing thermal efficiency in terms of volume ratio as

$$\eta_O = 1 - \left(\frac{V_2}{V_1}\right)^{\gamma-1} = 1 - \frac{1}{(r_c)^{\gamma-1}} \qquad \text{………. (6.34)}$$

where $r_c = V_1/V_2$ is called *compression ratio*. The compression ratio for maximum net work developed by the cycle can be derived by putting derivation of net work with respect to compression ratio equal to zero as

$$r_c = \left(\frac{T_3}{T_1}\right)^{\frac{1}{2(\gamma-1)}} \qquad \text{………(6.35)}$$

Equation (6.34) shows that thermal efficiency of the air standard Otto cycle increases with the increase in compression ratio r_c and in specific heats ratio γ, i.e., in the nature of working substance as shown in figure 6.11. Although high compression ratio is desirable for high efficiency but in reality high compression ratio causes high pressure and temperature and there is a limitation to which an actual engine cylinder can withstand maximum pressure or temperature. In actual petrol engine cycle the compression ratio is usually between 8 to 12 [1]. Moreover, at high compression ratio the temperature after combustion becomes high and that may lead to spontaneous and uncontrolled combustion of working substance in the cylinder. The phenomenon of uncontrolled combustion in Otto or petrol engines is called *detonation or auto-ignition* and it leads to poor engine efficiency and in structural damage of engine parts [2].

Figure 6.11 shows the variation of thermal efficiency of an ideal Otto cycle with compression ratio and specific heat ratio of the working substance. It can be observed that the thermal efficiency curve is rather steep at low compression ratios but flattens out starting with a compression ratio value of about 8. Therefore, the increase in thermal efficiency with the compression ratio is not as pronounced at high compression ratios due to the auto-ignition (engine knock) problem. Improvement of the thermal efficiency of petrol engines by utilizing higher compression ratios (up to about 12) without facing the auto-ignition problem has been made possible by using petrol blends that have good anti-detonation characteristics, such as petrol mixed with tetraethyl lead. The second parameter affecting the thermal efficiency of an ideal Otto cycle is the specific heat ratio, γ. For a given compression ratio, an ideal Otto cycle using a monatomic gas (such as argon or helium, γ =1.667) as the working substance will have the highest thermal efficiency. The specific heat ratio γ, and thus the thermal efficiency of the ideal Otto cycle, decreases as the molecules of the working substance get larger. At room temperature it is 1.4 for air and 1.3 for carbon dioxide as shown in figure 6.11 [3].

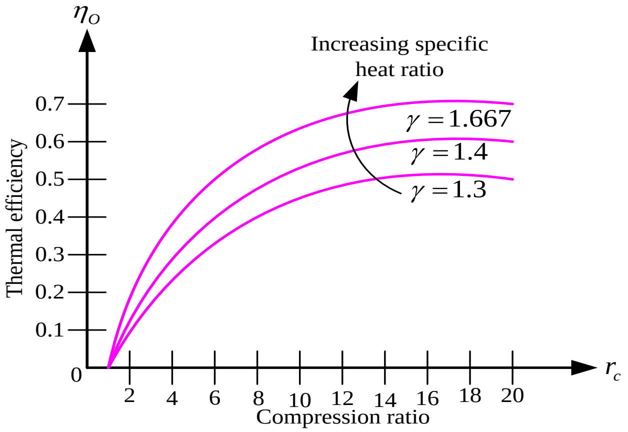


Figure 6.11. Variation of thermal efficiency of an ideal Otto cycle with the compression ratio r_c and specific heat ratio γ of the working substance [3]

Methods of Increasing Compression Ratio

The nomenclatures and different dimensions of an internal combustion engine are shown in figure 6.2 (see in last lecture). Since the compression ratio is the ratio of the maximum volume (volume at BDC) to the minimum volume (volume at TDC) occupied by the working substance, it is calculated by using equation (6.1) (see last lecture) as

$$r_c = \frac{V_1}{V_2} = \frac{V_C + V_S}{V_C} = 1 + \frac{V_S}{V_C} \qquad \text{……… (6.36)}$$

The stroke volume V_S can be expressed as function of the bore and stroke of the cylinder as

$$V_S = \frac{\pi}{4} {D_P}^2 L_S$$

where D_P is the bore or piston diameter and L_S is the stroke or stroke length of the engine cylinder.

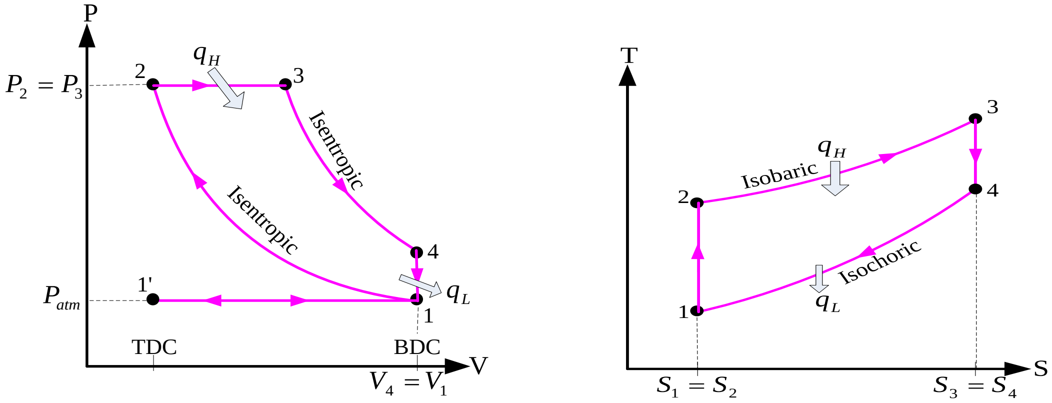
Putting the relation of stroke volume given above in equation (6.36), an expression for compression ratio in terms of engine dimensions can be derived as

$$r_c = 1 + \frac{\pi}{4} \frac{{D_P}^2 L_S}{V_C} \qquad \text{……… (6.37)}$$

Equation (6.37) indicates that the compression ratio of an internal combustion engine can be increased by increasing the diameter of the piston (bore) and the stroke length of the engine cylinder (stroke) as well as by decreasing the clearance volume of the cylinder.

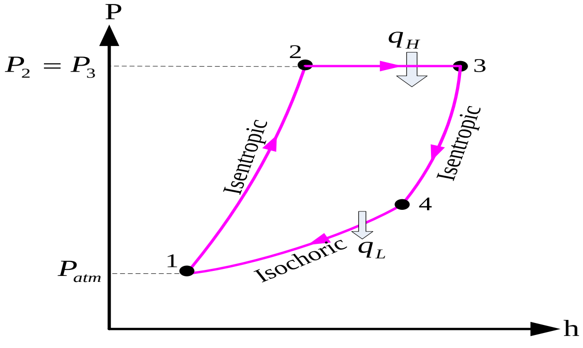
6.5.2. Air Standard Diesel Cycle

The Diesel cycle was conceived and developed by a German engineer Rudolph Diesel in 1893. It is an ideal cycle for the operation of compression ignition (CI) reciprocating engines which is very similar to the spark ignition (SI) engine or Otto cycle discussed in the last section, and is differing mainly in the method of ignition of working substance and in the condition of heat addition process as it will be discussed briefly below. This cycle is also known as a constant pressure cycle. It comprises of the following operations: isentropic compression, isobaric heat addition, isentropic expansion and isochoric heat rejection. Figure 6.12 (a, b and c) shows the *P-V*, *T-S* and *P-h* diagrams of Diesel cycle respectively which are quite similar to those of Otto cycle.



(a) *P- V* diagram

(b) *T-S* diagram



(c) *P- h* diagram

Figure 6.12: $P - V$, $T - S$ and $P - h$ diagrams for an ideal Diesel cycle

(i) Isentropic Compression (Process $\mathbf{1-2}$)

The piston is at the BDC position at the beginning of the compression, and the cylinder contains only air as the working substance. When the piston moves upwards from BDC to TDC position, the air inside the cylinder with initial state 1 is compressed isentropically to state 2 through compression ratio, $r_c = V_1/V_2$. During this isentropic compression process the pressure, temperature and enthalpy of the system increase, its volume decreases while entropy remains constant.

(ii) Isobaric Heat Addition (Process $\mathbf{2-3}$)

When the piston approaches TDC position at the end of the compression stroke (state 2), the temperature of the air reaches a value greater than the self- or auto-ignition temperature of the diesel. At this state, a fuel injector injects the fuel (diesel) into the cylinder and the diesel ignites immediately. The fuel injection process continues during the first part of the power stroke, i.e., the piston moves from TDC towards the BDC position simultaneously with the combustion process. Therefore, the combustion process cannot complete instantaneously and it takes place over a longer interval. Because of this longer duration, the combustion process in the ideal Diesel cycle is approximated as a constant-pressure heat-addition process. The fuel injection process is stopped at state 3 which is called the cut-off point, and the volume ratio, $\propto = V_3/V_2$ is called *cut off ratio or isobaric expansion ratio*. Thus, during this constant pressure heat addition process the volume, temperature, enthalpy and entropy of the system increase. In fact, this is the only process where the Otto and the Diesel cycles differ.

(iii) Isentropic Expansion (Process $\mathbf{3-4}$)

The increased high pressure due to the impact of combustion exerts a greater amount of force on the piston and pushes it towards the BDC position. Further expansion of the working substance (air) takes place isentropically and work is done by the system. The volume ratio, $r_e = V_4/V_3$ is called isentropic expansion ratio. During this isentropic expansion process the pressure, temperature and enthalpy of the system decrease, volume increases while entropy remains constant.

(iv) Isochoric Heat Rejection (Process $\mathbf{4-1}$)

Heat is rejected by the system to the surroundings (external sink) through the combustion products (exhaust gas) via exhaust valve. This process is replaced by an equivalent constant volume (isochoric) heat rejection process and it is so controlled that finally the working substance (air) comes to its initial state 1 to complete the cycle. Hence, during this isochoric heat rejection process the temperature, pressure, enthalpy and entropy of the system decrease.

Calculation of Efficiency of an Air Standard Diesel Cycle

The thermal efficiency of an ideal Diesel cycle (internal combustion cycle) under the air standard assumptions can be determined as

$$\eta_D = \frac{w_{net}}{q_H} = \frac{q_H - q_L}{q_H} = 1 - \frac{q_L}{q_H} \qquad \text{……… (6.38)}$$

where q_H and q_L are the heat added to the working substance and heat rejected from the working substance per kg of air per cycle respectively.

The Diesel cycle is executed in a piston cylinder device which forms a closed system, and neglecting the changes in kinetic and potential energies, the energy balance for any of the processes is given by first law of thermodynamics *(du = q - w).* Since the heat addition to the working substance takes place at constant pressure, work is done by the system during the heat addition due to expansion but the heat rejection by the system takes place at constant volume, so no work interaction involves in this process. Therefore, heat added to and heat rejected from the working substance during the cycle can be expressed as

$$\begin{aligned} q_H = q_{23} &= (du)_{23} + w_{23} = u_3 - u_2 + w_{23} \\ &= u_3 - u_2 + P_2(v_3 - v_2) = h_3 - h_2 = c_P(T_3 - T_2) \end{aligned} \qquad \text{……… (6.39)}$$

and $$q_L = q_{41} = u_4 - u_1 = c_V(T_4 - T_1) \qquad \text{……… (6.40)}$$

Putting equations (6.39) and (6.40) in equation (6.41), we get

$$\eta_D = 1 - \frac{c_V}{c_P}\frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{1}{\gamma}\frac{T_1}{T_2}\left[\frac{\frac{T_4}{T_1} - 1}{\frac{T_3}{T_2} - 1}\right] \qquad \text{……… (6.41)}$$

As per equation (6.41) it requires temperatures of each state to determine the thermal efficiency of the cycle. Equation (6.41) can be further simplified to reduce the number of required variables. For this, applying temperature – volume relationship for isentropic compression process $1 - 2$,

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma - 1} = (r_c)^{\gamma - 1} \qquad \text{……… (6.42)}$$

where $r_c = V_1/V_2$ is called compression ratio.

Similarly, applying temperature – volume relationship for an isobaric heat addition process $2-3$ from Charle's law for an ideal gas,

$$\frac{T_3}{T_2}=\frac{V_3}{V_2}=\alpha \qquad \text{………. (6.43)}$$

where α is called *cut-off ratio* because the heat addition (fuel injection) process gets cut off or stops from state 3. Therefore, state 3 is known as cut-off state.

Again, applying temperature – volume relationship for isentropic expansion process $3-4$,

$$\frac{T_4}{T_3}=\left(\frac{V_3}{V_4}\right)^{\gamma-1}=\left(\frac{V_3}{V_2}\frac{V_2}{V_4}\right)^{\gamma-1} \qquad \text{………. (6.44)}$$

By substituting $V_4=V_1$ from the isochoric heat rejection process 4 – 1, and values of the compression ratio as well as cut-off ratio into equation (6.44), it reduces to

$$\frac{T_4}{T_3}=\left(\frac{V_3}{V_2}\frac{V_2}{V_1}\right)^{\gamma-1}=\left(\frac{\alpha}{r_c}\right)^{\gamma-1} \qquad \text{………. (6.45)}$$

Multiplying equations (6.42), (6.43) and (6.45) yields

$$\frac{T_4}{T_1}=\frac{T_4}{T_3}\,\frac{T_3}{T_2}\,\frac{T_2}{T_1}=\left(\frac{\alpha}{r_c}\right)^{\gamma-1}.\alpha.(r_c)^{\gamma-1}=(\alpha)^{\gamma} \qquad \text{……….(6.46)}$$

By putting equation (6.42), (6.43) and (6.46) in equation (6.41), an expression for the efficiency of diesel cycle can be derived as

$$\eta_D=1-\frac{1}{r_c^{\gamma-1}}\left[\frac{\alpha^{\gamma}-1}{\gamma(\alpha-1)}\right] \qquad \text{……….(6.47)}$$

It is observed from equation (6.47) that the thermal efficiency of an ideal Diesel cycle differs from the thermal efficiency of an ideal Otto cycle by the quantity in the brackets. This quantity is always greater than 1. Therefore, the thermal efficiency of an ideal Otto cycle is greater than that of an ideal Diesel cycle when both cycles operate on the same compression ratio. For the limiting case of cut-off ratio, $\alpha \to 1$, the quantity in the brackets becomes unity, and the efficiencies of the Otto and Diesel cycles become identical. However, this aspect is of little importance because Diesel cycle operates at much higher compression ratio (12 to 24) and thus is usually more efficient than Otto cycle. Furthermore, as the cut-off ratio decreases, i.e., as the quantity of heat addition decreases, the efficiency of the Diesel cycle increases as s shown in figure 6.13 [3].

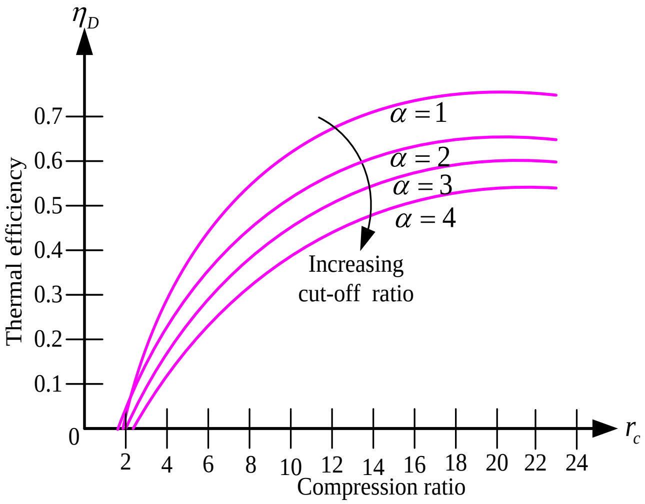


Figure 6.13. Thermal efficiency of the ideal Diesel cycle as a function of compression ratio r_c and cut-off ratio α (for $\gamma = 1.4$) [3]

The higher efficiency and lower fuel costs of diesel engines make them attractive in applications requiring relatively large amounts of power, such as in locomotive engines, emergency power generation units, large ships, and heavy trucks.

6.6. Vapor Compression Refrigeration Cycle

A vapor compression refrigeration cycle is the most widely used cycle for heating and cooling of a desired space. In other words, it is the most common method of providing air conditioning and chilling as well as heat pumping. This cycle uses a suitable working substance called *refrigerant* which condenses and evaporates at temperature and pressure close to the atmospheric conditions, e.g. Ammonia, Freon (R-12) and other fluorinated hydrocarbons. For residential and commercial air conditioners, various fluorinated hydrocarbons are used, and where lower temperatures are required such as in domestic or commercial freezing equipment, ammonia is often used as the refrigerants. Figure 6.18 shows the schematic arrangement of different components or devices used in an ideal vapor compression refrigeration cycle. The various processes involved in an ideal vapor compression refrigeration cycle are shown on *P-h*, *T-s* and *P-v* diagrams in the figures 6.19 (a), (b) and (c) respectively. The cycle consists of four thermodynamic processes and the sequence of operation of the ideal cycle is described as follows:

(i) Isentropic Compression (Process 1-2)

The refrigerant enters the compressor at state 1 as saturated vapor and is compressed isentropically with the help of work input (electricity) to the condenser pressure at state 2.

During this isentropic compression process the temperature of the refrigerant increases to well above the temperature of the surrounding medium. The pressure and enthalpy of the refrigerant increase, volume decreases while its entropy remains constant.

(ii) Isobaric Heat Rejection or Condensation (Process 2-3)

The refrigerant at high pressure and high temperature then enters the condenser as superheated vapor at state 2 and leaves as saturated liquid at state 3 as a result of heat rejection to the surroundings. While rejecting heat the refrigerant vapor at the condenser inlet gets condensed. During the constant pressure condensation process, the temperature of the refrigerant decreases first to become a saturated vapor and then remains constant along two phase mixture until the state 3 which is still above the temperature of the surroundings. The volume, enthalpy and entropy of the refrigerant decrease during the condensation process.

(iii) Isenthalpic Expansion or Throttling (Process 3-4)

The saturated liquid refrigerant at state 3 is throttled at constant enthalpy to the evaporator pressure at state 4 by passing it through an expansion valve or capillary tube. The temperature of the refrigerant decreases below the temperature of the refrigerated or cooled space during this isenthalpic process. Moreover, the pressure and temperature decrease while the volume increases due to the expansion. The entropy also increases due to the friction as well as irreversibilities involved in the throttling process.

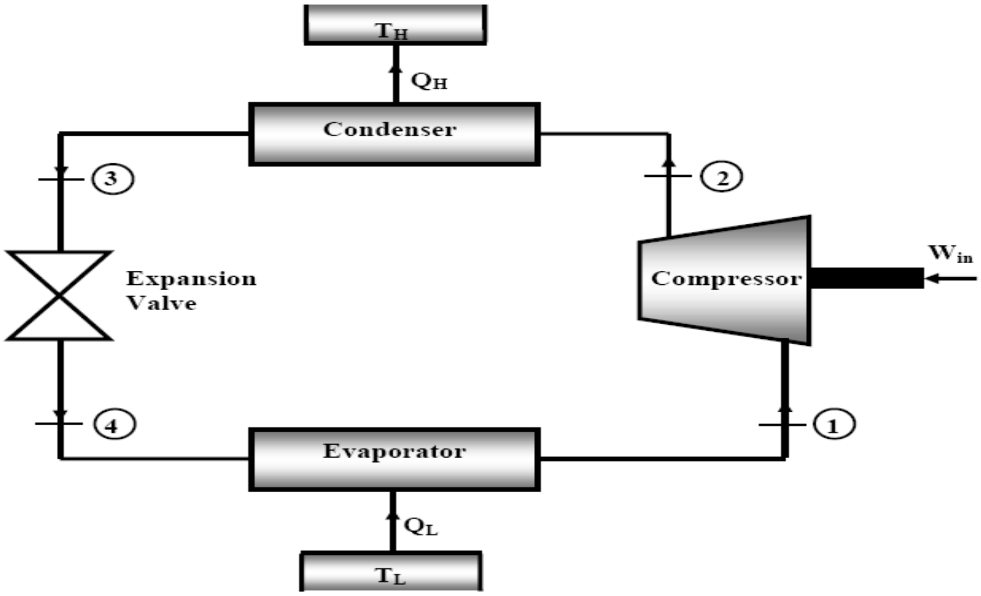
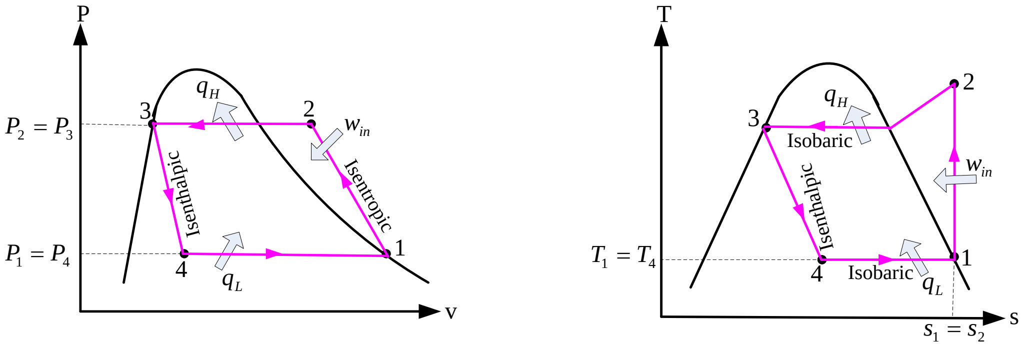


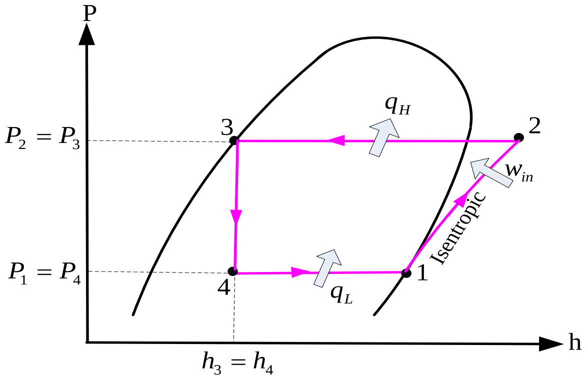
Figure 6.18: Schematic diagram of arrangement for an ideal vapor compression refrigeration cycle with different components [1]

(iv) Isobaric Heat Addition or Evaporation (Process 4-1)

The refrigerant at low pressure and low temperature enters the evaporator at state 4 as a low quality saturated mixture and it completely evaporates by absorbing latent heat from its surroundings (the refrigerated space which is to be cooled). The refrigerant leaves the evaporator as saturated vapor at initial state 1 and reenters the compressor to complete the cycle. This evaporation process occurs at constant pressure during which the temperature remains constant since the refrigerant is a two phase mixture while the volume, enthalpy and entropy of the refrigerant increase.



(a) *P-v* diagram (b) *T-s* diagram



(c) *P-h* diagram

Figure 6.19: *P-v*, $T - s$ and $P - h$ diagrams for an ideal vapor compression refrigeration cycle

Calculation of Thermal Efficiency of an Ideal Vapor Compression Refrigeration Cycle

All four components or devices used in the ideal vapor-compression refrigeration cycle are steady flow devices, and thus all four processes that make up the cycle can be analyzed as steady flow processes. The kinetic and potential energy changes of the refrigerant are usually small relative to the work and heat transfer terms, and therefore they can be neglected.

The evaporator and the condenser both are flow applications. Hence, they do not involve any work, and the compressor can be approximated as adiabatic. Then, by using the steady flow energy equation on a unit mass basis, the Coefficient of Performances (COP) of refrigerators and heat pumps operating on the vapor-compression refrigeration cycle can be expressed as following:

If the cycle is used for the cooling of a desired space then its COP is given as

$$(COP)_R = \frac{q_L}{w_{in}} = \frac{h_1 - h_4}{h_2 - h_1} \qquad \text{……… (6.48)}$$

If the cycle is used for the heating of a desired space then its COP is given as

$$(COP)_{HP} = \frac{q_H}{w_{in}} = \frac{h_2 - h_3}{h_2 - h_1} \qquad \text{……… (6.49)}$$

Since the throttling process 3 - 4 is an isenthalpic process, i.e., $h_3 = h_4$, a comparison of equations (6.48) and (6.49) reveals that

$$(COP)_{HP} = (COP)_R + 1 \qquad \text{………… (6.50)}$$

for fixed values of Q_H and Q_L which is the same relation as already derived in the last chapter. This relation implies that $(COP)_{HP} > 1$ since $(COP)_R$ is a positive quantity.

Lecture Highlights

- *Air standard analysis:* An idealized analysis of a cycle considering only air as the work substance is called an *air standard analysis*. Such a simplified analysis can be carried out in Otto or petrol cycle and Diesel cycle by considering only air as its working substance. Although this analysis differs from the actual operation, it gives basic idea about the variation of efficiency of the cycle with different parameters.
- *Air standard efficiency:* The efficiency of the engine using air as the working substance is known as an *air standard efficiency*.
- *Assumptions of air standard analysis:*
  - (i) The cycle consists of fixed mass of air.
  - (ii) The expansion and compression processes are isentropic.
  - (iii) The combustion process is replaced by an equivalent heat addition process from an external source.
  - (iv) The exhaust process is replaced by an equivalent heat rejection process to an external sink.

(v) The properties of air such as c_p, c_v, R etc. remain constant.

- *Air Standard Otto cycle:* It is an idealized model for the operation of petrol engines. It consists of
  - two isentropic processes, namely an isentropic compression process and an isentropic expansion process and
  - two isochoric processes, namely an isochoric heat addition process and an isochoric heat rejection process.
- *Efficiency of air standard Otto cycle* is given by

$$\eta_O = \frac{w_{net}}{q_H} = \frac{q_H - q_L}{q_H} = 1 - \frac{q_L}{q_H} = 1 - \left(\frac{1}{r_c}\right)^{\gamma-1}$$

where $r_c = \frac{V_1}{V_2}$ is the compression ratio. The compression ratio for maximum net work developed by the cycle can be derived as

$$r_c = \left(\frac{T_3}{T_1}\right)^{\frac{1}{2(\gamma-1)}}$$

Efficiency of Otto cycle increases with increase in compression ratio, but high compression ratio causes high pressure and temperature and there is a limitation to which an actual engine cylinder can withstand maximum pressure or temperature. Hence, the compression ratio is usually from 8 to 12.

- *Compression ratio* can be expressed as the function of cylinder dimensions as:

$$r_c = \frac{V_1}{V_2} = \frac{V_c + V_s}{V_c} = 1 + \frac{V_s}{V_c} = 1 + \frac{\pi D_p^2 L_s}{4V_c}$$

where V_c is the clearance volume, D_p is the diameter of the piston and L_s is the stroke length of the cylinder.

- *Air Standard Diesel cycle:* It is an idealized model for the operation of diesel engines. It consists of
  - Two isentropic processes, namely an isentropic compression process and an isentropic expansion process,
  - one isobaric heat addition process and
  - one isochoric heat rejection process.
- *Efficiency of air standard Diesel cycle* is derived as

$$\eta_D = \frac{w_{net}}{q_H} = \frac{q_H - q_L}{q_H} = 1 - \frac{q_L}{q_H} = 1 - \frac{1}{\gamma}\left(\frac{1}{r_c}\right)^{\gamma-1}\left(\frac{\alpha^{\gamma} - 1}{\alpha - 1}\right)$$

where $\alpha = \frac{V_3}{V_2}$ is the cut-off ratio.

- *Differences between Otto cycle and Diesel cycle are:*

Otto cycle	**Diesel cycle**
1. It is also called spark ignition (SI) engine cycle. 2. A mixture of air and fuel is compressed during isentropic compression process. 3. Fuel is ignited by the electric spark produced by spark plug at the end of compression stroke. 4. It is also known as constant volume cycle. 5. Compression ratio is usually between 8 and 12. 6. Generally, it is less efficient than Diesel cycle but for the same compression ratio and heat supplied its efficiency is higher than that of Diesel cycle.	1. It is also called compression ignition (CI) engine cycle. 2. Only air is compressed during the isentropic compression process. 3. Fuel is injected to a high temperature air at the end of compression stroke and gets self - burnt. 4. It is also known as constant pressure cycle. 5. Compression ratio is usually between 16 and 22. 6. Generally, it is more efficient than Otto cycle but for the same compression ratio and heat supplied its efficiency is less than that of Otto cycle.

- *Vapor compression refrigeration cycle*: It is the most widely used cycle for heating and cooling of the desired space. The working substance used in this cycle is called refrigerant. It consists of four processes, namely
  - one isentropic compression process,
  - one isenthalpic process in a throttling or expansion valve,
  - two isobaric processes, namely an isobaric heat rejection process in a condenser, and an isobaric heat addition process in an evaporator.
- When the cycle is working as a heat pump for heating of a desired space, its *coefficient of performance (COP)* is given by

$$(COP)_{HP} = \frac{q_H}{w} = \frac{h_2 - h_3}{h_2 - h_1}$$

- When the cycle is working as a refrigerator for cooling of a desired space, its *coefficient of performance (COP)* is given by

$$(COP)_R = \frac{q_L}{w} = \frac{h_1 - h_4}{h_2 - h_1}$$

References

[1] *Fundamentals of Thermodynamics & Heat Transfer*: Luintel M.C., Heritage Publishers & Distributors Pvt. Ltd., Kathmandu, Nepal, 2016.

[2] *Thermal Science and Engineering:* Dr. Kumar D.S., S. K. Kataria & Sons, India, 2009.

[3] *Thermodynamics: An Engineering Approach:* Cengel Y. A. and Boles M. A., McGraw-Hill Education, New York, 2018.