Chapter 5

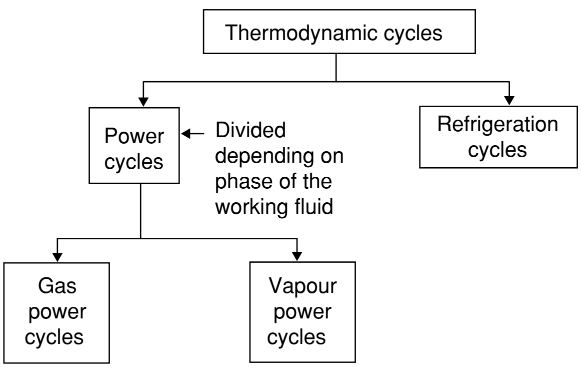
Thermodynamic Cycle

CHAPTER HIGHLIGHTS

- *Gas Power Cycles*
- *Air Standard Cycles*
- *Vapour Power Cycles*
- *Deviation of Actual Cycle Form Theoretical Cycles*
- *Methods to Improve the Performance of Simple Rankine Cycle*
- *Regenerative Rankine Cycle*
- *Heat Addition*
- *Heat Rejection*
- *Reheat Rankine Cycle*
- *Gas Power Cycles*
- *Otto Cycle and Diesel Cycle*
- *Dual Cycle and Thermal Efficiency*
- *Stirling Cycle and Ericsson Cycle*
- *Lenoir Cycle and Atkinson Cycle*
- *9 Brayton Cycle*
- *Brayton Cycle with Reheat Arrangement and with Intercooling*

Applications

Power generation and refrigeration



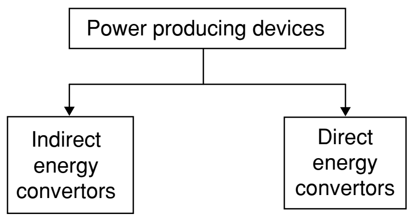
- The devices or systems used to produce a net power output are often called engines, and the thermodynamic cycles they operate on are called power cycles.
- The devices or systems used to produce a refrigeration effect are called refrigerators, cycles.

Gas Power Cycles

The working fluid remains in the gaseous phase throughout the entire cycle.

Vapour Power Cycles

Working fluid exists in the vapour phase during one part of the cycle and in the liquid phase during another part.



Indirect Energy Converters

Example: IC engines, gas turbines, steam power plants, nuclear power plants, all form of power plants, etc.

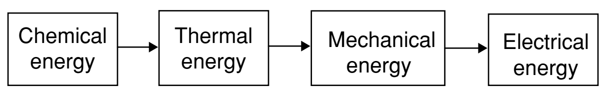


Figure 1 Indirect energy conversion system.

Direct Energy Converters

Example: Fuel cells.

Thermal electric generators, thermo ionic generators, solar cells, Magneto Hydro Dynamic power plant (MHO).

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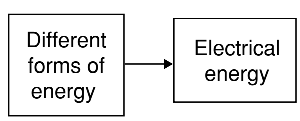


Figure 2 Direct energy conversion system.

Power Cycles

Elements of thermodynamic power cycles:

1. Working fluid
2. Heat source and sink
3. Arrangement

Air Standard Cycles

- Working fluid is pure air.
- In gas power plants such as IC engines and gas turbines, the working fluid remains gas throughout the cycle.
- The plants take in either a mixture of air and fuel separately compresses it to a high pressure, and cause it to burn in a combustion chamber liberating heat energy.
- The product of combustion at high pressure, temperature expands and do work and the exhaust leaves the engine or turbine.
- In most of the gas power cycles, the working fluid consists mainly air.

Example:

Device	A/F ratio
IC engine	10:1
Gas turbine	50:1 to 250:1

Air-Standard Assumptions

In gas power cycle, the practical conditions are very complex and difficult to analyze due to irreversibilities and non-equilibrium conditions. To analyze the cycle, various assumptions are made and by this assumptions the irreversibilities can be neglected and approximating the cycle to be reversible. These assumptions are termed as air-standard assumptions.

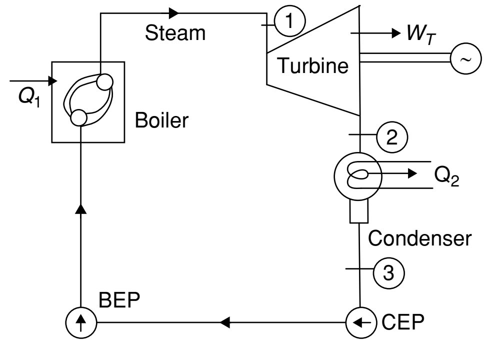
- The working fluid is air, which continuously circulates in a closed loop and always behaves as an ideal gas.
- All the processes that make up the cycle are internally reversible.
- The combustion process is replaced by a heat addition process from an external source.
- The exhaust process is replaced by a heat rejection process that restores the working fluid to its initial state.

A cycle for which the air-standard assumptions are applicable is known as the air-standard cycle.

Vapour Power Cycles

Applications: Steam turbine power plant

Rankine Cycle



BEP: Boiler feed pump
CEP: Condensate extraction pump
Basic elements of steam power plant:

(i) Boiler
(ii) Steam turbine
(iii) Condenser
(iv) Feed pump

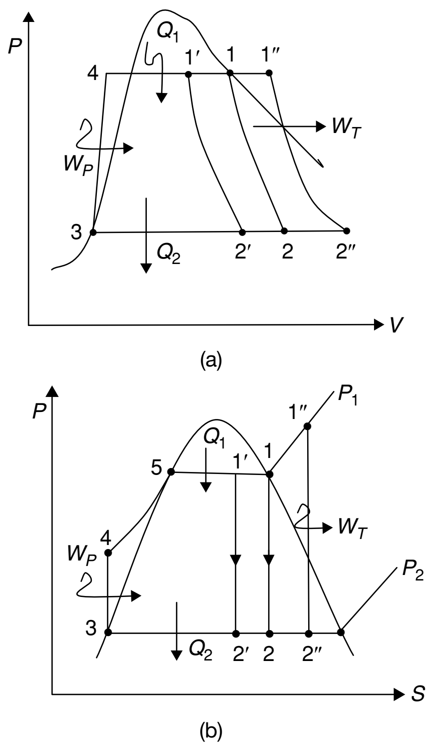


Figure 3 Rankine cycle. (a) P–V diagram; (b) T–S diagram.

Processes:

1 – 2: Isentropic expansion (Turbine)
2 – 3: Constant pressure heat rejection (Condenser)
3 – 4: Pumping process
4 – 5: Sensible heating
5 – 1: Constant pressure heat addition (Latent heat of vaporization)

Thermal Efficiency of the Plant

$$\eta_{th} = \frac{W_{net}}{Q_1} = \frac{(h_1 - h_2) - (h_{w4} - h_{w3})}{h_1 - h_{w4}}$$

$$\eta_{th} = \frac{(h_1 - h_2) - (h_{w4} - h_{w3})}{(h_1 - h_{w3}) - (h_{w4} - h_{w3})}$$

Compared to turbine work, pump work is neglected since specific volume of water is low.

$$W_p = 0, h_{w4} = h_{w3} = h_{w2}.$$

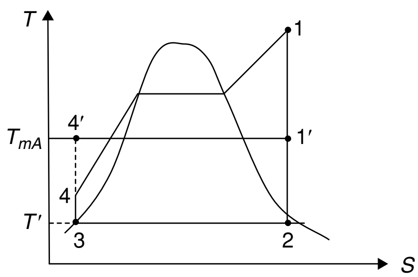
$$\therefore \eta_{th} = \frac{h_1 - h_2}{h_1 - h_{w3}} = \frac{h_1 - h_2}{h_1 - h_{w2}}$$

NOTE

The overall thermal efficiency of a steam power plant varies from 35 to 38%.

Mean Temperature of Heat Addition (TmA)

In Rankine cycle, heat is added at infinite temperatures but the pressure remains constant. Hence T_{mA} is the mean of all the infinite temperatures in which heat is added so that we can say that the heat addition remains same.



Area under 4 and 1 is equal to the area under 4′ and 1′, then heat is added.

$$Q_{add} = h_1 - h_4 = h_{1^1} - h_{4^1} = T_{m_A}(S_1 - S_4)$$

$$T_{m_A} = \frac{h_1 - h_4}{S_1 - S_4}$$

Heat rejected, $Q_{rej} = h_2 - h_3 = T_2(S_2 - S_3)$

$$\eta_{Rankine} = 1 - \frac{Q_{rej}}{Q_{add}} = 1 - \frac{T_2(S_2 - S_3)}{T_{mA}(S_1 - S_4)}$$

$\because$ $S_1 = S_2$ and $S_3 = S_4 \rightarrow$ Isentropic process

$$\therefore \eta_{Rankine} = 1 - \frac{T_2}{T_{mA}}$$

where T_2 is the temperature of heat rejection. To increase the efficiency of engine, either T_2 can be decreased or T_{mA} can be increased. But the lowest practicable temperature of the heat rejection is the temperature of the surroundings (T_o). Hence the only way to increase the efficiency of the cycle is to increase the T_{mA}.

$$\eta_{Rankine} = f(T_{mA}) \text{ only}$$

Principle of Increasing Thermal Efficiency

Rankine cycle efficiency can be increased by

1. Increasing the average temperature at which heat is added to the cycle.
2. Decreasing the average temperature at which heat is rejected to the cycle.

Deviation of Actual Cycle Form Theoretical Cycle

The actual steam turbine power plant cycle deviates from the theoretical, i.e., ideal cycle because losses in various components like turbine, pump piping and condenser.

Efficiencies of turbine and pump

1. **Turbine efficiency**
   - $\eta_t = \dfrac{\text{Actual work in the turbine}}{\text{Isentropic work in the turbine}}$

     $= \dfrac{h_1 - h_2^1}{h_1 - h_2}$
   - η_t varies from 75 to 86%
2. **Pump efficiency**

   $$\eta_{pump} = \frac{\text{Isentropic work supplied}}{\text{Actual work supplied}}$$

   $$\eta_{pump} = \frac{h_{w4} - h_{w3}}{h_{w4}^1 - hw_3}$$

   - Pump work is around 2 to 2.5% of turbine output.
   - The pump efficiency varies from 70 to 90%.
3. **Overall efficiency**
   - $\eta_{ov} = (\eta_{th})_{Rankine} \times \eta_{turbine} \times \eta_{mech} \times \eta_{boiler} \times \eta_{generator}$
   - η_{ov} varies from 35 to 38%.
4. **Work ratio (R_w)**

   $$R_w = \frac{\text{Network output}}{\text{Turbine work}} = \frac{W_t - W_p}{W_t}$$

5. **The specific steam consumption (SSC)**
   The amount of steam consumed per unit of power developed.

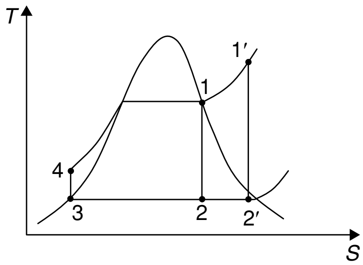
   $$SSC = \frac{3600}{W_{net}} = \frac{3600}{h_1 - h_2} \text{ kg/kWh}$$

   SSC varies from 3 to 5 kg/kWh
6. **Heat rate (H_R)**
   Amount of heat consumed per unit power developed.

   $$H_R = \frac{3600}{\eta_{th}} = \frac{3600 Q_1}{Q_1 - Q_2} \text{ kJ/kWh}$$

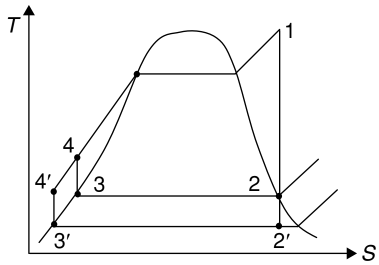
Methods to Improve the Performance of Simple Rankine Cycle

Effect of superheating the steam in the boiler In superheating, the initial temperature of the steam is increased at constant pressure in the boiler.



By increasing the temperature from 1 to 1′ at constant pressure, T_{mA} between 1′ and 4 is increased than T_{mA} between 1 and 4. Thus the efficiency of the cycle also increases. Net work output also increases.

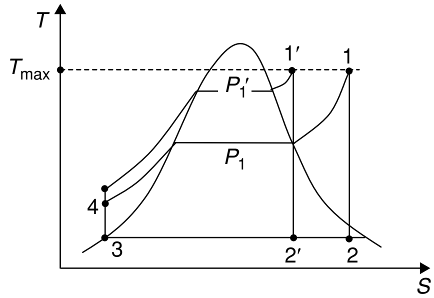
Effect of increasing the condenser pressure keeping the boiler pressure constant As decreasing the condenser pressure, the mean temperature of heat rejection decreases and hence the efficiency of the cycle increases and net work output also increases.



But increasing the condenser pressure is not preferable due to some boundations.

- Minimum practical temperature of heat rejection is surrounding temperature and decreasing the condenser pressure means decreasing the saturation temperature. Hence the saturation temperature of corresponding pressure is difficult to decrease beyond the surrounding conditions.
- The pressure of the condenser cannot reach the vapour pressure of water. If this happens then cavitation may take place.

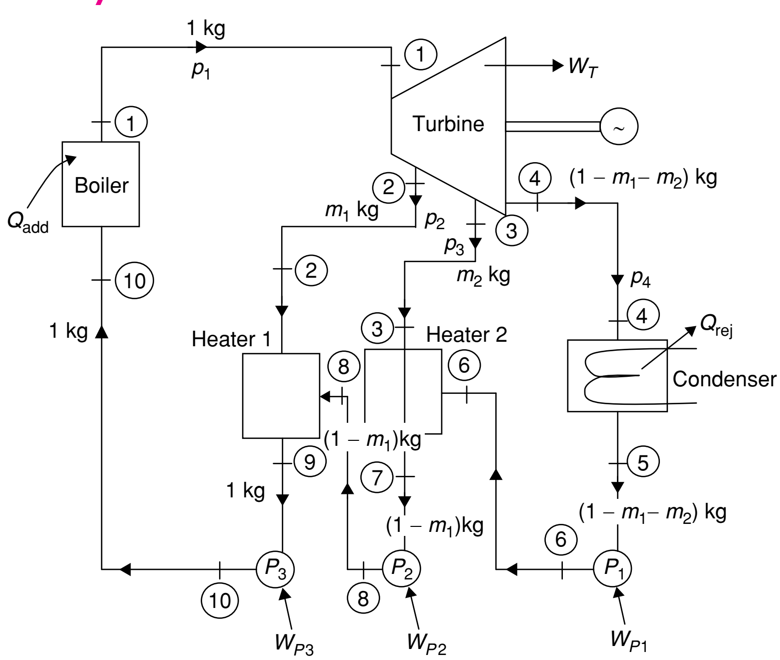
Effect of increasing boiler pressure keeping condenser pressure constant



Due to the mechanical consideration the maximum temperature of steam is fixed. When the maximum temperature is fixed, the increase in the boiler pressure increases the saturation temperature at which heat is added to the steam and thus the mean temperature of heat addition also increases and efficiency increases.

Drawbacks: When the boiler pressure is increased from P_1 to P_1', the isentropic expansion line shifts towards left and the quality of steam decreases at the turbine exit from 2 to 2′. This may cause erosion of the blade surface.

Regenerative Rankine cycle



For 1 kg of steam entering the turbine at pressure p_1, m_1 kg of steam is extracted from the intermediate stage of expansion in turbine at a pressure of p_2 and it is used to heat up feed water [$(1 - m_1)$ kg at state 8] by mixing in heater 1. Then the remaining $(1 - m_1)$ kg of steam expand in the turbine from pressure p_2 to p_3. At an intermediate pressure of p_3, again m_2 kg of steam is extracted from the turbine and is used to heat up feed water [$(1 - m_1 - m_2)$ kg at state 6] by mixing in heater 2. So $(1 - m_1 - m_2)$ kg of steam further expands in the turbine to the pressure p_4, get condensed in the condenser at constant pressure of p_4 and then pumped into heater 2 where it mixes with the extracted steam of mass m_2 at pressure p_3. Further $(1 - m_1)$ kg of water is pumped to heater 1 where *I* mixes with the extracted steam of mass m_1 at pressure p_1. Then the resulting 1 kg of water is then pumped to the boiler.

1 – 2 – 3 – 4 – 5 – 6 – 7 – 8 – 9 – 10 – 1 → Rankine cycle with regeneration

1 – 2 – 3 – 4 – 5 – 10^1 – 1 – Simple Rankine cycle

Net Work Output (w_{net})

Turbine work: $W_T = 1(h_1 - h_2) + (1 - m_1)(h_2 - h_3) + (1 - m_1 - m_2)(h_3 - h_4)$

When no regenerator is used, turbine work is

$$W_T = (h_1 - h_2) + (h_2 - h_3) + (h_3 - h_4)$$

Hence turbine work decreases when using regenerator.

Pump work: $W_C = (1 - m_1 - m_2)(h_6 - h_5) + (1 - m_1)(h_8 - h_7) + (1)(h_{10} - h_9)$

When no regenerator is used, pump work is

$$W_P = (h_{10^1} - h_5)$$

$$\therefore \quad W_{net} = W_T - W_C$$

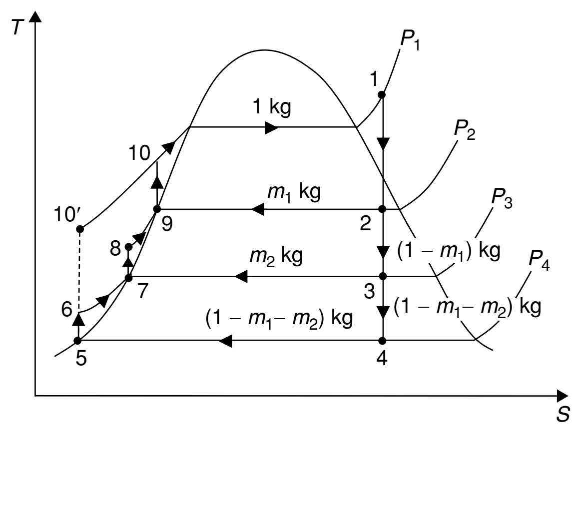
Net work output decreases when using regeneration.

Heat addition When regeneration is used

$$Q_{add} = (h_1 - h_{10})$$

Without regeneration,

$$Q_{add} = (h_1 - h_{10^1})$$



Energy balance for heater 1

$$m_1 h_2 + (1 - m_1) h_8 = 1 \times h_9$$

or
$$m_1 = \frac{h_9 - h_8}{h_2 - h_8}$$

Energy balance for heater 2

$$m_2 h_3 + (1 - m_1 - m_2)h_6 = (1 - m_1)h_7$$

$$m_2 = (1 - m_1)\frac{h_7 - h_6}{h_3 - h_6}$$

Heat addition decreases when regeneration is used

Efficiency (η) Since the entry of water to the boiler is at higher temperature when regeneration is used as compare to the temperature without regeneration, therefore the mean temperature of heat addition increases and hence efficiency also increases.

$$\eta = 1 - \frac{T_{rej}}{T_{mA}}$$

$\because$ T_{mA} increases, η also increases.

Heat rejection (Q_{rej})

$$Q_{rej} = (1 - m_1 - m_2)(h_4 - h_5)$$

Q_{rej} also decreases when using regeneration

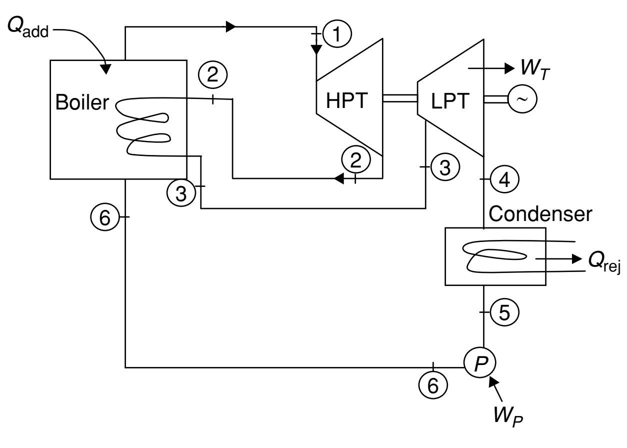
NOTE

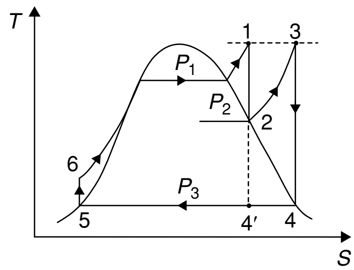
When number of water heater increases to infinity, it is known as ideal regeneration and the efficiency of the cycle will approximate the Carnot efficiency operating between same boiler and condenser temperature.

Reheat Rankine Cycle

Reheating is used to maintained the quality of the steam at the exit of turbine more than 85%, i.e., Dryness fraction $(x)_{exit}$ of turbine ≥ 0.85

If dryness fraction at exit of the turbine is lower than 0.85, then erosion of blades due to high density of liquid as compare to the vapor and formation of cavity will be more and the life of blade will be reduced and thus the efficiency is also less.





Heat addition $Q_{add} = (h_1 - h_6) + (h_3 - h_2)$

Without reheat $Q_{add} = (h_1 - h_6)$

Heat addition increases in reheat Rankine cycle.

Network output (W_{net}) $W_{net} = W_T - W_P$

Turbine work: $W_T = (h_1 - h_2) + (h_3 - h_4)$

Without reheat: $W_T = (h_1 - h_{4^1})$

Turbine work increases in reheat Rankine cycle.

Pump work, $W_P = h_6 - h_5$

Pump work remains the same

Net work output increases in reheat Rankine cycle.

Efficiency $\eta = 1 - \dfrac{T_{rej}}{T_{mA}}$

Efficiency increases by 2 to 3% in reheat Rankine cycle.

Gas Power Cycles

Carnot Cycle

It consists of the following reversible processes:

1 – 2: Isothermal heat addition process
2 – 3: Isentropic expansion
3 – 4: Isothermal heat rejection process
4 – 1: Isentropic compression

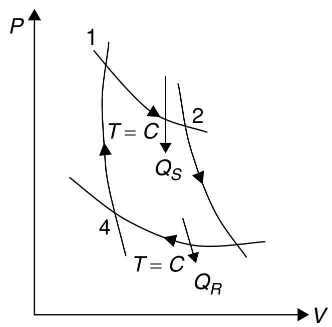


Figure 4 P–V diagram

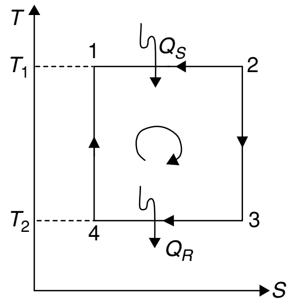


Figure 5 T–S diagram

- Thermal efficiency, $\eta_{carnot} = \dfrac{W_{net}}{Q_s} = \dfrac{Q_S - Q_R}{Q_S}$

$$= 1 - \frac{Q_R}{Q_S}$$

- $\eta_{carnot} = \dfrac{T_1 - T_2}{T_1} = 1 - \dfrac{T_2}{T_1}$
- Carnot cycle is ideal cycle used to compare the other thermodynamic cycles.
- Carnot cycle is not possible practically.

Otto Cycle (Constant Volume Cycle)

- Invented by Dr. A. N. Otto (1876), a German scientist, for spark ignition IC engine.
- Heat addition takes place at constant volume hence it is named as constant volume cycle.

Cycle consists of the following reversible processes.

1 – 2: Isentropic compression
2 – 3: Constant volume heat addition
3 – 4: Isentropic expansion
4 – 1: Constant volume heat rejection

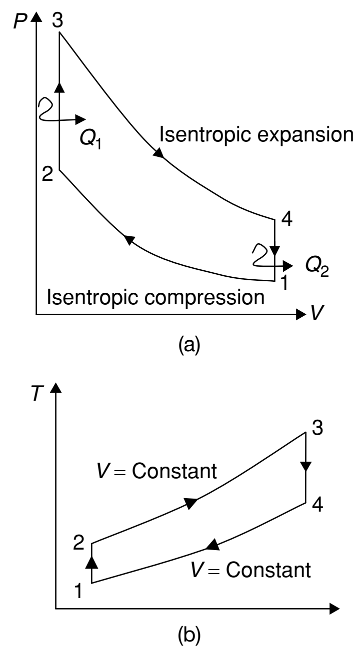


Figure 6 Ideal Otto cycle. (a) P–V diagram; (b) T–S diagram

Heat supplied $Q_1 = Q_{2-3} = mc_v(T_3 - T_2)$

Heat rejected $Q_2 = Q_{4-1} = mc_v(T_4 - T_1)$

Efficiency $\eta = 1 - \dfrac{Q_2}{Q_1} = 1 - \dfrac{(T_4 - T_1)}{(T_3 - T_2)}$

For process 1 – 2; $\dfrac{T_2}{T_1} = \left(\dfrac{V_1}{V_2}\right)^{\gamma - 1}$

For process 3 – 4; $\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$

$$\therefore \quad \frac{T_2}{T_1} = \frac{T_3}{T_4}; \ \frac{T_3}{T_2} = \frac{T_4}{T_1}$$

$$\therefore \quad \eta_{otto} = 1 - \frac{T_1}{T_2}$$

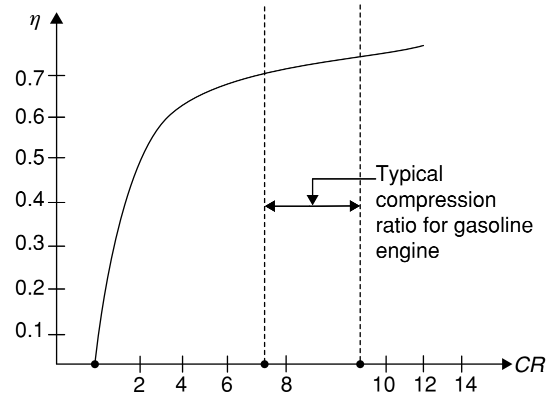
$$\eta_{otto} = 1 - \frac{1}{(r)^{\gamma-1}}$$

where r = compression ratio $= \frac{V_1}{V_2}$

γ = specific heat ratio $= \frac{C_P}{C_V}$

NOTES

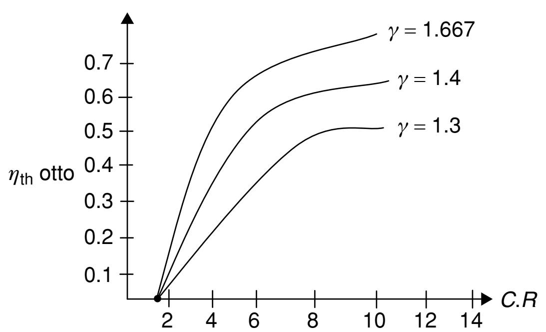
1. η_{Otto} depends on compression ratio and specific heat ratio.
2. η_{Otto} increases with increasing r and γ.



Compression Ratio (r)

Thermal efficiency of Otto cycle is a function of compression ratio (r = 1.4).

- Thermal efficiency increases with increasing compression ratio, but at high compression ratio, the engine is subjected to knocking, which hurts the performance of the engine.
- Therefore the normal compression ratio is 7–10.
- The compression ratio up to 12 is used when tetraethyllead is added to the gasoline mixture which increases the antiknock characteristic of the fuel and reduces the tendency of knocking.



Compression ratio (r)

The thermal efficiency of the Otto cycle increases with the specific heat ratio (γ) of the working fluid.

Work Output

$$W_{net} = \frac{P_1 V_1}{\gamma - 1}(\gamma_p - 1)(r^{\gamma-1} - 1)$$

where $r_p = \frac{P_3}{P_2} = \frac{P_4}{P_1}$ pressure ratio

Mean Effective Pressure

$$P_{mep} = \frac{\text{Net work output}}{\text{swept volume}}$$

$$P_m = \frac{P_1 r(\gamma_p p - 1)(r^{\gamma-1} - 1)}{(\gamma - 1)(r - 1)}$$

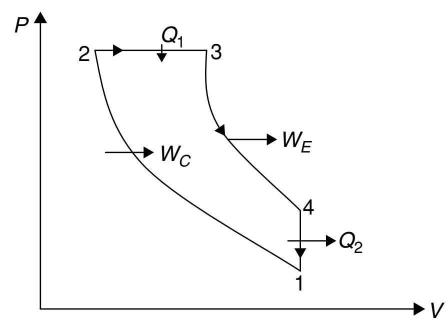
NOTE

For an Otto cycle an increase in compression ratio (r), increases P_m, W_{net} and $\eta_{th\ Otto}$.

Diesel Cycle (Constant Pressure Cycles)

- It is proposed by Rudolph Diesel in the 1890s.
  In SI engines, a mixture of fuel and air is compressed during the compression stroke, and the compression ratios are limited by the onset of the auto-ignition or engine knock. In diesel engines, only air is compressed during the compression stroke, eliminating the possibility of auto-ignition. Therefore, diesel engines are designed to operate at much higher compression ratios, typically between 12 and 24.
- Heat addition takes place at constant pressure hence it is named as constant pressure cycles.

Processes:
1 – 2: Isentropic Compression
2 – 3: Constant pressure heat addition
3 – 4: Isentropic expansion
4 – 1: Constant volume heat rejection process.



(a)

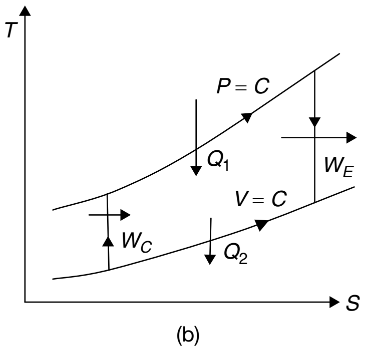


Figure 7 Diesel cycle (CI engines). (a) P–V diagram; T–S diagram

Thermal Efficiency

$$\eta_{th} = \frac{\text{Work done}}{\text{heat supplied}} = \frac{C_P(T_3 - T_2) - C_V(T_4 - T_1)}{C_P(T_3 - T_2)}$$

$$= 1 - \frac{1}{\gamma}\left[\frac{T_4 - T_1}{T_3 - T_2}\right]$$

Let cut-off ratio $(\alpha_C) = \frac{V_3}{V_2}$

$$\eta_{th} = 1 - \frac{1}{(r)^{\gamma-1}}\left[\frac{\alpha_C{}^{\gamma} - 1}{\gamma(\alpha_C - 1)}\right]$$

NOTES

1. $\alpha_C > 1$ and $\frac{1}{\gamma}\left(\frac{\alpha_C^{\gamma} - 1}{\alpha_C - 1}\right) > 1$, therefore

   $\eta_{Otto} > \eta_{Diessel}$ for the same compression ratio.
2. Lower cut-off ratio leads to better thermal efficiency but high value of cut-off ratio leads to more power output.

   i.e., If $\alpha_c \uparrow \to \eta \downarrow$ but $W_{net} \uparrow$

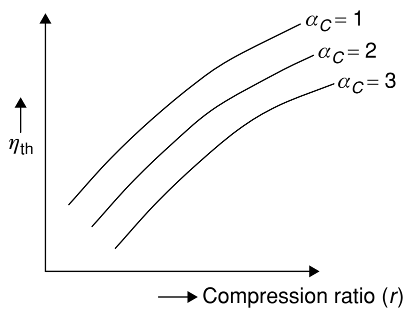


Figure 8 Diesel cycle efficiency.

Mean Effective Pressure

$$\text{mep (or) } P_m = P_1 \cdot r\left[\frac{\gamma \cdot r^{\gamma-1}(\alpha_C - 1) - (\alpha_c^{\gamma} - 1)}{(r-1)(\gamma-1)}\right]$$

Dual Cycle (Limited Pressure Cycle)

- In dual cycle, part of heat addition takes place of constant volume and rest at constant pressure.
- The dual cycle is also called mixed or limited pressure cycle.

Processes:

1 – 2 Reversible adiabatic compression
2 – 3 Constant volume heat supply
3 – 4 Constant pressure heat supply
4 – 5 Reversible adiabatic expansion
5 – 1 Constant volume heat rejection

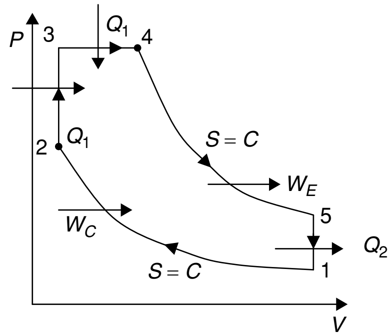


Figure 9 P–V diagram

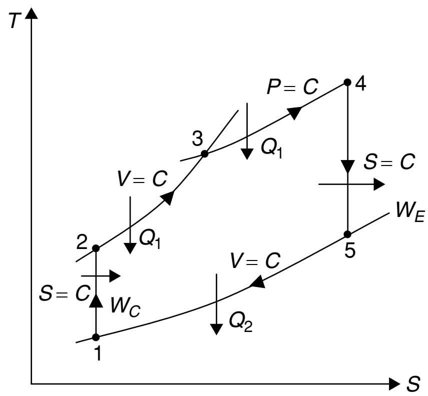


Figure 10 T–S diagram

Compression ratio $r = \frac{V_1}{V_2}$

Expansion ratio $r_e = \frac{V_5}{V_4}$

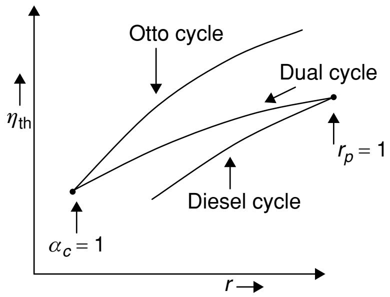
Cut-off ratio $\alpha_c = \frac{V_4}{V_3}$

Constant volume pressure ratio, $r_p = \frac{P_3}{P_2}$

Thermal Efficiency

$$\eta_{th} = 1 - \frac{1}{(r)^{\gamma-1}}\left[\frac{(r_p \alpha_c^{\gamma} - 1)}{(r_p - 1) + \gamma r_p(\alpha_c - 1)}\right]$$

Note:



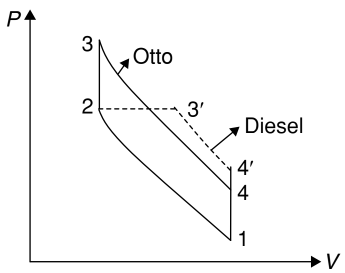
NOTES

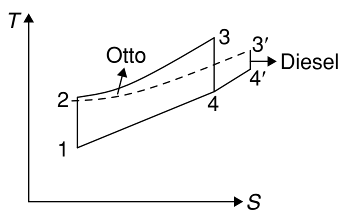
1. When $\alpha_c = 1$, $\eta_{dual} = \eta_{Otto}$
2. When $r_p = 1$, $\eta_{dual} = \eta_{Diesel}$

Comparison of Cycles

Comparison of Otto and Diesel Cycles on the Basis of

CR = constant
Heat supplied = constant



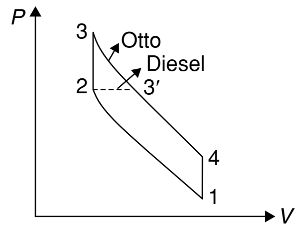


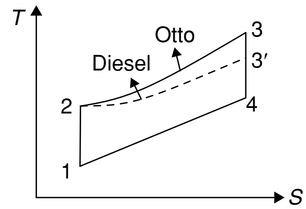
Comparing these two cycles, from the diagram we get,

1. (Peak pressure)$_{otto}$ > (Peak pressure)$_{diesel}$
2. (Peak temperature)$_{otto}$ > (Peak temperature)$_{diesel}$
3. (Expansion ratio)$_{otto}$ > (Expansion ratio)$_{diesel}$
4. (Heat rejected)$_{otto}$ > (Heat rejected)$_{diesel}$
5. (Temperature beginning of heat rejection)$_{otto}$ > (Temperature beginning of heat rejection)$_{diesel}$
6. (Work)$_{otto}$ > (Work)$_{diesel}$
7. $(\eta_{th})_{otto} > (\eta_{th})_{diesel}$

Comparison on the Basis Of

CR = constant
Heat rejected = constant



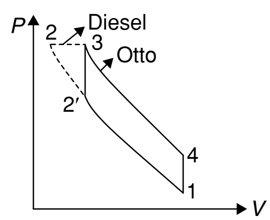


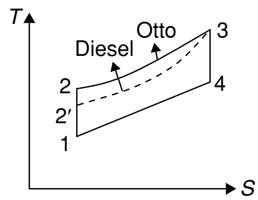
From the diagram we get

1. (Peak pressure)$_{otto}$ > (Peak pressure)$_{diesel}$
2. (Peak temperature)$_{otto}$ > (Peak temperature)$_{diesel}$
3. (Work)$_{otto}$ > (Work)$_{diesel}$
4. (Heat supplied)$_{otto}$ > (Heat supplied)$_{diesel}$
5. $(\eta_{th})_{otto} > (\eta_{th})_{diesel}$
6. (Expansion ratio)$_{otto}$ > (Expansion ratio)$_{diesel}$

Comparison on the Basis Of

Peak pressure = constant
Peak temperature = constant
Heat rejected = constant



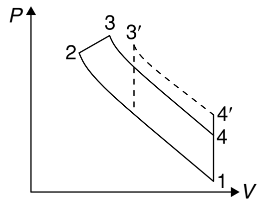


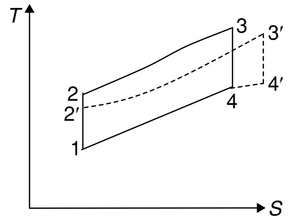
Comparing these two from the diagram, we get

1. (Comparison ratio)$_{otto}$ < (Comparison ratio)$_{diesel}$
2. (Temperature at the end of compression)$_{otto}$ < (Temperature at the end of compression)$_{diesel}$
3. (Work)$_{otto}$ > (Work)$_{diesel}$
4. (Heat supplied)$_{otto}$ > (Heat supplied)$_{diesel}$
5. $(\eta_{th})_{otto} > (\eta_{th})_{diesel}$

Comparison on the Basis Of

Peak pressure = constant
Heat supplied = constant





Comparing these two cycles from the diagram, we get

1. (Compression ratio)$_{otto}$ < (Compression ratio)$_{diesel}$
2. (Temperature at the end of compression)$_{otto}$ < (Temperature at the end of compression)$_{diesel}$
3. (Peak temperature)$_{otto}$ > (Peak temperature)$_{diesel}$
4. (Heat rejected)$_{otto}$ > (Heat rejected)$_{diesel}$
5. (Temperature at the beginning of heat rejection)$_{otto}$ > (Temperature at the beginning of heat rejection)$_{diesel}$
6. (Expansion ratio)$_{otto}$ > (Expansion ratio)$_{diesel}$
7. (Work)$_{otto}$ > (Work)$_{diesel}$
8. $(\eta_{th})_{otto} > (\eta_{th})_{diesel}$

NOTES

1. For the same compression ratio
   $\eta_{Otto} > \eta_{Dual} > \eta_{Diesel}$
2. For all other conditions such as constant heat supplied constant peak temperature, etc.
   $\eta_{Diesel} > \eta_{Dual} > \eta_{Otto}$

Stirling Cycle (1827)

It consists of two reversible Isothermal processes and two reversible constant volume processes.

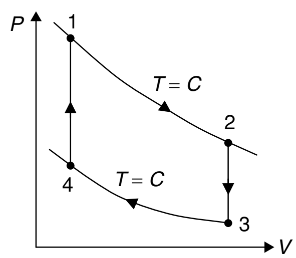


Figure 11 P–V diagram

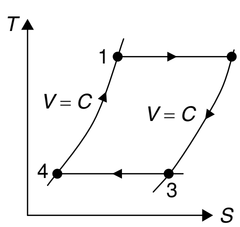


Figure 12 T–S diagram

$$\eta = \frac{T_1 - T_2}{T_1}$$

Ericsson Cycle (1850)

It consists of two reversible Isothermal processes and two reversible constant pressure processes.

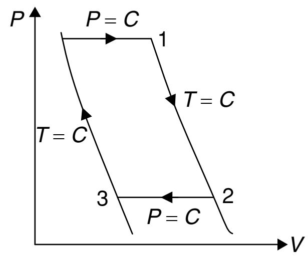


Figure 13 P–V diagram

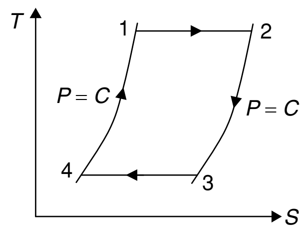


Figure 14 T–S diagram

$$\eta = \frac{T_1 - T_2}{T_1}$$

NOTE

In actual practice the efficiency of Stirling cycle and Ericsson cycle is less than the Carnot cycle. But, when a regenerator is employed in these cycles, the efficiencies will be equal to Carnot cycle.

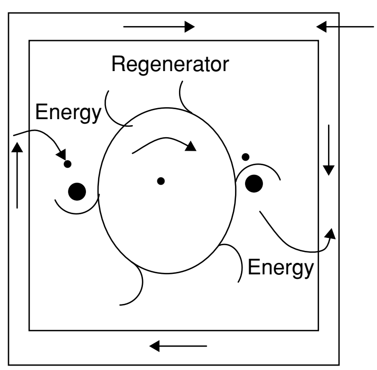


Figure 15 Regenerator

A regenerator is a device that borrows energy from the working fluid during one part of the cycle and pays it back during another part.

Hence,

$$\eta_{\text{regon Eri}} = \eta_{\text{regen stir}} = \eta_{\text{Carnot}} = \frac{T_1 - T_2}{T_1}$$

Lenoir Cycle

The Lenoir cycle is applicable to pulse jet engines. Lenoir cycle has only three processes. It has no compression strokes. It has less number of moving parts and back work is zero. It is mainly used in pulse jet engines.

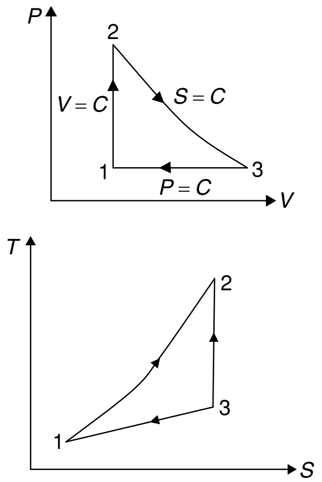


Figure 15 P–V diagram and T–S diagram

Processes

1 – 2: Constant volume heat supply
2 – 3: Reversible adiabatic expansion
3 – 4: Constant pressure heat rejection

Thermal Efficiency

Heat supplied, $Q_{in} = C_v(T_2 - T_1)$
Heat rejected, $Q_{out} = C_p(T_3 - T_1)$

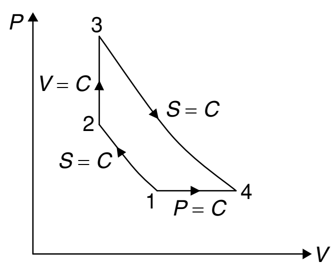
$$\eta_{th} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

$$\boxed{\eta_{th} = 1 - \gamma \frac{\left(r_p^{\frac{1}{\gamma}} - 1\right)}{r_p - 1}}$$

where r_p = pressure ratio $= \frac{P_2}{P_1}$

Useful tip: $\eta_{th} = f(r_p, \gamma)$

Atkinson Cycle



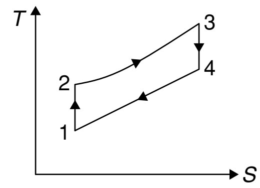


Figure 16 P–V diagram and T–S diagram

Processes

1 – 2: Reversible adiabatic compression
2 – 3: Constant volume heat supply
3 – 4: Reversible adiabatic expansion
4 – 1: Constant pressure heat rejection

Compression Ratio and Expansion Ratio

$$\text{C.R } r_K = \frac{V_1}{V_2}$$

$$\text{E.R } r_E = \frac{V_4}{V_3} = \frac{V_4}{V_2}$$

Heat supplied, $Q_S = C_V(T_3 - T_2)$
Heat rejected, $Q_R = C_P(T_4 - T_1)$

Thermal Efficiency

$$\eta_{th} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

$$= 1 - \frac{C_P(T_4 - T_1)}{C_V(T_3 - T_2)} = 1 - \frac{r[r_E - r_K]}{\left[r_E^r - r_K^r\right]}$$

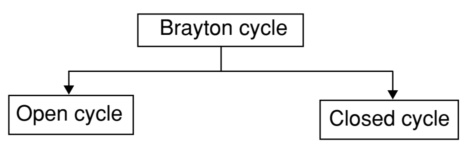
$$\eta_{th} = f(r_K, r_E, r)$$

Useful tip: If constant volume heat rejection process in Otto cycle is converted into constant pressure heat rejection, Otto cycle becomes Atkinson cycle.

For converting constant volume heat rejection into constant pressure heat rejection, we are using toggle joint. The excessive wear and tear of toggle joint resulted in the failure of the cycle.

Useful tip: Atkinson cycle gives higher work output and thermal efficiency compared to the Otto cycle. It is also known as constant volume gas turbine cycle.

Brayton Cycle



Used in aircraft, automotive (buses and trucks), and industrial gas turbine installations.

Used in gas-cooled nuclear reactor plant.

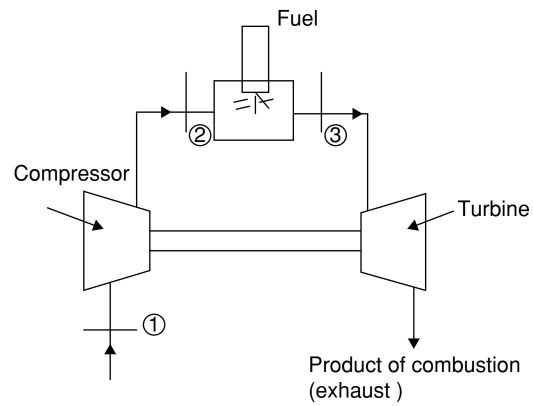


Figure 17 A simple open cycle gas turbine plant

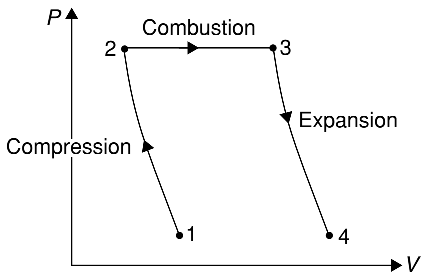


Figure 18 P–V plot.

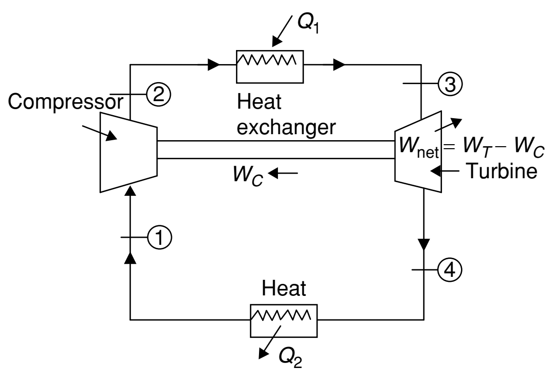


Figure 19 A simple closed cycle gas turbine plant

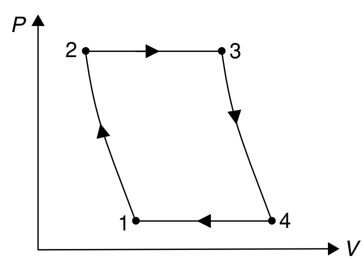


Figure 20 P–V diagram

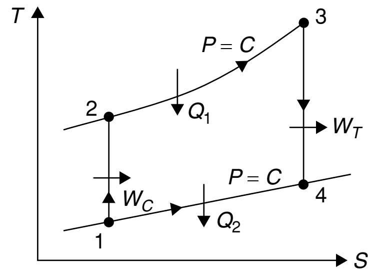


Figure 21 T–S diagram

Brayton cycle used in gas turbine power plant.

Processes:

1 – 2: Isentropic compression

2 – 3: Constant pressure heat addition

3 – 4: Isentropic expansion

4 – 1: Constant pressure heat rejection

Let r_p = pressure ratio $= \dfrac{P_2}{P_1}$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\left(\frac{\gamma-1}{\gamma}\right)}$$

γ = compression ratio $= \dfrac{V_1}{V_2}$

Efficiency

Efficiency of Brayton cycle, $\eta_{\text{Brayton}} = 1 - \dfrac{1}{(r)^{g-1}}$

$$\eta_{\text{Brayton}} = 1 - \frac{1}{(r_p)^{\left(\frac{\gamma-1}{\gamma}\right)}}$$

NOTES

1. $\eta_{\text{Brayton}} = f(r, r_p)$
2. For the same compression ratio

$$\eta_{\text{Otto}} = \eta_{\text{Brayton}}$$

Effect of Irreversibilities in Turbine and Compressor

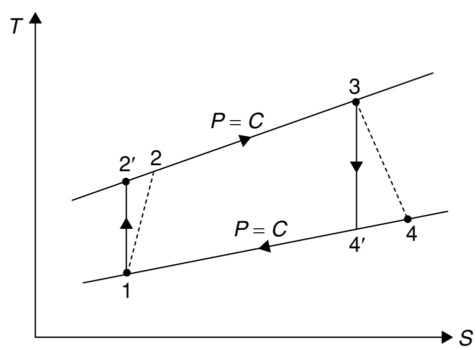


Figure 22 Effect of machine efficiencies on Brayton cycle

- $1-2^1-3-4^1-1$ is ideal cycle.
- $1-2-3-4-1$ is actual cycle.

Turbine efficiency $\eta_T = \dfrac{h_3-h_4}{h_3-h_4^1} = \dfrac{T_3-T_4}{T_3-T_4^1}$

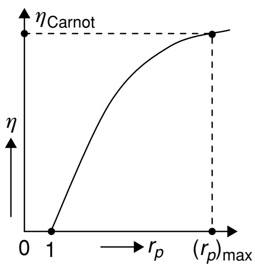
Compressor efficiency $\eta_c = \dfrac{h_2^1-h_1}{h_2-h_1} = \dfrac{T_2^1-T_1}{T_2-T_1}$

- The cycle efficiency depends on η_T and η_c.
- The cycle efficiency is high when η_T and η_c is high.
- The cycle efficiency is approaches to zero when η_T and $\eta_c = 60$ to 70%

  $\therefore$ η_T and η_c must be high i.e., around 80 to 95%.

Effect of Pressure Ratio on the Brayton Cycle

$$\eta = 1-\frac{1}{(r_p)^{\left(\frac{\gamma-1}{\gamma}\right)}}$$



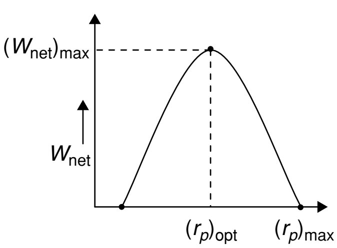
Effect of pressure ratio on Brayton cycle efficiency

1. When $r_p = 1$ η_{braton} and work output will be zero.
2. When $r_p = (r_p)_{max}$, $\eta_{brayton}$, $= \eta_{carnot}$.

$$\therefore \qquad 1-\frac{1}{(r_p)_{max}^{\frac{\gamma-1}{\gamma}}} = \eta_{Carnot} = 1-\frac{T_{min}}{T_{max}}$$

$$\therefore \qquad (r_p)_{max} = \left(\frac{T_{max}}{T_{min}}\right)^{\frac{\gamma}{(\gamma-1)}}$$

3. Effect of pressure ratio on net output



$$(r_p)_{opt} = \left(\frac{T_{max}}{T_{min}}\right)^{\frac{\gamma}{2(\gamma-1)}}$$

$$(r_p)_{opt} = \sqrt{(r_p)_{max}}$$

4. $(W_{net})_{max} = C_p(\sqrt{T_{max}}-\sqrt{T_{min}})^2$
5. $\eta_{cycle} = 1-\sqrt{\dfrac{T_{min}}{T_{max}}}$

NOTE

Work ratio $= \dfrac{W_{net}}{W_T} = \dfrac{W_T-W_C}{W_T} = 1-\dfrac{W_c}{W_T}$

Brayton Cycles with Ideal Regeneration

The efficiency of any power producing cycle is given as

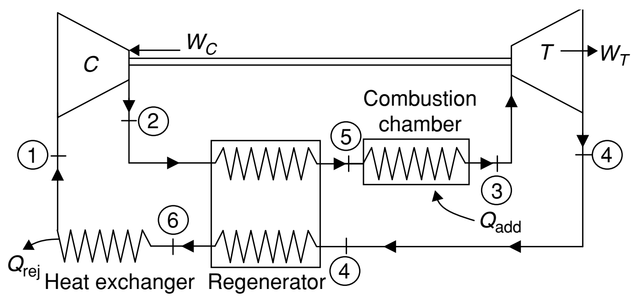
$$\eta = 1-\frac{T_{rej}}{T_{add}}$$

Here T_{rej} = Mean temperature of heat rejection

T_{add} = Mean temperature of heat addition

To increase the efficiency of any engine, it is required to either increase T_{add} or decrease T_{rej}. Decreasing T_{rej} beyond the atmospheric conditions requires another setup and energy consumptions. Thus decreasing T_{rej} is not preferable. Therefore, if we increase the T_{add} of the cycle, there is increase in the efficiency of the cycle.

The schematic diagram of the Brayton cycle with regeneration is shown below:



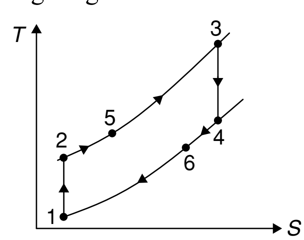
Here C = Compressor, T = Turbine

By utilizing the energy of the exhaust gas from the turbine (state 4), the compressed gas (state 2) is heated up (from state 2 to 5) in a heat exchanger known as regenerator, and hence the heat is supplied at state 5 which is at high temperature than state 2. Therefore mean temperature of heat addition increases and also the mean temperature of heat rejection decreases. Thereby decreasing the amount of heat supplied and heat rejected.

If, $T_4 = T_2 \rightarrow$ No need of regenerator

$T_4 > T_2 \rightarrow$ Using a regenerator will increase the efficiency

$T_4 < T_2 \rightarrow$ Using a regenerator will decrease the efficiency



Pressure ratio: $r_P = \dfrac{P_2}{P_1} = \dfrac{P_3}{P_4}$

Heat addition: $Q_{\text{add}} = h_3 - h_5 = mC_P(T_3 - T_5)$

Heat rejected: $Q_{\text{rej}} = h_6 - h_1 = mC_P(T_6 - T_1)$

Net work output: $W_{\text{net}} = W_T - W_C$

$$\Rightarrow \quad W_{\text{net}} = (h_3 - h_4) - (h_2 - h_1)$$
$$= mC_P[(T_3 - T_4) - (T_2 - T_1)]$$

Efficiency: $\eta = 1 - \dfrac{Q_{\text{rej}}}{Q_{\text{add}}} = 1 - \dfrac{(T_6 - T_1)}{(T_3 - T_5)}$

For ideal regeneration, $T_5 = T_4$ and $T_2 = T_6$

$$\therefore \quad \eta = 1 - \frac{T_1}{T_3}\left[\frac{\left(\frac{T_2}{T_1}\right) - 1}{1 - \left(\frac{T_4}{T_3}\right)}\right] = 1 - \frac{T_1}{T_3}\cdot\frac{T_2}{T_1}\left[\frac{1 - \left(\frac{T_1}{T_2}\right)}{1 - \left(\frac{T_4}{T_3}\right)}\right]$$

$$\because \quad \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = \frac{T_3}{T_4}$$

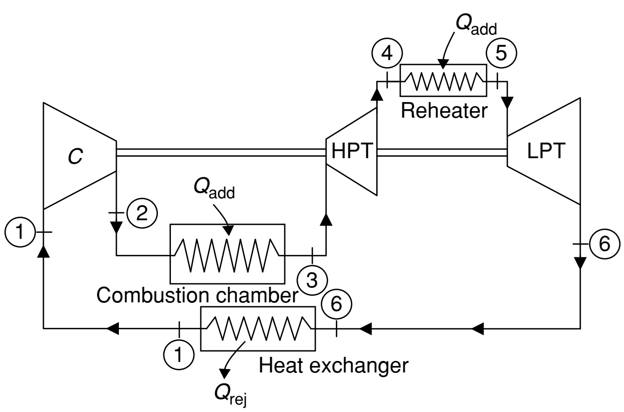
$$\therefore \quad \eta = 1 - \frac{T_1}{T_3}\cdot(r_P)^{\frac{\gamma-1}{\gamma}}$$

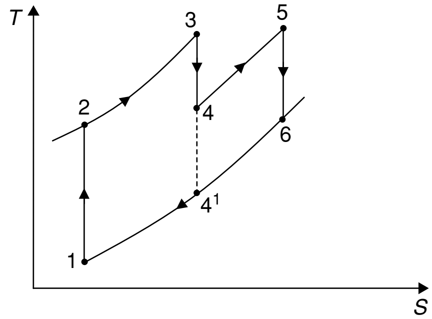
Effectiveness of Regenerator It is the ratio of actual temperature rise of air to the maximum possible rise.

$$\in = \frac{T_5 - T_2}{T_4 - T_2}$$

Brayton Cycle with Reheat Arrangement

In reheat Brayton cycle, the working fluid is reheated after expansion in the high pressure turbine and then again expanded in the low pressure turbine. Hence the work output of the turbine using reheat will increase. It accomplishes this by increasing the average temperature at which the expansion takes place. Since the expansion takes place at higher temperatures of the same pressure ratio, the shaft work produced is more. The schematic diagram of reheat Brayton cycle is shown below:





Heat addition: $Q_{\text{add}} = (h_3 - h_2) + (h_5 - h_4)$

Q_{add} increases in reheat Brayton cycle.

$1 - 2 - 3 - 4^1 - 1 \rightarrow$ Simple Brayton cycle without reheat

$1 - 2 - 3 - 4 - 5 - 6 - 1 \rightarrow$ Brayton cycle with reheat

Heat rejection: $(h_6 - h_1) = Q_{\text{rej}}$

Q_{rej} increases in reheat Brayton cycle.

Net work output: $W_{\text{net}} = W_T - W_C$

$W_T \rightarrow$ Turbine work

W_T for $1 - 2 - 3 - 4^1 - 1 \rightarrow (h_3 - h_4{}^1)$

W_T for $1 - 2 - 3 - 4 - 5 - 6 - 1 \rightarrow (h_3 - h_4) + (h_5 - h_6)$

Since the constant pressure curve on T–S plane is diverging when moves towards the higher temperature region, therefore $(h_5 - h_6) > (h_4 - h_4{}^1)$

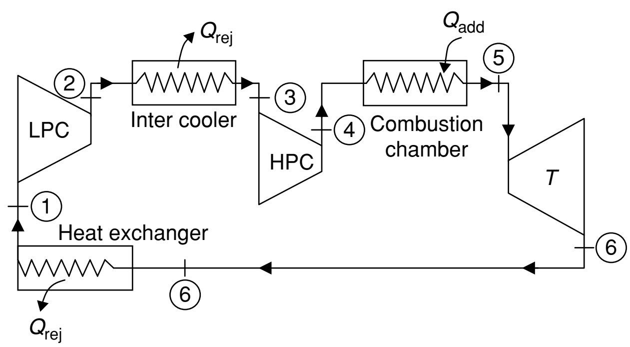
$\therefore$ W_T increases in reheat Brayton cycle.

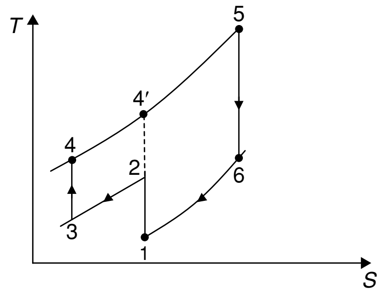
In reheat Brayton cycle, the mean temperature of heat addition decreases and mean temperature of heat rejection increases as compare to simple Brayton cycle and therefore the thermal efficiency of the reheat Brayton cycle decreases.

For perfect reheating, $T_3 = T_5$

Brayton Cycle with Intercooling

In this arrangement, the working fluid (air) after compression in low pressure compressor is send to a heat exchanger known as intercooler where the air is cooled or heat is taken off from the compressed air at a constant pressure and again send it to a high pressure compressor where the cooled air is again compressed to high pressure. By doing this the net work output increases. The schematic arrangement is shown below:





$1-2-4^1-5-6-1 \rightarrow$ Simple Brayton cycle
$1-2-3-4-5-6-1 \rightarrow$ Brayton cycle with intercooler

Heat addition: $Q_{add} = (h_5 - h_4)$

Q_{add} increased with an addition of $(h_{4^1} - h_4)$ as compare to simple Brayton cycle.

Heat rejection: $Q_{rej} = (h_6 - h_1)$

Net work output: $W_{net} = W_T - W_C$

W_T = turbine work = $h_5 - h_6$

W_T remains same in Brayton cycle with inter cooling as compared to simple Brayton cycle.

$$W_C = (h_2 - h_1) + (h_4 - h_3)$$

Since the constant pressure curve on T–S plane is converging when moves towards lower temperature region, therefore

$$(h_{4^1} - h_2) > (h_4 - h_3)$$

Hence W_C decreases and W_{net} increases.

Efficiency: Since the mean temperature of heat addition decreases and mean temperature of heat rejection increases, the efficiency also decreases.

Solved Examples

Example 1: In an air standard cycle for petrol engine, air at 27°C and 1 bar is compressed adiabatically until the pressure is 14 bar. Heat is added to the cycle until the pressure reaches to 38 bar.

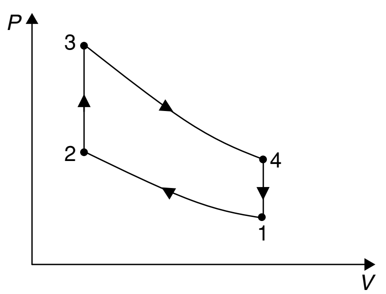
(1) The air-standard efficiency of the cycle will be
(A) 51 (B) 47 (C) 53 (D) 57

(2) The compression ratio for the cycle is
(A) 6.6 (B) 7.7 (C) 10 (D) 6.9

(3) The mean effective pressure (in bar) for the cycle will be
(1) 5.69 (B) 7.71 (C) 6.39 (D) 5.19

Solution:

(2) Process 1 – 2:



$$P_1V_1^{\gamma} = P_2V_2^{\gamma}$$

$$\frac{V_1}{V_2} = \left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}} = r$$

$$r = \left(\frac{14}{1}\right)^{\frac{1}{1.4}} = 6.5866$$

(1) $\eta = 1 - \dfrac{1}{(r)^{\gamma-1}} = 1 - \dfrac{1}{(6.5866)^{0.4}}$

$\Rightarrow \quad \eta = 0.5295 = 52.95\%$

(3) Mean effective pressure, $P_m = \dfrac{\text{Work done}}{\text{Swept volume}}$

Now, $\dfrac{P_1V_1}{T_1} = \dfrac{P_2V_2}{T_2} \quad \Rightarrow \quad T_2 = \dfrac{P_2}{P_1}\dfrac{V_2}{V_1}T_1 = 14 \times \dfrac{1}{6.5866} \times 300$

$\Rightarrow \quad T_2 = 637.66$ K

Process 2 – 3:

$$T_3 = \frac{P_3T_2}{P_2} = \frac{38}{14} \times 637.66$$

$\Rightarrow \quad T_3 = 1730.79$ K

Heat supplied, $Q_S = C_V(T_3 - T_2)$
$= 0.718 \times [1730.79 - 637.66]$
$= 784.87$ kJ/kg

Work done $= \eta \times Q_s = 0.5295 \times 784.87$

$\Rightarrow$ W.D = 415.589 kJ/kg

$$v_1 = \frac{V_1}{m} = \frac{RT_1}{P_1} = \frac{0.287 \times 300}{100} = 0.861 \text{ m}^3/kg$$

Now, $v_1 - v_2 = v_1\left[1 - \dfrac{v_2}{v_1}\right] = \dfrac{5.5866}{6.5866} \times 0.861$

$\Rightarrow \quad v_1 - v_2 = 0.73028$ m³/kg

$$P_m = \frac{W.D}{v_1 - v_2} = \frac{415.589}{0.73028} \times 10^3 = 5.69 \times 10^5 \text{ N/m}^2$$

$\therefore \quad P_m = 5.69$ bar

Example 2: An engine working on the Otto cycle has a cylinder dimension: Bore = 0.25 m; stroke = 0.25 m. If the clearance volume is 200 cm³ then the air standard efficiency of the cycle will be
(A) 57.6 (B) 47.3 (C) 51.3 (D) 54.4

Solution:

Stroke volume, $V_s = \dfrac{\pi}{4}D^2L = \dfrac{\pi}{4} \times 0.25^3$

$\Rightarrow \quad V_s = 0.01227\, m^3 = 12271.84$ cm³

Compression ratio, $r_c = 1 + \dfrac{V_s}{V_c} = 1 + \dfrac{12271.84}{2000}$

$\Rightarrow \quad r_c = 7.136$

$\Rightarrow \quad \eta = 1 - \dfrac{1}{(r)^{\gamma-1}} = 1 - \dfrac{1}{(7136)^{0.4}}$

$\Rightarrow \quad \eta = 0.5443$ or 54.43%

Example 3: A diesel engine having a cylinder with bore 0.3 m, stroke 0.4 m and a clearance volume of 2000 cm^3. If the fuel cut-off occurring at 5% of the stroke then the air standard efficiency of the cycle will be
(A) 64% (B) 51% (C) 62% (D) 58%

Solution:

Swept volume, $V_s = \frac{\pi}{4} \times D^2 L = \frac{\pi}{4} \times 30^2 \times 40$

$\Rightarrow \quad V_S = 28274.33$ cm^3

Compression ratio $r = 1 + \frac{V_s}{V_c} = 1 + \frac{28274.33}{2000}$

$\Rightarrow \qquad r = 15.14$

$$\eta = 1 - \frac{1}{(r)^{\gamma-1}} \frac{r_c^{\gamma} - 1}{\gamma(r_c - 1)}$$

$$r_c = \frac{V_3}{V_2}$$

Cut-off volume = $V_3 - V_2 = 0.05\ V_S$
$\Rightarrow \quad V_3 - V_2 = 0.05 \times 1.14\ V_c \quad \Rightarrow \quad V_3 = 0.707\ V_C + V_2$
or $\quad V_3 = 0.707\ V_C + V_C \quad \Rightarrow \quad V_3 = 1.707\ V_C$

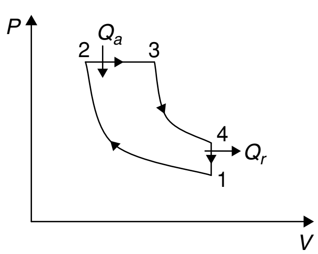
or $\frac{V_3}{V_2} = r_c = 1.707$

$$\therefore \quad \eta = 1 - \frac{1}{(15.14)^{0.4}} \left[\frac{1.707^{1.4} - 1}{1.4 \times (1.707 - 1)} \right]$$

$\Rightarrow \eta = 0.6204$ or 62.04%

Example 4: The inlet pressure and temperature of a diesel cycle are 1 bar and 22°C, respectively. The expansion ratio is given as 5. If the pressure at the end of adiabatic compression is 38 bar then the net work output of the cycle (in kJ/kg) will be
(A) 814 (B) 768 (C) 712 (D) 891

Solution:
Given:
$P_1 = 100$ kPa, $T_1 = 295$ K,
$\frac{V_4}{V_3} = \frac{V_1}{V_3} = 5$, $P_2 = 3800$ kPa



Process 1 – 2:

$$\frac{V_1}{V_2} = r = \left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}}$$

$$\Rightarrow \quad \frac{V_1}{V_2} = r = (38)^{\frac{1}{1.4}}$$

$$\Rightarrow \quad r = \frac{V_1}{V_2} = 13.44$$

Now $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \quad \Rightarrow \quad T_2 = 295 \times (35)^{\frac{0.4}{1.4}}$

$\Rightarrow \quad T_2 = 814.675$ K

Process 2 – 3 $\rightarrow$ $T_3 = T_2 \times \frac{V_3}{V_2} = 814.675 \times \frac{V_3}{V_2}$

$$r_c = \frac{V_3}{V_2} = \frac{V_3}{V_1} \times \frac{V_1}{V_2} = \frac{\frac{V_1}{V_2}}{\frac{V_4}{V_3}} \{\because \quad V_1 = V_4\}$$

$$\therefore \qquad r_c = \frac{13.44}{5} = 2.688 = \frac{V_3}{V_2}$$

$\therefore \ T_3 = 814.675 \times 2.688 = 2189.8464$ K
Process 3 – 4:

$$T_4 = T_3 \times \left(\frac{V_3}{V_4}\right)^{\gamma-1} = 2189.8464 \times \left(\frac{1}{5}\right)^{0.4}$$

$\Rightarrow \quad T_4 = 1150.34$ K
Heat added, $Q_a = C_P(T_3 - T_2) = 1.005\ (2189.8464 - 814.675)$
$\Rightarrow \quad Q_a = 1382.047$ kJ/kg
Heat rejected, $Q_r = C_v(T_4 - T_1) = 0.718(1150.34 - 295)$
$\Rightarrow \quad Q_r = 614.134$ kJ/kg
$W_{\text{net}} = Q_a - Q_r = 1382.047 - 614.134$
$\Rightarrow \quad W_{\text{net}} = 767.913$ kJ/kg

Example 5: A Diesel cycle operates at an inlet pressure of 1 bar and the volume is compressed to $\frac{1}{15}$ of the initial volume. If the heat is supplied until the volume is twice that of the clearance volume, then the mean effective pressure of the cycle (in bar) will be
(A) 6.928 (B) 5.321
(C) 6.685 (D) 5.839

Solution:
Given: $P_1 = 100$ kPa

$$V_1 = 15V_2 \quad \Rightarrow \quad r = \frac{V_1}{V_2} = 15$$

and $V_3 = 2V_2$
Swept volume = $V_1 - V_2 = (r - 1)V_2 = 14V_2$

$$V_2 = \frac{V_S}{14}$$

Process 1 – 2 → $P_2 = P_1\left(\dfrac{V_1}{V_2}\right)^{\gamma} = 1\times(15)^{1.4}$

$$= 44.312 \text{ bar}$$

$$P_2 = P_3 = 44.312 \text{ bar}$$

$$P_4 = P_3\left(\frac{V_3}{V_4}\right)^{1.4} = 44.312\times\left(\frac{2}{15}\right)^{1.4}$$

$\Rightarrow$ $P_4 = 2.64$ bar

Mean effective pressure, P_m

$$P_m = \frac{1}{V_s}\left[P_2(V_3 - V_2) + \frac{P_3V_3 - P_4V_4}{\gamma - 1} - \frac{P_2V_2 - P_1V_1}{\gamma - 1}\right]$$

$$\Rightarrow P_m = \frac{V_2}{V_S}\left[P_3\left[\frac{V_3}{V_2} - 1\right] + \frac{\left[P_3\dfrac{V_3}{V_2} - P_4\dfrac{V_4}{V_2}\right]}{\gamma - 1} - \frac{\left[P_2 - P_1\dfrac{V_1}{V_2}\right]}{\gamma - 1}\right]$$

$$\Rightarrow P_m = \frac{1}{14}\left[44.312\{2-1\} + \frac{[(44.312\times 2) - (2.64\times 15)]}{0.4} - \frac{[44.312 - 1\times 15]}{0.4}\right]$$

$\Rightarrow$ $P_m = 6.685$ bar

Example 6: Air enters the compressor of a gas turbine operating a Brayton cycle at 100 kPa, 27°C. The pressure ratio is 6. Assume compression and expansion process to be isentropic and turbine work is 2.5 times of compressor work. The maximum temperature in the cycle will be

(A) 1252 K (B) 1413 K
(C) 1113 K (D) 1973 K

Solution:

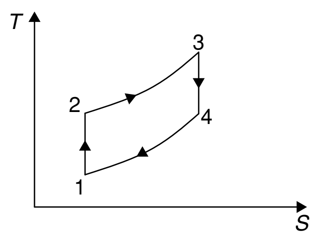
Given:

$$P_1 = 100 \text{ kPa}$$

$$T_1 = 300 \text{ K}$$

$$\frac{P_2}{P_1} = r_p = 6$$

$$W_T = 2.5\, W_c$$



Now $\eta = 1 - \dfrac{1}{(r_p)^{\frac{\gamma-1}{\gamma}}}$

$$\Rightarrow \eta = 1 - \frac{1}{(6)^{\frac{0.4}{1.4}}} = 0.4006$$

1 – 2 – Reversible adiabatic

$$\frac{T_2}{T_1} = (r_p)^{\frac{\gamma-1}{\gamma}} \Rightarrow T_2 = 300(6)^{\frac{0.4}{1.4}} = 500.5\ K$$

$\therefore$ $W_C = h_2 - h_1 = C_p(T_2 - T_1) = 1.005(500.5 - 300)$

$\Rightarrow$ $W_c = 201.5$ kJ/kg

$W_T = 2.5 \times 201.5 = 503.8$ kJ/kg

Now, $\eta = \dfrac{W_{net}}{Q_s} \Rightarrow Q_s = \dfrac{503.8 - 201.5}{0.4006}$

$\Rightarrow$ $Q_s = 754.8$ kJ/kg

$Q_s = h_3 - h_2 = C_p(T_3 - T_2) = 1.005(T_3 - 500.5)$

$\Rightarrow$ $754.8 = 1.005(T_3 - 500.5)$

$\Rightarrow$ $T_3 = 1252$ K

Example 7: A gas turbine plant operates on the Brayton cycle between temperature limit of 1100 K and 310 K. The maximum work done per kg of air (kJ/kg) and corresponding cycle efficiency (in %) will be

(A) 301.3 and 51.2
(B) 243.3 and 46.9
(C) 297.6 and 41.2
(D) 267.3 and 57.6

Solution:

$$(W_{net})_{max} = C_p[\sqrt{T_{max}} - \sqrt{T_{min}}]^2$$

$$\Rightarrow (W_{net})_{max} = 1.005[\sqrt{1100} - \sqrt{310}]^2$$

$$\Rightarrow (W_{net})_{max} = 243.3 \text{ kJ/kg}$$

$$\eta_{cycle} = 1 - \frac{1}{(r_p)^{\frac{\gamma-1}{\gamma}}} = 1 - \sqrt{\frac{T_{min}}{T_{max}}}$$

$$\Rightarrow \eta_{cycle} = 1 - \sqrt{\frac{310}{1100}} = 0.4691 \text{ or } 46.91\%$$

Example 8: In a Brayton cycle with regenerator of 80% effectiveness, the air at the inlet to the compressor is at 0.1 MPa, 27°C, the pressure ratio is 6. Consider the turbine and compressor cycle temperature is 927°C, the percentage increase in the cycle efficiency due to regeneration will be

(A) 42.56% (B) 21.23%
(C) 33.34% (D) 37.32%

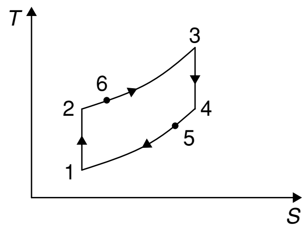
Solution:

Given:

$$\frac{T_2}{T_1} = (r_p)^{\frac{\gamma-1}{\gamma}}$$

$$\Rightarrow T_2 = 300(6)^{\frac{0.4}{1.4}}$$

$$\Rightarrow T_2 = 500.55 \text{ K and } \frac{T_3}{T_4} = (r_p)^{\frac{\gamma-1}{\gamma}}$$



$$\Rightarrow \quad T_4 = \frac{1200}{(6)^{\frac{0.4}{1.4}}} \quad \Rightarrow \quad T_4 = 719.2 \text{ K}$$

$$\eta = \frac{W_T - W_C}{Q_1} = \frac{C_P[(T_3 - T_4) - (T_2 - T_1)]}{C_P(T_3 - T_2)}$$

$$\Rightarrow \quad \eta = \frac{[(1200 - 719.2) - (500.55 - 300)]}{[1200 - 500.55]}$$

$\Rightarrow \quad \eta = 0.40067 \sim 40\%$

With regenerator:

$$\in = \frac{T_6 - T_2}{T_4 - T_2} = 0.80$$

$$T_6 - 500.55 = 0.80(719.2 - 500.55)$$

$\Rightarrow \quad T_6 = 675.47$ k

Now $Q_1 = h_3 - h_6 = C_P(T_3 - T_6)$

$$\therefore \quad \eta = \frac{[(T_3 - T_4) - (T_2 - T_1)]}{(T_3 - T_6)}$$

$$\Rightarrow \quad \eta = \frac{(1200 - 719.2) - (500.55 - 300)}{[1200 - 675.44]}$$

$\Rightarrow \quad \eta = 0.53426$ or 53.426%

$\Rightarrow$ Percentage increase due to regeneration

$$= \frac{0.53426 - 0.40067}{0.40067} = 0.3334 \textit{ or } 33.34\%$$

Example 9: A Rankine cycle operates between 80 bar and 0.1 bar. The maximum cycle temperature is 600°C. If the turbine and pump efficiency are 90% and 80%, respectively, the specific work output of the cycle (in kJ/kg) is

P(bar)	T_{sat}(°C)	v_f(m³/kg)	v_g(m³/kg)	h_f(kJ/kg)	h_g(kJ/kg)	s_f(kJ/kgK)	s_g(kJ/kgK)
0.1	45.84	0.0010103	14.68	191.9	2584.2	0.6488	8.1494
80	295.1	0.001385	0.0235	1317	2757.5	3.2073	5.7424

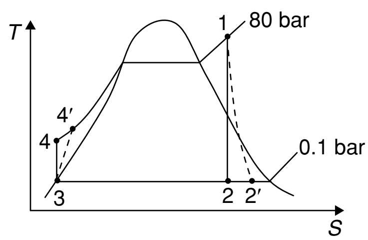
Superheated table

At $P = 80$ bar, $T = 600$°C, $h = 3642$ kJ/kg, $S = 7.0206$ kJ/kgK

(A) 1212.34 (B) 1439.64

(C) 1321.61 (D) 1264.69

Solution:



$h_1 = 3642$ kJ/kg, $S_1 = 7.0206$ kJ/kgK

$S_1 = S_2 = [x_2 S_g + (1 - x_2)S_f]_{0.1 \text{ bar}}$

$\therefore \quad 7.0206 = x_2(8.1494) + (1 - x_2) \times 0.6488$

$\Rightarrow \quad x_2 = 0.85$

$\therefore \quad h_2 = h_g + (1 - x_2)\, h_f = (0.85 \times 2584.2) + (1 - 0.85) \times 191.9$

$\Rightarrow \quad h_2 = 2225.35$ kJ/kg

$$\eta_T = 0.9 = \frac{h_1 - h_2'}{h_1 - h_2} = \frac{3642 - h_2'}{3642 - 2225.35}$$

$\Rightarrow \quad h_2' = 2367.015$ kJ/kg

$\therefore \quad W_T = \text{h}_1 - h_2' = 3642 - 2367.015 = 1274.985$ kJ/kg

Now $h_3 = h_f = 191.9$ kJ/kg

$$\eta_p = \frac{h_3 - h_4}{h_3 - h_4^1} = \frac{191.9 - h_4}{191.9 - h_4^1} = 0.8$$

Now $h_4 - h_3 = v_{f3}\,(P_4 - P_3) = 0.0010103(8000 - 10)$

$$\therefore \quad \eta_P = 0.8 = \frac{191.9 - 200.132}{191.9 - h_4^1}$$

$\Rightarrow \quad h_4' = 202.19$ kJ/kg

$W_P = h_3 - h_4' = 191.9 - 202.19 = -10.29$ kJ/kg

Specific work output = (1274.985 – 10.29)
= 1264.69 kJ/kg

Exercises

Practice Problems I

1. An engine working on air standard Otto cycle has a cylinder diameter of 12 cm and stroke length of 16 cm. The ratio of specific heats for air is 1.4. If the clearance volume is 300 CC and the heat supplied per kg of air per cycle is 2000 kJ/kg, the work output per cycle per kg of air is

(A) 879.1 kJ/kg (B) 973.31 kJ/kg
(C) 1500 kJ/kg (D) 1803.30 kJ/kg

2. For an engine operating on air standard Otto cycle, the clearance volume is 10% of the swept volume. The specific heat ratio of air is 1.4. The air-standard cycle efficiency is

(A) 38.3% (B) 39.8%
(C) 60.2% (D) 61.7%

3. An ideal air standard Otto cycle has a compression ratio of 8.5, the ratio of the specific heats of air (γ) is 1.4, the thermal efficiency (in %) of the Otto cycle is

(A) 57.5 (B) 60.2
(C) 43.4 (D) 45.7

4. Match List-I (heat engines) with List-II (cycles) and select the correct Answer using the codes given below:

	List-I (Heat engines)		List-II (Cycles)
(a)	Petrol engine	1.	Constant pressure heat addition and constant volume heat rejection
(b)	Gas turbine	2.	Constant volume heat addition and constant volume heat rejection
(c)	Stirling engine	3.	Constant pressure heat addition and constant pressure heat rejection
(d)	Diesel engine	4.	Heat addition at constant volume followed by heat addition at constant temperature. Heat rejection at constant volume followed by heat rejection at constant temperature.

Codes:	*a*	*b*	*c*	*d*
(A)	3	1	4	2
(B)	2	3	4	1
(C)	3	1	2	4
(D)	1	3	2	4

5. Air (C_p = 1 kJ/kg, γ = 1.4) enters a compressor at a temperature of 27°C. The compressor pressure ratio is 4. Assuming an efficiency of 80%, the compressor work required in kJ/kg is

(A) 200 (B) 182
(C) 152 (D) 145

6. An air-standard diesel cycle has a compression ratio is 16. The pressure at the beginning of the compression stroke is 1 bar and the temperature is 27°C. The maximum temperature is 1427°C. The thermal efficiency of the cycle is

(A) 58.4% (B) 59.4%
(C) 62% (D) 62.5%

Direction for questions 7 and 8: A gas turbine plant operates on the Brayton cycle between T_{min} = 303 K and T_{max} = 1073 K then

7. The maximum work done per kg of air is

(A) 400 kJ/kg (B) 325.5 kJ/kg
(C) 236.79 kJ/kg (D) 200.12 kJ/kg

8. The corresponding cycle efficiency is

(A) 45% (B) 46.8%
(C) 65% (D) 72.1%

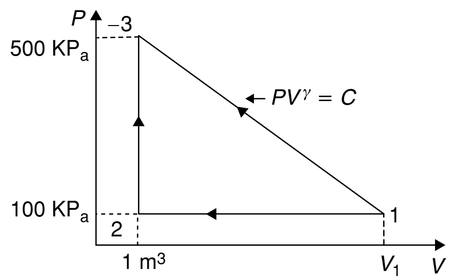
9. In a gas turbine, hot combustion products with the specific heats C_p = 0.98 kJ/kgK and Cv = 0.75 38 kJ/kgK enters the turbine at 20 bar, 1500 K exit at 1 bar. The isentropic efficiency of the turbine is 0.94. The work developed by the turbine per kg of gas flow is

(A) 689.64 kJ/kg (B) 794.66 kJ/kg
(C) 1312.00 kJ/kg (D) 1450 kJ/kg

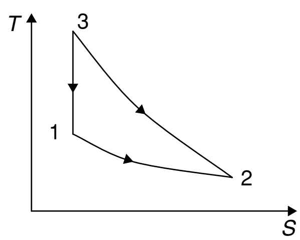
10. In a diesel cycle the compression ratio is 16 and cut-off occurs at 1/15th of stroke. The expansion ratio is

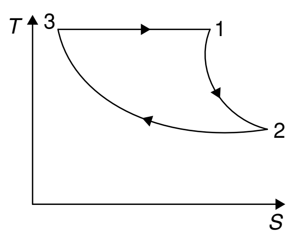
(A) 10 (B) 8
(C) 6 (D) 2

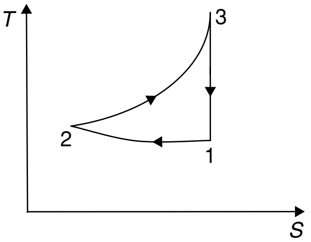
Direction for questions 11 and 12: A Thermo-dynamic cycle with an ideal gas as working fluid is shown below.

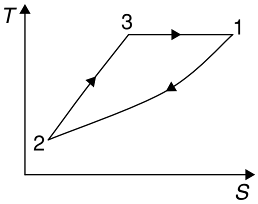


11. The above cycle is represented on *T*–*S* plane by

(A)


(B)


(C) 

(D) 

12. If the specific heats of the working fluid are constant and the value of specific heat ratio is 1.4, the thermal efficiency (%) of the cycle is
(A) 21 (B) 24.5
(C) 42.6 (D) 59.7

Direction for questions 13 and 14: An isentropic air turbine is used to supply 0.2 kg/s of air at 0.1 MN/m^2 and at 285 K to a chamber. The pressure at inlet to the turbine is 0.4 MN/m^2

13. The temperature at inlet to turbine in K is
(A) 423.5 (B) 350
(C) 345 (D) 325.5

14. The power developed by the turbine in kW; is (assume C_p = 1.0 kJ/kg)
(A) 10 (B) 15.8
(C) 19.8 (D) 27.7

Direction for questions 15 and 16: The German Mercedes 1900 car has 4-stroke cylinder in line diesel engine with compression ratio 20:1 and expansion ratio 10:1. Then

15. Cut-off ratio is
(A) 2 (B) 4
(C) 10 (D) 20

16. Air-standard efficiency is
(A) 64.7% (B) 58.4%
(C) 55.4% (D) 48.2%

17. The equivalent evaporation (kg/hr) of a boiler producing 2000 kg/hr of steam with enthalpy content of 2426 kJ/kg from feed water at temperature 40°C (liquid enthalpy = 168 kJ/kg) is (enthalpy of vaporization of water at 100°C = 2258 kJ/kg)
(A) 186 (B) 1649
(C) 2000 (D) 2149

18. A steam power plant has the boiler efficiency of 93% turbine efficiency (mechanical) of 95% generator efficiency of 94% and cycle efficiency of 43%. If 5% of the generated power is used to run the auxiliaries, the overall plant efficiency is
(A) 34% (B) 39%
(C) 45% (D) 50%

Direction for questions 19 and 20: In a steam power plant operating on the Rankine cycle, steam enters the turbine at 4MP$_a$, 350°C and exits at a pressure of 15 KPa. Then it enters the condenser and exits as saturated water. Next, a pump feeds back the water to the boiler. The adiabatic efficiency of the turbine is 90%. The thermodynamic states of water and steam are given in the table.

State	*h*(kJ/kg)		*S*(kJ/kg)		*V*(m^3/kg)	
Steam 4Mpa, 350°C	3092.5		6.5821		0.06645	
	h_f	h_g	S_f	S_g	V_f	V_g
Water 15 kpa	225.94	2599.1	0.7549	8.0085	0.001014	10.02

h is specific enthalpy, *S* is specific entropy and *v* is specific volume; subscripts *f* and *g* denote saturated liquid state and saturated vapour state.

19. The net work output (kJ kg^{-1}) of the cycle is
(A) 498 (B) 775
(C) 860 (D) 957

20. Heat supplied (kJ kg^{-1}) of the cycle is
(A) 2372
(B) 2576
(C) 2863
(D) 3092

Practice Problems 2

1. A perfect heat engine works on Carnot cycle between 927° C and 227°C. If this engine receives heat at the higher temperature at the rate of 4200 kJ/min, then the power developed by the engine in kW is
(A) 43.96 (B) 40.83
(C) 30.5 (D) 25.8

2. If the compression ratio of Otto cycle is increased from 6 to 8, then the percentage of increase in efficiency is
(A) 6% (B) 8%
(C) 10% (D) 14%

3. The efficiency of an Otto cycle is 48.5% and γ is 1.4 then the compression ratio is
(A) 4 (B) 6
(C) 8 (D) 10

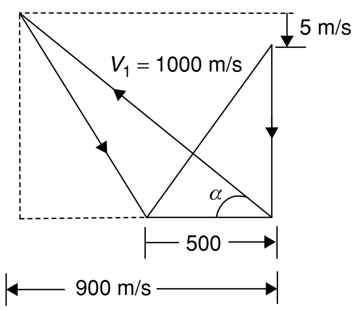
4. The upper and lower temperature limits for an Otto cycle are 1600 K and 400 K, then the maximum theoretical power (in kW) developed by the engine when the rate of flow of air through the cycle is 0.33 kg/min is
(A) 95 (B) 110
(C) 150 (D) 250

5. The loss in the ideal efficiency of a diesel engine with compression ratio 14 if the fuel cut-off is delayed from 6% to 9% is
(A) 6% (B) 9%
(C) 4% (D) 2%

6. Stirling cycle and a Carnot cycle operate between 50° and 350°C. Their efficiencies are η_s and η_c, respectively. In this case, which of the following states is true?
(A) $\eta_s > \eta_c$
(B) $\eta_s = \eta_c$
(C) $\eta_s < \eta_c$
(D) The sign of $(\eta_s - \eta_c)$ depends on the working fluids used

7. The adiabatic enthalpy drop across the prime mover of the Rankine cycle is 850 kJ/kg. The enthalpy of steam supplied is 3000 kJ/kg. If the back pressure is 0.2 bar the specific steam consumption in kg/kwh is
(A) 10.25 (B) 8.45
(C) 6.235 (D) 4.235

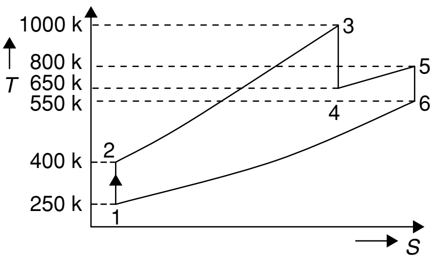
8. Velocity diagram shown below is for an impulse turbine state. The tangential force and axial thrust per kg/s of steam respectively are



(A) 950 N, 5 N (B) 1000 N, 500 N
(C) 950 N, 500 N (D) 1000 N, 5 N

9. The following data pertains to a single stage impulse steam turbine;
Nozzle angle = 20°
Blade velocity = 200 m/s
Relative steam velocity at entry = 350 m/s
Blade inlet = 30°, Blade exit angle = 25°
If blade friction is neglected, the work done per kg steam is
(A) 150 kJ (B) 140 kJ
(C) 124 kJ (D) 100 kJ

10. The given figure shows an open cycle gas turbine employing reheating, on T–S plane. Assuming that the specific heats are same for both air and gas, and neglecting the increasing in mass flow due to addition of fuel the efficiency is



(A) 50% (B) 60%
(C) 70% (D) 80%

11. A single-stage impulse turbine with a diameter of 100 cm runs at 2500 rpm. If the blade speed ratio is 0.4, then the inlet velocity of steam will be
(A) 400 m/s (B) 327 m/s
(C) 250 m/s (D) 127 m/s

Direction for questions 12 and 13: An ideal, air-standard regenerative Brayton cycle is working between minimum and maximum temperature of 27°C and 927°C, respectively.

12. The value of critical pressure ratio where the degree of regeneration become zero, will be
(A) 11.3 (B) 12.5
(C) 10 (D) 8

13. Efficiency of the cycle when the operating pressure ratio in 65% of the critical pressure ratio, will be
(A) 25.2% (B) 35%
(C) 40% (D) 43.44%

Direction for questions 14 and 15: A Gas turbine operating on Brayton cycle between the lower and upper temperature limit of 37°C and 1027°C. The inlet and outlet pressure after compression are 1 bar and 6 bar, respectively.

14. The maximum work done per kg of air is
(A) 542 (B) 442
(C) 342 (D) 242

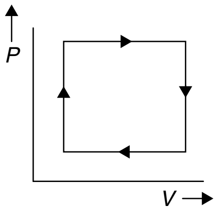
15. The ratio of efficiency of Carnot cycle to Brayton cycle is
(A) 2 (B) 1.98
(C) 1.54 (D) 1.49

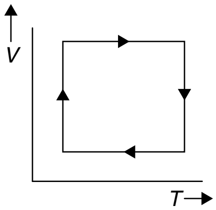
16. The compression ratio of a gas power plant cycle corresponding to maximum work output for the given temperature limits of $T_{\min}$ and $T_{\max}$

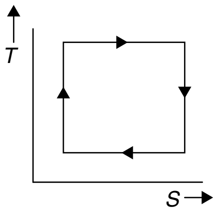
(A) $\left(\dfrac{T_{\max}}{T_{\min}}\right)^{\frac{r}{2(r-1)}}$ (B) $\left(\dfrac{T_{\min}}{T_{\max}}\right)^{\frac{r}{2(r-1)}}$

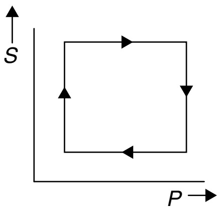
(C) $\left(\dfrac{T_{\max}}{T_{\min}}\right)^{\frac{r-1}{r}}$ (D) $\left(\dfrac{T_{\min}}{T_{\max}}\right)^{\frac{r-1}{r}}$

17. Which of the following represents the Carnot cycle (ideal engine)?

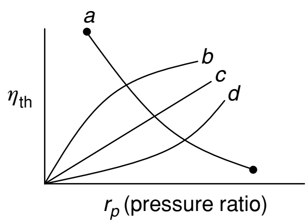
(A)


(B)


(C)


(D)


18. The given figure shows four plots *A*, *B*, *C* and *D* of thermal efficiency against pressure ratio.



The curve which represents that of a gas turbine plant using Brayton (without regeneration) is the one labelled

(A) *a* (B) *b*
(C) *c* (D) *d*

19. If T_{max} and T_{min} be the maximum and minimum temperatures in an Otto cycle, then for the ideal conditions, the temperature after compression should be

(A) $\dfrac{T_{max} + T_{min}}{2}$ (B) $\sqrt{\dfrac{T_{max}}{T_{min}}}$
(C) $\sqrt{T_{max} \times T_{min}}$ (D) None of these

20. Thermal power plant works on
(A) Rankine cycle (B) Brayton cycle
(C) Carnot cycle (D) Otto cycle

21. The efficiency of Carnot engine depends on
(A) working substance
(B) design of engine
(C) size of engine
(D) temperature of source and sink

22. The pressure ratio in case of Bell-Coleman cycle is of the order of
(A) 5 – 6 (B) 7 – 9
(C) 10 – 15 (D) 15 – 22

23. Air refrigerators work on
(A) Reversed Carnot cycle
(B) Reversed Joule cycle
(C) Otto cycle
(D) Diesel cycle

24. A Bell-Coleman cycle is a reversed
(A) Carnot cycle (B) Otto cycle
(C) Joule cycle (D) Stirling cycle

25. Diesel cycle efficiency is maximum when the cut-off is
(A) Zero (B) Increased
(C) Decreased (D) Maximum

26. Ericsson cycle consists of the following four processes
(A) two isothermals and two isentropics
(B) two isothermals and two constant volumes
(C) two isothermals and two constant pressures
(D) two adiabatics and two constant pressures

27. Gas turbine works on
(A) constant pressure cycle
(B) constant volume cycle
(C) constant temperature cycle
(D) constant enthalpy cycle

28. Most of high speed compression engines operate on
(A) diesel cycle
(B) Otto cycle
(C) dual combustion cycle
(D) special type of air cycle

29. The accumulation of carbon in a cylinder results in increase of
(A) effective compression ratio
(B) clearance volume
(C) volumetric efficiency
(D) ignition time

30. A perfect engine works on the Carnot cycle between 72.7°C and 227°C. The efficiency of the engine is
(A) 0.5 (B) 2
(C) $\dfrac{227}{727}$ (D) $\dfrac{500}{727}$

31. Efficiency of Stirling cycle is same as
(A) Otto cycle (B) Diesel cycle
(C) Carnot cycle (D) Ericsson cycle

32. Mean effective pressure of Otto cycle is
(A) inversely proportional to pressure ratio.
(B) directly proportional to pressure ratio.
(C) does not depend on pressure ratio.
(D) proportional to square root of pressure ratio.

33. For the same compression ratio and heat addition
(A) $\eta_{Otto} > \eta_{Diesel} > \eta_{Dual}$ (B) $\eta_{Diesel} > \eta_{Otto} > \eta_{Dual}$
(C) $\eta_{Dual} > \eta_{Diesel} > \eta_{Otto}$ (D) $\eta_{Otto} > \eta_{Dual} > \eta_{Diesel}$

34. For the same peak pressure and heat input
(A) $\eta_{Diesel} > \eta_{Dual} > \eta_{Otto}$
(B) $\eta_{Otto} > \eta_{Dual} > \eta_{Diesel}$
(C) $\eta_{Dual} > \eta_{Diesel} > \eta_{Otto}$
(D) $\eta_{Diesel} > \eta_{Otto} > \eta_{Dual}$

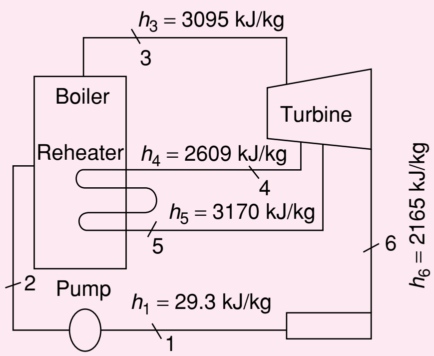
35. Lenoir cycle is used in
(A) SI engine (B) CI engine
(C) Pulse jet engine (D) Gas turbine

Previous Years' Questions

1. An engine working on air standard Otto cycle has a cylinder diameter of 10 cm and stroke length of 15 cm. The ratio of specific heats for air is 1.4. If the clearance volume is 196.3 cc and the heat supplied per kg of air per cycle is 1800 kJ/kg, the work output per cycle per kg of air is **[2004]**
(A) 879.1 kJ (B) 890.2 kJ
(C) 895.3 kJ (D) 973.5 kJ

Direction for questions 2 and 3: Solve the problem and choose the correct answer.

Consider a steam power plant using a reheat cycle as shown. Steam leaves the boiler and enters the turbine at 4 MPa, 350°C (h_3 = 3095 kJ/kg). After expansion in the turbine to 400 kPa (h_4 = 2609 kJ/kg), the steam is reheated to 350°C (h_5=3170 kJ/kg) and then expanded in a low pressure turbine to 10 kPa (h_6 = 2165 kJ/kg) the specific volume of liquid handled by the pump can be assumed to be



2. The thermal efficiency of the plant neglecting pump work is **[2004]**
(A) 15.8%
(B) 41.1%
(C) 48.5%
(D) 58.6%

3. The enthalpy at the pump discharge (h_2) is **[2004]**
(A) 0.33 kJ/kg
(B) 3.33 kJ/kg
(C) 4.0 kJ/kg
(D) 33.3 kJ/kg

4. The compression ratio of a gas power plant cycle corresponding to maximum work output for the given temperature limits of T_{min} and T_{max} will be **[2004]**

(A) $\left(\frac{T_{max}}{T_{min}}\right)^{\frac{\gamma}{2(\gamma-1)}}$ (B) $\left(\frac{T_{min}}{T_{max}}\right)^{\frac{\gamma}{2(\gamma-1)}}$

(C) $\left(\frac{T_{max}}{T_{min}}\right)^{\frac{\gamma-1}{\gamma}}$ (D) $\left(\frac{T_{min}}{T_{max}}\right)^{\frac{\gamma-1}{\gamma}}$

Direction for questions 5 and 6: In two air-standard cycles—one operating on Otto and the other on Brayton cycle-air is isentropically compressed from 300 to 450 K. Heat is added to raise the temperature to 600 K in Otto cycle and to 550 K in Brayton cycle.

5. If η_0 and is η_B are the efficiencies of Otto and Brayton cycles, then **[2005]**
(A) $\eta_0 = 0.25$, $\eta_B = 0.18$
(B) $\eta_0 = \eta_B = 0.33$
(C) $\eta_0 = 0.5$, $\eta_B = 0.45$
(D) It is not possible to calculate the efficiencies unless the temperature after the expansion is given.

6. If W_0 and W_B are work outputs per unit mass, then **[2005]**
(A) $W_0 > W_B$
(B) $W_0 < W_B$
(C) $W_0 = W_B$
(D) It is not possible to calculate the work outputs unless the temperature after the expansion is given.

7. Determine the correctness or otherwise of the following Assertion (a) and the Reason (r)
Assertion (a): In a power plant working on a Rankine cycle, the regenerative feed water heating improves the efficiency of the steam turbine.
Reason (r): The regenerative feed water heating raises the average temperature of heat addition in the Rankine cycle. **[2006]**
(A) Both (a) and (r) are true and r is the correct reason for (a)
(B) Both (a) and (r) are true but (r) is NOT the correct reason for (a)
(C) Both (a) and (r) are false
(D) (a) is false (r) is true

8. Determine the correctness or otherwise of the following Assertion (a) and the Reason (r).
Assertion (a): Condenser is an essential equipment in a steam power plant.
Reason (r): For the same mass flow rate and the same pressure rise, a water pump requires substantially less power than a steam compressor. **[2006]**
(A) Both (a) and (r) are true and r is the correct reason for (a)
(B) Both (a) and (r) are true but (r) is NOT the correct reason for (a)
(C) Both (a) and (r) are false
(D) (a) is false and (r) is true

9. Group I shows different heat addition processes in power cycles. Likewise, Group II shows different heat removal processes. Group III lists power cycles. Match items from groups I, II and III. **[2006]**

Group I		Group II		Group III	
(P)	Pressure constant	(S)	Pressure constant	(1)	Rankine cycle
(Q)	Volume constant	(T)	Volume constant	(2)	Otto cycle
(R)	Temperature constant	(U)	Temperature constant	(3)	Carnot cycle
				(4)	Diesel cycle
				(5)	Brayton cycle

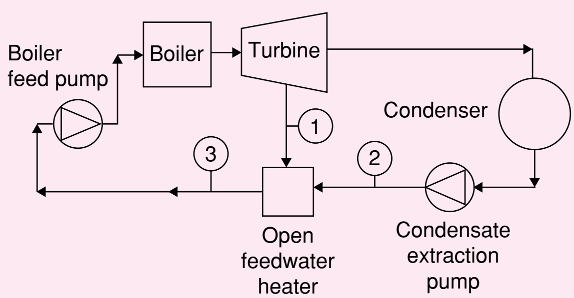
(A) P – S – 5, R – U – 3, P – S – 1, Q – T – 2
(B) P – S – 1, R – U – 3, P – S – 4, P – T – 2
(C) R – T – 3, P – S – 1, P – T – 4, Q – S – 5
(D) P – T – 4, R – S – 3, P – S – 1, P – S – 5

10. The stroke and bore of a 4-stroke spark ignition engine are 250 mm and 200 mm, respectively. The clearance volume is 0.001 m^3. If the specific heat ratio $\gamma = 1.4$, the air-standard cycle efficiency of the engine is **[2007]**
(A) 46.40% (B) 56.10%
(C) 58.20% (D) 62.80%

11. Which combination of the following statements is correct?
The incorporation of reheater in a steam power plant:
P: always increases the thermal efficiency of the plant
Q: always increases the dryness fraction of steam at condenser inlet
R: always increases the mean temperature of heat addition
S: always increases the specific work output **[2007]**
(A) P and S (B) Q and S
(C) P, R and S (D) P, Q, R and S

12. Which one of the following is NOT a necessary assumption for the air-standard Otto cycle? **[2008]**
(A) All processes are both internally as well as externally reversible.
(B) Intake and exhaust processes are constant volume heat rejection processes.
(C) The combustion process is a constant volume heat addition process.
(D) The working fluid is an ideal gas with constant specific heats.

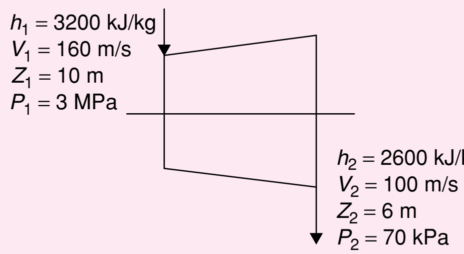
13. A thermal power plant operates on a regenerative cycle with a single open feedwater heater, as shown in the figure. For the state points shown, the specific enthalpies are: h_1 = 2800 kJ/kg and h_2 = 200 kJ/kg. The bleed to the feed water heater is 20% of the boiler steam generation rate. The specific enthalpy at state 3 is **[2008]**



(A) 720 kJ/kg (B) 2280 kJ/kg
(C) 1500 kJ/kg (D) 3000 kJ/kg

14. In an air-standard Otto cycle, the compression ratio is 10. The condition at the beginning of the compression process is 100 kPa and 27°C. Heat added at constant volume is 1500 kJ/kg, while 700 kJ/kg of heat is rejected during the other constant volume process in the cycle. Specific gas constant for air = 0.287 kJ/kgK. The mean effective pressure (in kPa) of the cycle is **[2009]**
(A) 103 (B) 310
(C) 515 (D) 1032

Direction for questions 15 and 16: The inlet and the outlet conditions of steam for an adiabatic steam turbine are as indicated. The notations are as usually followed:



15. If mass flow rate of steam through the turbine is 20 kg/s, the power output of the turbine (in MW) is **[2009]**
(A) 12.157 (B) 12.941
(C) 168.001 (D) 168.785

16. Assume the above turbine to be part of a simple Rankine cycle. The density of water at the inlet to the pump is 1000 kg/m^3. Ignoring kinetic and potential energy effects, the specific work (in kJ/kg) supplied to the pump is **[2009]**
(A) 0.293 (B) 0.351
(C) 2.930 (D) 3.510

17. A turbo-charged 4-stroke direct injection diesel engine has a displacement volume of 0.0259 m^3 (25.9 L). The engine has an output of 950 kW at 2200 rpm. The mean effective pressure in MPa is closest to **[2010]**
(A) 2 (B) 1
(C) 0.2 (D) 0.1

Direction for questions 18 and 19: In a steam power plant operating on the Rankine cycle, steam enters the turbine at 4 MPa, 350°C and exits at a pressure of 15 kPa. Then it enters the condenser and exits as saturated water. Next, a pump feeds back the water to the boiler. The adiabatic efficiency of the turbine is 90%. The thermodynamic states of water and steam are given in the table.

State	h(kJ kg^{-1})		s(kJ kg^{-1}K^{-1})		v(m^{3}kg^{-1})	
Steam: 4 MPa, 350°C	3092.5		6.5821		0.06645	
Water: 15 kPa	h_f	h_g	s_f	s_g	v_f	v_g
	225.94	2599.1	0.7549	8.0085	0.001014	10.02

h is specific enthalpy, s is specific entropy and v the specific volume; subscripts f and g denote saturated liquid state and saturated vapour state.

18. The net work output (kJ kg^{-1}) of the cycle is **[2010]**
(A) 498 (B) 775
(C) 860 (D) 957

19. Heat supplied (kJ kg^{-1}) to the cycle is **[2010]**
(A) 2372 (B) 2576
(C) 2863 (D) 3092

20. The values of enthalpy of steam at the inlet and outlet of a steam turbine in a Rankine cycle are 2800 kJ/kg and 1800 kJ/kg respectively. Neglecting pump work the specific steam consumption in kg/kW-hour is **[2011]**
(A) 3.60 (B) 0.36
(C) 0.06 (D) 0.01

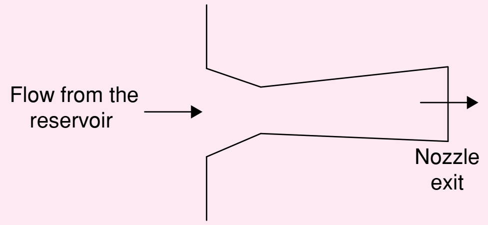
21. The crank radius of a single-cylinder I.C engine is 60 mm and the diameter of the cylinder is 80 mm. The swept volume of the cylinder in cm^3 is **[2011]**
(A) 48 (B) 96
(C) 302 (D) 603

22. A pump handling a liquid raises its pressure from 1 bar to 30 bar. Take the density of the liquid as 990 kg/m^3. The isentropic specific work done by the pump in kJ/kg is **[2011]**
(A) 0.10 (B) 0.30
(C) 2.50 (D) 2.93

23. An ideal Brayton cycle, operating between the pressure limits of 1 bar and 6 bar, has minimum and maximum temperatures of 300 K and 1500 K. The ratio of specific heats of the working fluid is 1.4. The approximate final temperatures in Kelvin at the end of the compression and expansion processes are respectively. **[2011]**
(A) 500 and 900 (B) 900 and 500
(C) 500 and 500 (D) 900 and 900

Direction for questions 24 and 25: The temperature and pressure of air in a large reservoir are 400 K and 3 bar respectively.

A converging-diverging nozzle of exit area 0.005 m^2 is fitted to the wall of the reservoir as shown in the figure. The static pressure of air at the exit section for isentropic flow through the nozzle is 50 kPa. The characteristic gas constant and the ratio of specific heats of air are 0.287 kJ/kgK and 1.4, respectively.



24. The density of air in kg/m^3 at the nozzle exit is **[2011]**
(A) 0.560 (B) 0.600
(C) 0.727 (D) 0.800

25. The mass flow rate of air through the nozzle in kg/s is **[2011]**
(A) 1.30 (B) 1.77
(C) 1.85 (D) 2.06

26. Steam enters an adiabatic turbine operating at steady state with an enthalpy of 3251.0 kJ/kg and leaves as a saturated mixture at 15 kPa with quality (dryness fraction) 0.9. The enthalpies of the saturated liquid and vapor at 15 kPa are h_f = 225.94 kJ/kg and h_g = 2598.3 kJ/kg respectively. The mass flow rate of steam is 10 kg/s. Kinetic and potential energy changes are negligible. The power of the turbine in MW is **[2012]**
(A) 6.5 (B) 8.9
(C) 9.1 (D) 27.0

27. Specific enthalpy and velocity of steam at inlet and exit of a steam turbine, running under steady state, are as given below:

	Specific enthalpy (kJ/kg)	Velocity (m/s)
Inlet steam condition	3250	180
Exit steam condition	2360	5

The rate of heat loss from the turbine per kg of steam flow rate is 5 kW. Neglecting changes in potential energy of steam, the power developed in kW by the steam turbine per kg of steam flow rate, is **[2013]**
(A) 901.2 (B) 911.2
(C) 17072.5 (D) 17082.5

Direction for questions 28 and 29: In a simple Brayton cycle, the pressure ratio is 8 and temperatures at the entrance of compressor and turbine are 300 K and 1400 K, respectively. Both compressor and gas turbine have isentropic efficiencies equal to 0.8. For the gas, assume a constant value of C_p (specific heat at constant pressure) equal to 1 kJ/kgK and ratio of specific heats as 1.4. Neglect changes in kinetic and potential energies.

28. The power required by the compressor in kW/kg of gas flow rate is **[2013]**
(A) 194.7 (B) 243.4
(C) 304.3 (D) 378.5

29. The thermal efficiency of the cycle in percentage (%) is **[2013]**
(A) 24.8 (B) 38.6
(C) 44.8 (D) 53.1

30. In a power plant, water (density = 1000 kg/m^3) is pumped from 80 kPa to 3 MPa. The pump has an isentropic efficiency of 0.85. Assuming that the temperature of the water remains the same, the specific work (in kJ/kg) supplied to the pump is **[2014]**
(A) 0.34 (B) 2.48
(C) 2.92 (D) 3.43

31. In an air-standard Otto cycle, air is supplied at 0.1 MPa and 308 K. The ratio of the specific heats (γ) and the specific gas constant (R) of air are 1.4 and 288.8 J/kg.k, respectively. If the compression ratio is 8 and the maximum temperature in the cycle is 2660 K, the heat (in kJ/kg) supplied to the engine is ____. **[2014]**

32. An ideal reheat Rankine cycle operates between the pressure limits of 10 kPa and 8 MPa, with reheat being done at 4 MPa. The temperature of steam at the inlets of both turbines is 500°C and the enthalpy of steam is 3185 kJ/kg at the exit of the high pressure turbine and 2247 kJ/kg at the exit of low pressure turbine. The enthalpy of water at the exit from the pump is 191 kJ/kg. Use the following table for relevant data.

Superheated steam temperature (°C)	Pressure (MPa)	*v* (m^3/kg	*h* (kJ/kg)	*s* (kJ/kgK)
500	4	0.08644	3446	7.0922
500	8	0.04177	3399	6.7266

Disregarding the pump work, the cycle efficiency (in percentage) is ____ **[2014]**

33. The thermal efficiency of an air-standard Brayton cycle in terms of pressure ratio r_p and γ (= c_p/c_v) is given by **[2014]**

(A) $1-\dfrac{1}{r_p^{\gamma-1}}$ (B) $1-\dfrac{1}{r_p^{\gamma}}$

(C) $1-\dfrac{1}{r_p^{\frac{1}{\gamma}}}$ (D) $1-\dfrac{1}{r_p^{\frac{(\gamma-1)}{\gamma}}}$

34. In an ideal Brayton cycle, atmospheric air (ratio of specific heats, c_p/c_v = 1.4, specific heat at constant pressure = 1.005 kJ /kg.K) at 1 bar and 300 K is compressed to 8 bar. The maximum temperature in the cycle is limited to 1280 K. If the heat is supplied at the rate of 80 MW, the mass flow rate (in kg/s) of air required in the cycle is ____. **[2014]**

35. For a gas turbine power plant, identify the correct pair of statements.
P. Similar in size compared to steam power plant for same power output
Q. Starts quickly compared to steam power plant
R. Works on the principle of Rankine cycle
S. Good compatibility with solid fuel **[2014]**
(A) P, Q (B) R, S
(C) Q, R (D) P, S

36. A diesel engine has a compression ratio of 17 and cut-off takes place at 10% of the stroke. Assuming ratio of specific heats (γ) as 1.4, the air-standard efficiency (in percent) is ____. **[2014]**

37. Steam with specific enthalpy (h) 3214 kJ/kg enters an adiabatic turbine operating at steady state with a flow rate 10 kg/s. As it expands, at a point where *h* is 2920 kJ/kg, 1.5 kg/s is extracted for heating purposes. The remaining 8.5 kg/s further expands to the turbine exit, where *h* = 2374 kJ/kg. Neglecting changes in kinetic and potential energies, the net power output (in kW) of the turbine is ______. **[2014]**

38. In a compression ignition engine, the inlet air pressure is 1 bar and the pressure at the end of isentropic compression is 32.42 bar. The expansion ratio is 8. Assuming ratio of specific heats (γ) as 1.4, air standard efficiency (in percent) is ____. **[2014]**

39. Air enters a diesel engine with a density of 1.0 kg/m^3. The compression ratio is 21. At steady state, the air intake is 30 × 10^{-3} kg/s and the network output is 15 kW. The mean effective pressure (in kPa) is ______. **[2015]**

40. Steam enters a well insulated turbine and expands isentropically throughout. At an intermediate pressure, 20 percent of the mass is extracted for process heating and the remaining steam expands isentropically to 9 kPa.

Inlet to turbine: P = 14 MPa, T = 560ºC, h = 3486 kJ/kg, s = 6.6 kJ/(kg.K)

Intermediate stage: h = 2776 kJ/kg

Exit of turbine: P = 9 kPa, h_f = 174 kJ/kg, h_g = 2574 kJ/kg, s_f = 0.6 kJ/(kg.K), s_g = 8.1 kJ/(kg.K)

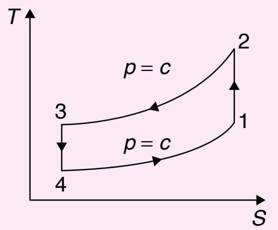
If the flow rate of steam entering the turbine is 100 kg/s, then the work output (in MW) is _________. **[2015]**

41. Which of the following statements regarding a Rankine cycle with reheating are TRUE? **[2015]**
(i) increase in average temperature of heat addition.
(ii) reduction in thermal efficiency
(iii) drier steam at the turbine exit
(A) only (i) and (ii) are correct
(B) only (ii) and (iii) are correct
(C) only (i) and (iii) are correct
(D) (i), (ii) and (iii) are correct

42. For the same values of peak pressure, peak temperature and heat rejection, the correct order of efficiencies for Otto, Dual and Diesel cycles is: **[2015]**
(A) $\eta_{Otto} > \eta_{Dual} > \eta_{Diesel}$
(B) $\eta_{Diesel} > \eta_{Dual} > \eta_{Otto}$
(C) $\eta_{Dual} > \eta_{Diesel} > \eta_{Otto}$
(D) $\eta_{Diesel} > \eta_{Otto} > \eta_{Dual}$

43. In a Rankine cycle, the enthalpies at turbine entry and outlet are 3159 kJ/kg and 2187 kJ/kg respectively. If the specific pump work is 2 kJ/kg, the specific steam consumption (in kg/kW-h) of the cycle based on net output is _______. **[2015]**

44. The thermodynamic cycle shown in figure (T-s diagram) indicates: **[2015]**



(A) reversed Carnot cycle
(B) reversed Brayton cycle
(C) vapor compression cycle
(D) vapor absorption cycle

45. An air-standard Diesel cycle consists of the following processes.
1 – 2: Air is compressed isentropically.
2 – 3: Heat is added at constant pressure.
3 – 4: Air expands isentropically to the original volume.
4 – 1: Heat is rejected at constant volume

If γ and T denote the specific heat ratio and temperature, respectively, the efficiency of the cycle is **[2015]**

(A) $1-\frac{T_4\ T_1}{T_3\ T_2}$ (B) $1-\frac{T_4-T_1}{\gamma(T_3-T_2)}$

(C) $1-\frac{\gamma(T_4-T_1)}{T_3-T_2}$ (D) $1-\frac{T_4-T_1}{(\gamma-1)(T_3-T_2)}$

46. The INCORRECT statement about regeneration in vapour power cycle is that **[2016]**
(A) it increases the irreversibility by adding the liquid with higher energy content to the steam generator
(B) heat is exchanged between the expanding fluid in the turbine and the compressed fluid before heat addition
(C) the principle is similar to the principle of Stirling gas cycle
(D) it is practically implemented by providing feed water heaters

47. In a steam power plant operating on an ideal Rankine cycle, superheated steam enters the turbine at 3 MPa and 350°C. The condenser pressure is 75 kPa. The thermal efficiency of the cycle is _______ percent. **[2016]**

Given data:

For saturated liquid, at

$P = 75$ kPa,
$h_f = 384.39$ kJ/kg,
$v_f = 0.001037$ m^3/kg,
$s_f = 1.213$ kJ/kg-K

At 75 kPa,

$h_{fg} = 2278.6$ kJ/kg,
$s_{fg} = 6.2434$ kJ/kg-K

At $P = 3$ MPa and $T = 350°$C (superheated steam),

$h = 3115.3$ kJ/kg,
$s = 6.7428$ kJ/kg-K

48. Consider a simple gas turbine (Brayton) cycle and a gas turbine cycle with perfect regeneration. In both the cycles, the pressure ratio is 6 and the ratio of the specific heats of the working medium is 1.4. The ratio of minimum to maximum temperatures is 0.3 (with temperatures expressed in K) in the regenerative cycle. The ratio of the thermal efficiency of the simple cycle to that of the regenerative cycle is ______. **[2016]**

49. A refrigerator uses R-134a as its refrigerant and operates on an ideal vapour-compression refrigeration cycle between 0.14 MPa and 0.8 MPa. If the mass flow rate of the refrigerant is 0.05 kg/s, the rate of heat rejection to the environment is ______ kW. **[2016]**
Given data:

At $P = 0.14$ MPa
$h = 236.04$ kJ/kg
$s = 0.9322$ kJ/kg-K

At $P = 0.8$ MPa
$h = 272.05$ kJ/kg (superheated vapour)

At $P = 0.8$ MPa, $h = 93.42$ kJ/kg (saturated liquid)

Answer Keys

Exercises

Practice Problems 1

1. D	**2.** D	**3.** A	**4.** B	**5.** B	**6.** C	**7.** C	**8.** B	**9.** A	**10.** B
11. C	**12.** B	**13.** A	**14.** D	**15.** A	**16.** A	**17.** C	**18.** A	**19.** C	**20.** C

Practice Problems 2

1. B	**2.** C	**3.** B	**4.** A	**5.** D	**6.** B	**7.** D	**8.** A	**9.** C	**10.** B
11. B	**12.** A	**13.** D	**14.** C	**15.** D	**16.** A	**17.** C	**18.** B	**19.** C	**20.** A
21. D	**22.** C	**23.** B	**24.** C	**25.** A	**26.** C	**27.** A	**28.** C	**29.** A	**30.** A
31. C	**32.** B	**33.** D	**34.** A	**35.** A					

Previous Years' Questions

1. D	**2.** B	**3.** D	**4.** A	**5.** B	**6.** A	**7.** A	**8.** B	**9.** A	**10.** C
11. B	**12.** B	**13.** A	**14.** D	**15.** A	**16.** C	**17.** A	**18.** C	**19.** C	**20.** A
21. D	**22.** D	**23.** A	**24.** C	**25.** D	**26.** B	**27.** A	**28.** C	**29.** A	**30.** D
31. 1400 to 1420		**32.** 40 to 42		**33.** D	**34.** 105 to 112		**35.** A	**36.** 58 to 62	
37. 7580 to 7582		**38.** 59 to 61		**39.** 525	**40.** 123.56 to 127.56		**41.** C	**42.** B	
43. 3.6 to 3.8		**44.** B	**45.** B	**46.** A	**47.** 25.8 to 26.1		**48.** 0.8	**49.** 8.9 to 8.95	