

Basic Mechanical Engineering (3110006)

Chapter 5 Heat Engine

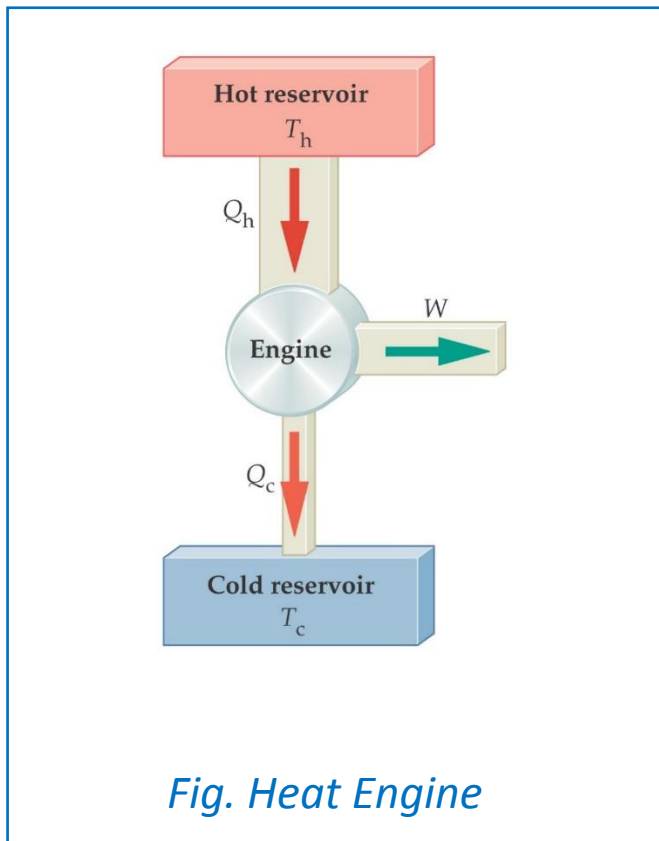
Outline

- 5.1 Heat engine cycle and heat engine
- 5.2 Working substances
- 5.3 Classification of heat engines
- 5.4 Description and thermal efficiency of Carnot cycle
- 5.5 Description and thermal efficiency of Otto cycle
- 5.6 Description and thermal efficiency of Diesel cycle
- 5.7 Description and thermal efficiency of Rankine cycle

5.1 Heat engine cycle and heat engine

A device which can produce the work continuously at the expense of heat input is called a heat engine

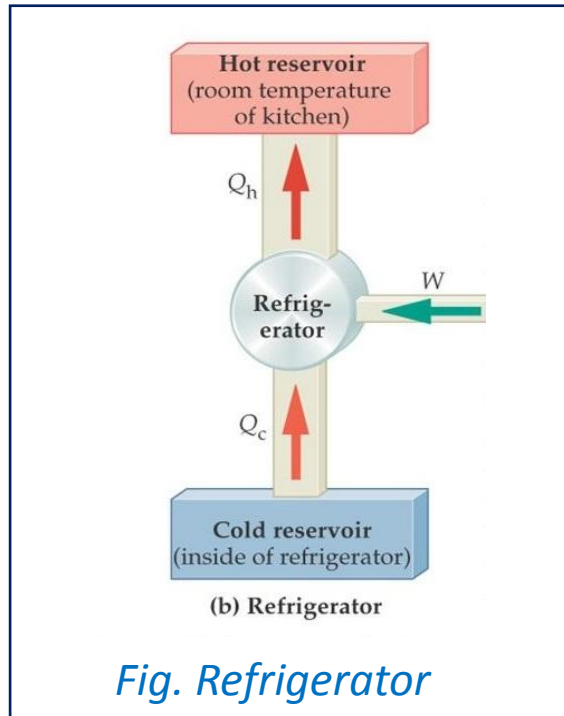
Example:- Steam engine, Steam turbine power plants, Petrol & Diesel engines, gas turbines etc.



$$Q_h = Q_c + W$$

$$\eta = \frac{\text{Work output}}{\text{Heat supply}}$$
$$= \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h} = 1 - \frac{Q_c}{Q_h}$$

Refrigerators & heat pumps



A **Refrigeration** is a device operating on a cycle which removes heat from a low temperature body and reject it to a body at high temperature on the expense of external work supplied.

$$(COP)_{Ref} = \frac{\text{Desire effect}}{\text{Energy input}} = \frac{Q_c}{W} = \frac{Q_c}{Q_h - Q_c}$$

Heat pump :- If the objective the system is to deliver heat energy at higher temperature then the temperature corresponds to ambient temperature such a device is called heat pump.

$$(COP)_{pump} = \frac{\text{Desire effect}}{\text{Energy input}} = \frac{Q_h}{W} = \frac{Q_h}{Q_h - Q_c}$$

$$(COP)_{pump} - (COP)_{Ref} = 1$$

5.2 Working substances

Source of heat

- Chemical Energy
- Atomic or Nuclear Energy
- Heat Energy

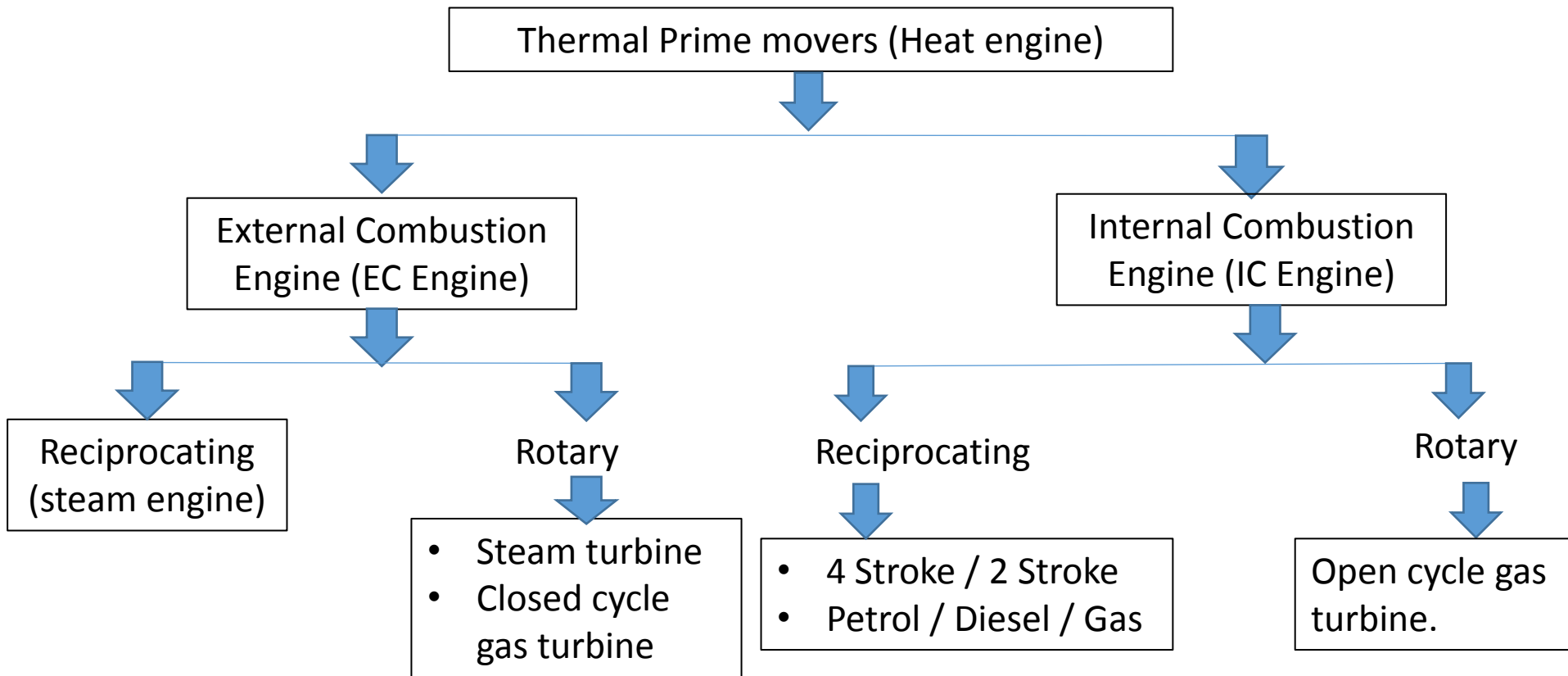
Working Substance

- Usually the steam and gas are used as working substance.
- Steam is used in steam engines, steam turbine, nuclear power plants
- Gas or air is used in I.C. engines, gas turbine power plants, jet engines etc.

Heat reservoir is defined as the source of infinite heat energy and a finite amount of heat absorbed or heat rejected from the heat reservoir will not affect its temperature i.e. the temperature of heat reservoir remains constant.

- Example :- Ocean, Atmosphere.
- A heat reservoir which supplies heat to a system is called **Source**.
- A heat reservoir which absorbs heat from the system is called **Sink**.

5.3 Classification of heat engines



- **Air Standard efficiency or Ideal efficiency**

The efficiency of the theoretical cycle with working medium as air is called air standard efficiency. Theoretical

$$\text{Air Standard efficiency} = \frac{\text{Ideal (Theoretical) work done}}{\text{Heat supply}}$$

- **Thermal efficiency**

$$\text{Thermal efficiency} = \frac{\text{Actual work done}}{\text{Heat supply}}$$

- **Relative efficiency**

$$\begin{aligned} \text{Relative efficiency} &= \frac{\text{Thermal efficiency}}{\text{Air Standard efficiency}} \\ &= \frac{\text{Actual work done}}{\text{Ideal (Theoretical) work done}} \end{aligned}$$

5.4 Carnot cycle

Working substance is **gas**

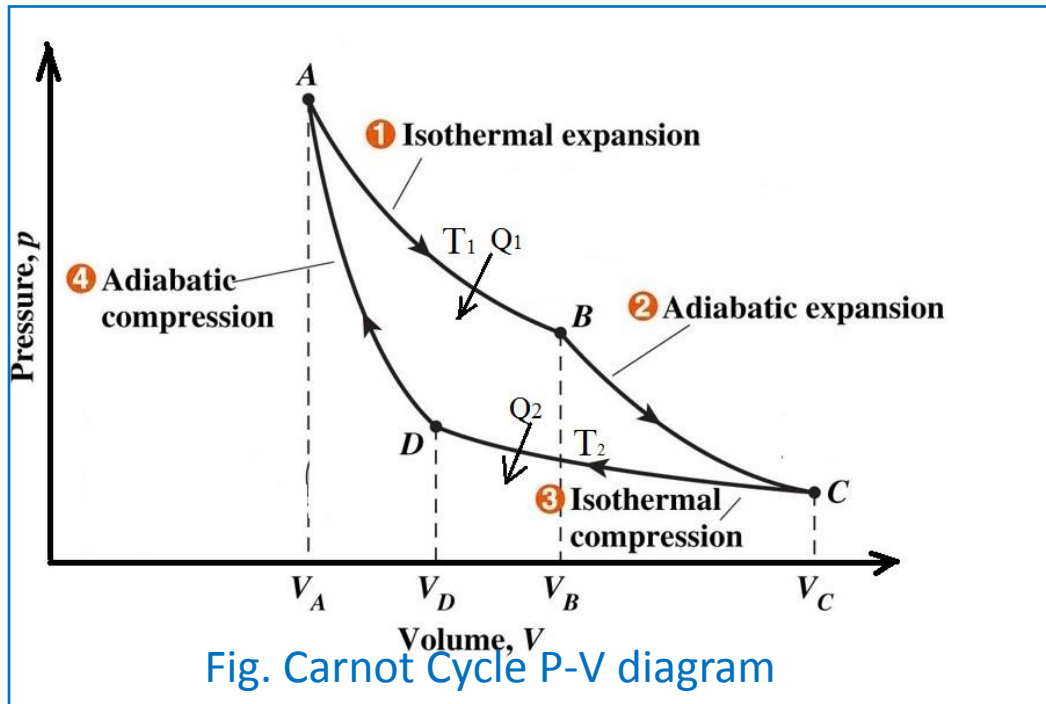
Assumption:-

- 1) Piston cylinder arrangement is weightless and frictionless
- 2) Heat transfer takes place with the help of reservoirs.
- 3) The walls of cylinder and piston are perfectly insulated.

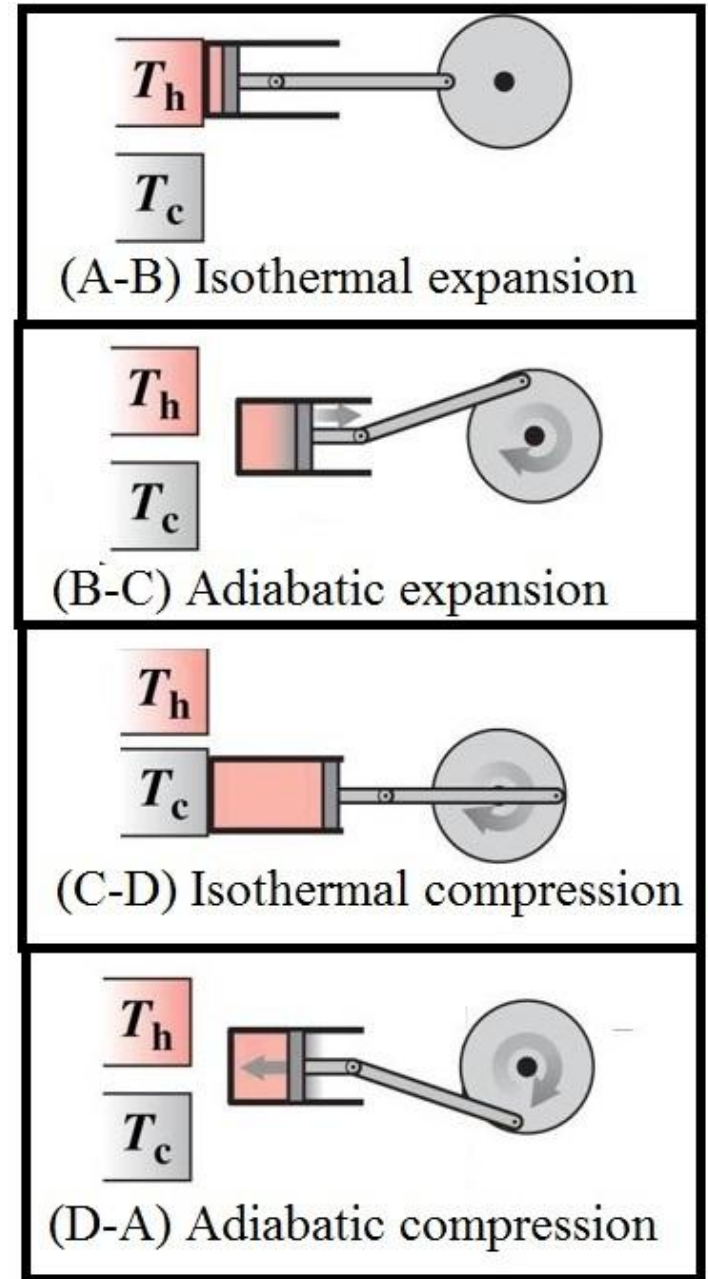
Process:-

It consist **two isothermal** and **two reversible adiabatic** process. (STST)

5.4 Carnot cycle



- 1) Process (A-B) :- Isothermal Expansion
 Q_1 heat supply at constant temperature T_1
- 2) Process (B-C) :- Reverse adiabatic expansion,
Temperature decrease from T_1 to T_2
- 3) Process (C-D) :- Isothermal Compression
 Q_2 heat remove at constant temperature T_2
- 4) Process (D-A) :- Reverse adiabatic compression,
Temperature increase from T_2 to T_1



5.4 Carnot cycle

$$\eta_{\text{carnot}} = \frac{\text{Net Work Output}}{\text{Heat input}} = \frac{W_{\text{net}}}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1} \quad \dots(1)$$

1) Process (A-B) :- Q_1 heat supply at constant temperature T_1

- $\Delta U = m C_v \Delta T = 0$ (from ch.3, $\Delta T = 0$)

- $\frac{V_b}{V_a} = \frac{P_a}{P_b}$ (from Eq. of state) ...(2)

- $Q_1 = m R T_1 \ln \frac{V_b}{V_a}$ (from ch.3) ...(3)

2) Process (B-C) :- Reverse adiabatic expansion, Temperature decrease from T_1 to T_2

3) Process (C-D) :- Q_2 heat remove at constant temperature T_2

- $\Delta U = m C_v \Delta T = 0$ (from ch.3, $\Delta T = 0$) ...(4)

- $Q_2 = -m R T_2 \ln \frac{V_d}{V_c} = m R T_2 \ln \frac{V_c}{V_d}$ (from ch.3) ...(5)

3) Process (D-A) :- Reverse adiabatic compression, Temperature increase from T_2 to T_1

5.4 Carnot cycle

From reversible adiabatic processes (B-C) & (D-A) $PV^\gamma = \text{Const}$

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

$$(PV)V^{\gamma-1} = \text{const}$$

$$(mRT)V^{\gamma-1} = \text{Const}$$

$$TV^{\gamma-1} = \text{Cont} \quad \dots(6)$$

For Process B-C

$$T_b V_b^{\gamma-1} = T_c V_c^{\gamma-1} \quad (\text{From eq. (6)})$$

$$\frac{T_b}{T_c} = \left(\frac{V_c}{V_b}\right)^{\gamma-1} \quad \dots(7)$$

For Process D-A

$$T_a V_a^{\gamma-1} = T_d V_d^{\gamma-1} \quad (\text{From Eq.(6)})$$

$$\frac{T_a}{T_d} = \left(\frac{V_d}{V_a}\right)^{\gamma-1} \quad \dots(8)$$

5.4 Carnot cycle

In Isothermal Processes

$$T_a = T_b = T_1 \quad \& \quad T_c = T_d = T_2$$

$$\left(\frac{V_c}{V_b}\right)^{\gamma-1} = \left(\frac{V_d}{V_a}\right)^{\gamma-1} \quad \text{(From eq. (7) \& (8))}$$
$$\frac{V_c}{V_b} = \frac{V_d}{V_a}$$

$$\frac{V_c}{V_d} = \frac{V_b}{V_a} \quad \dots(9)$$

In the equation of efficiency

$$\eta_{carnot} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{mR T_2 \ln \frac{V_c}{V_d}}{mR T_1 \ln \frac{V_b}{V_a}} = 1 - \frac{T_2 \ln \frac{V_c}{V_d}}{T_1 \ln \frac{V_b}{V_a}} = 1 - \frac{T_2}{T_1} \quad \dots(10)$$

From above equation, $\frac{Q_2}{Q_1} = \frac{T_2}{T_1}$

“The heat transfer from a heat reservoir is proportional to its temperature. It is called **carnot’s principle**”

5.4 Carnot cycle

Important points regarding Carnot cycle

- It's hypothetical device
- Thermal efficiency is depend on the temperature of source and sink and not on the working substance.
- A Practical engine based on Carnot cycle can not be built because of following reasons
 - a) Practically it is not possible to bring in contact and remove alternately the heat reservoirs and adiabatic cover in order to complete the cycle.
 - b) Isothermal process could only achieved by very slow motion of piston while for achieving reverse adiabatic process, we must do the piston movement very quickly. Such a large variation of speed of piston can not achieved in practice
 - c) In order to get sufficient work, large range of pressure and volume required since the slop difference of isothermal and adiabatic is small.
- Carnot engine has the maximum efficiency compared to another engine while operating between the given temperature.

5.5 Otto cycle

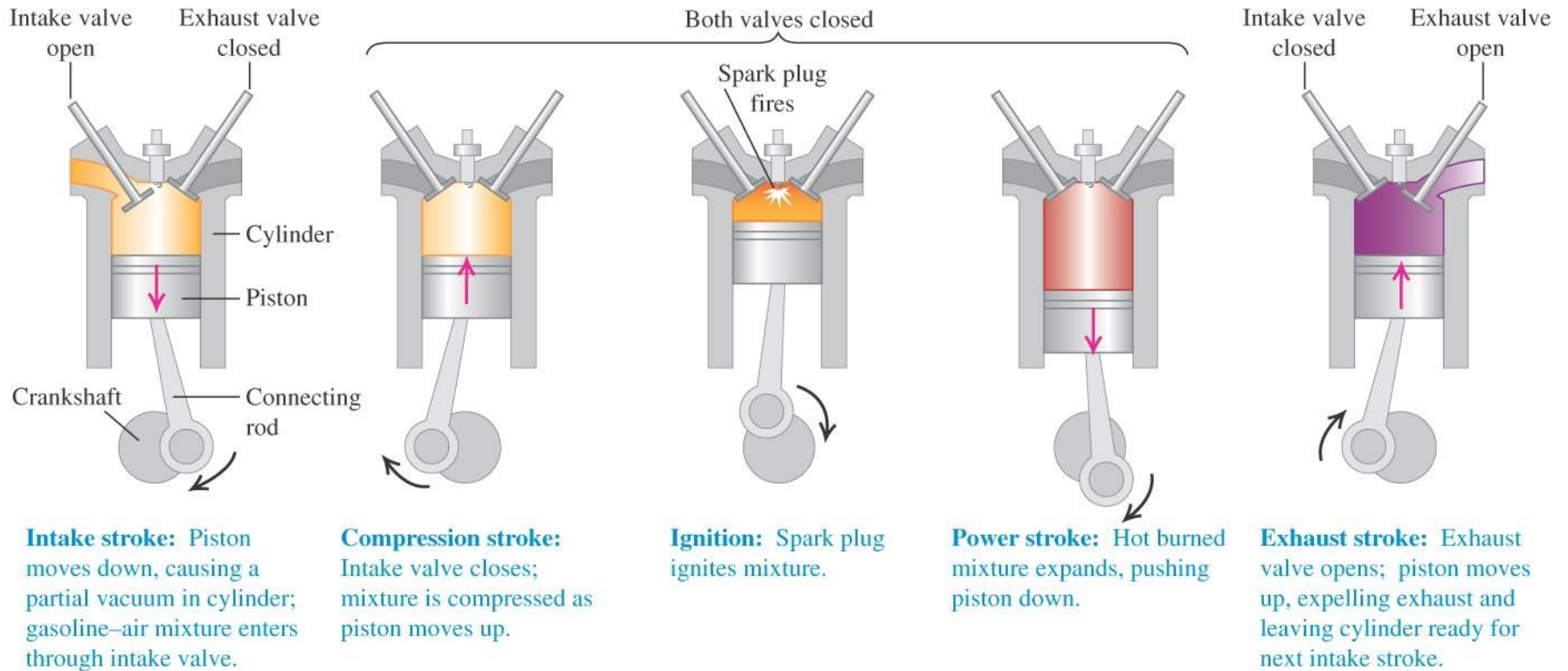


Fig. 4 stroke Petrol Engine

5.5 Otto cycle

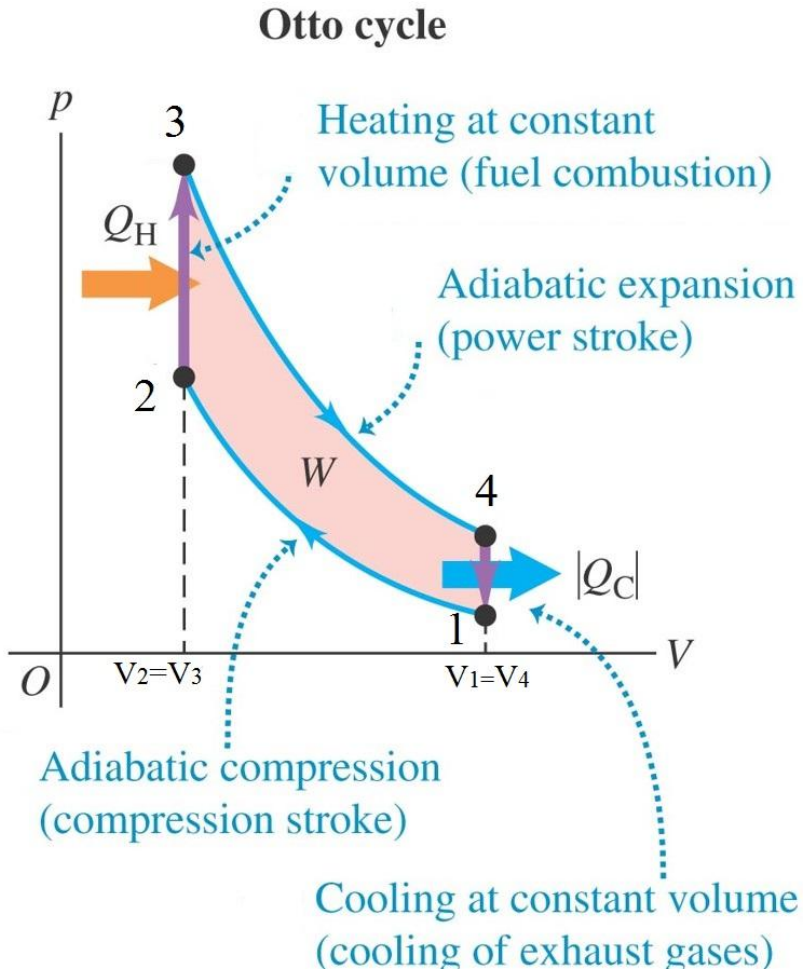


Fig. P-V diagram of Otto cycle

- S.I (Spark Ignition) or petrol engine operate on theoretical Otto cycle. The P-V diagram of Otto cycle is shown.
- Otto cycle consist of **two constant volume** and **two reversible adiabatic** processes. (SVSV)
- Compression ratio, $r = \frac{V_1}{V_2} = \frac{V_4}{V_3}$
- **(1-2) Revers adiabatic compression,**
 - $\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = (r)^{\gamma-1}$...**(11)**
 - Work input, $W_{1-2} = mC_v(T_2 - T_1)$...**(12)**
 - $\Delta Q_{1-2} = 0$

5.5 Otto cycle

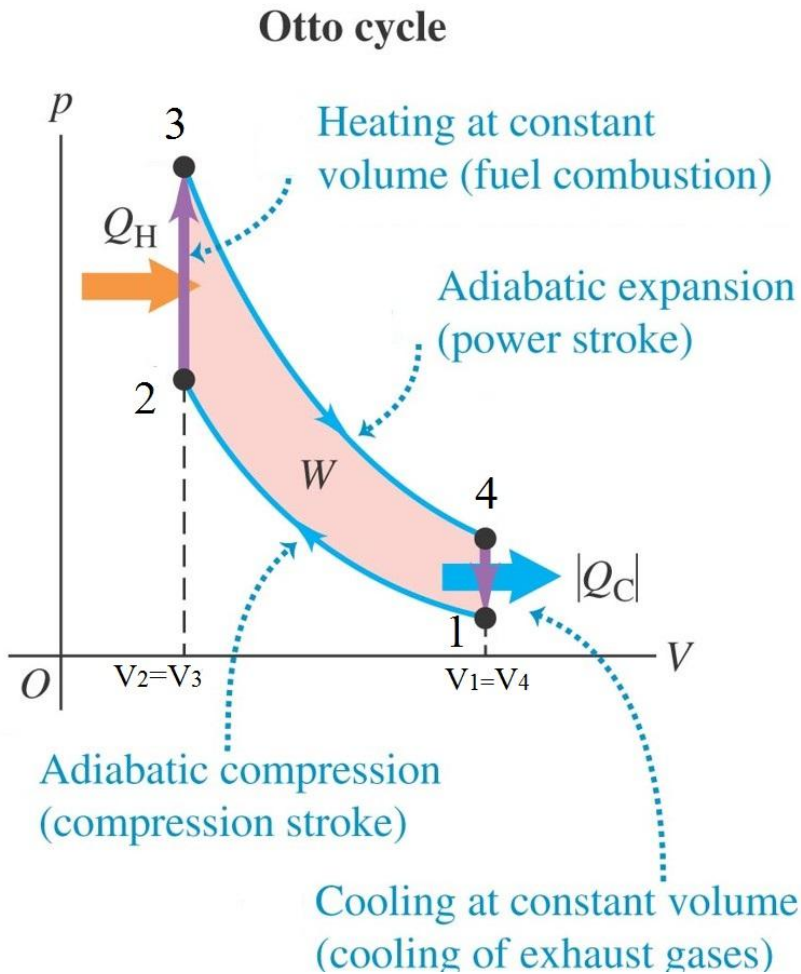


Fig. P-V diagram of Otto cycle

- **(2-3) Constant volume heat addition**

$$Q_H = mC_v(T_3 - T_2) \quad \dots(13)$$

- **(3-4) Revers adiabatic expansion**

$$\triangleright \frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1} = (r)^{\gamma-1} \quad \dots(14)$$

$$\triangleright \text{Work output, } W_{3-4} = mC_v(T_3 - T_4) \quad \dots(15)$$

$$\triangleright \Delta Q_{1-2} = 0$$

- **(4-1) Constant volume heat rejection**

$$Q_C = mC_v(T_4 - T_1) \quad \dots(16)$$

5.5 Otto cycle

- Net work done, $W_{net} = \text{Expansion Work} - \text{Compression Work}$

$$= mC_v(T_3 - T_4) - mC_v(T_2 - T_1)$$

- Air standard efficiency, $\eta_{Otto} = \frac{\text{Net work done}}{\text{heat addition}}$

$$= \frac{mC_v(T_3 - T_4) - mC_v(T_2 - T_1)}{mC_v(T_3 - T_2)} \quad (\text{From Eq. (12,15 \& 13)})$$

$$= \frac{mC_v(T_3 - T_2) - mC_v(T_4 - T_1)}{mC_v(T_3 - T_2)}$$

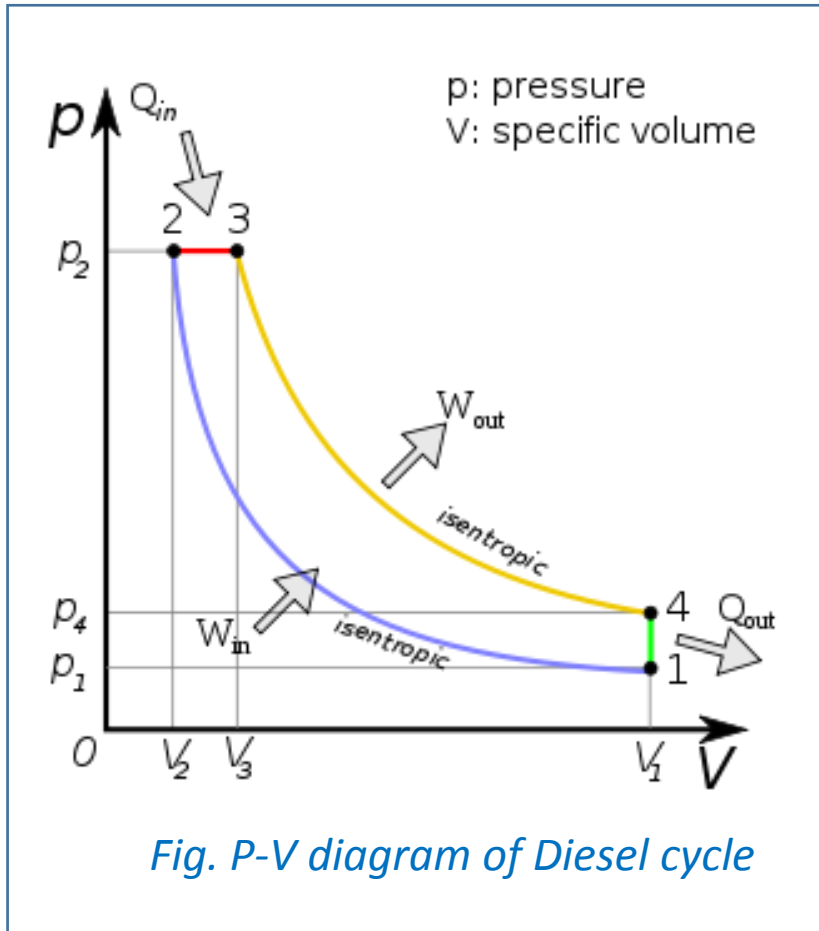
$$= 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

$$= 1 - \frac{T_4 - T_1}{T_4(r)^{\gamma-1} - T_1(r)^{\gamma-1}} \quad (\text{From Eq. (14 \& 11)})$$

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

...(17)

5.6 Diesel cycle



- Compression Ignition or diesel engine operate on theoretical Diesel cycle.
- Diesel cycle consist of **one constant volume, one constant pressure and two reversible adiabatic (isentropic) processes.** (SPSV)
- **Compression ratio, $r = \frac{V_1}{V_2}$... (18)**
- **Cutoff ratio (ρ)** is defined as the ratio of cylinder volume before and after the combustion or heat addition process in a diesel engine

$$\text{Cutoff ratio, } \rho = \frac{V_3}{V_2} \quad \dots (19)$$

- **Expansion ratio = $\frac{V_4}{V_3} = \frac{V_1}{V_3} = \frac{r}{\rho}$... (20)**
- **(1-2) Isentropic Compression Process**

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2} \right)^{\gamma-1} = (r)^{\gamma-1} \quad (\text{From eq.(17)})$$

$$T_1 = \frac{T_2}{(r)^{\gamma-1}} \quad \dots (21)$$

5.6 Diesel cycle

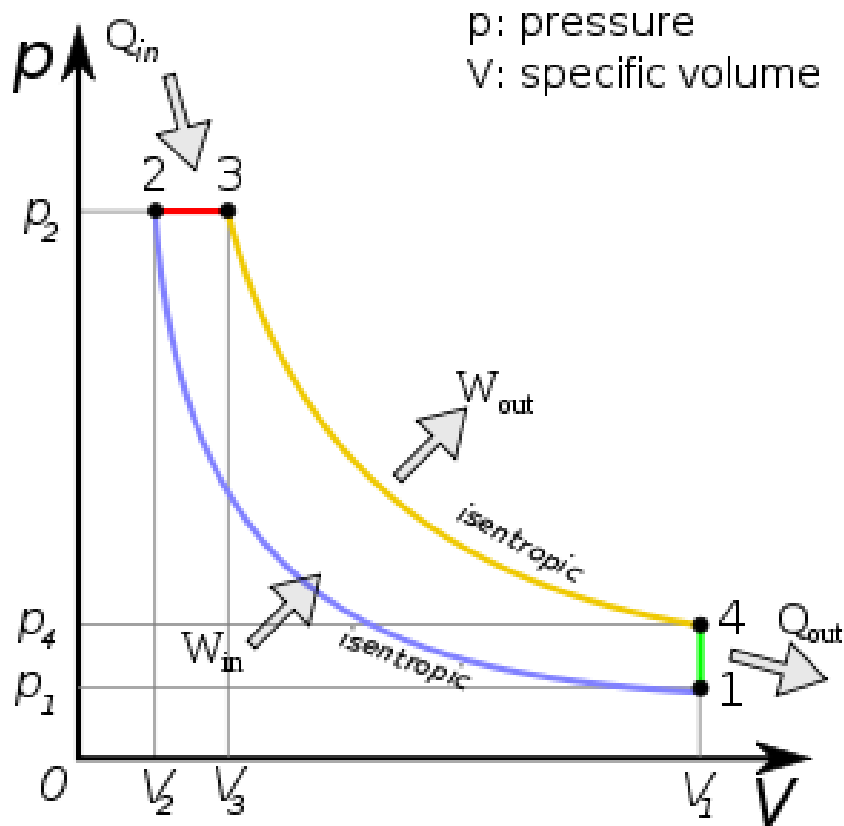


Fig. P-V diagram of Diesel cycle

- **(4-1) Constant Volume Process**

$$\text{Heat Reject } (Q_{out}) = mC_v(T_4 - T_1)$$

- **(2-3) Constant Pressure Process**

$$\text{Heat Supply } (Q_{in}) = mC_p(T_3 - T_2) \dots(22)$$

$$\frac{P_2 V_2}{T_2} = \frac{P_3 V_3}{T_3}$$

$$\frac{V_2}{T_2} = \frac{V_3}{T_3} \quad (P_2 = P_3)$$

$$\frac{T_3}{T_2} = \rho \quad \dots(23)$$

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

$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1} = \left(\frac{r}{\rho}\right)^{\gamma-1}$$

$$T_4 = \frac{T_3}{\left(\frac{r}{\rho}\right)^{\gamma-1}} \quad \dots(24)$$

$$\dots(25)$$

5.6 Diesel cycle

$$\text{Thermal efficiency, } \eta_{\text{Diesel}} = \frac{\text{Heat Supply}(Q_{in}) - \text{Heat Remove}(Q_{out})}{\text{Heat Supply}(Q_{in})}$$

$$= \frac{mC_p(T_3 - T_2) - mC_v(T_4 - T_1)}{mC_p(T_3 - T_2)} = 1 - \frac{(T_4 - T_1)}{\gamma(T_3 - T_2)} \quad (\because C_p/C_v = \gamma)$$

$$= 1 - \frac{\left(\frac{T_3}{(r/\rho)^{\gamma-1}} - \frac{T_2}{(r)^{\gamma-1}} \right)}{\gamma(T_3 - T_2)} \quad (\text{from Eq.(24) \& (21)})$$

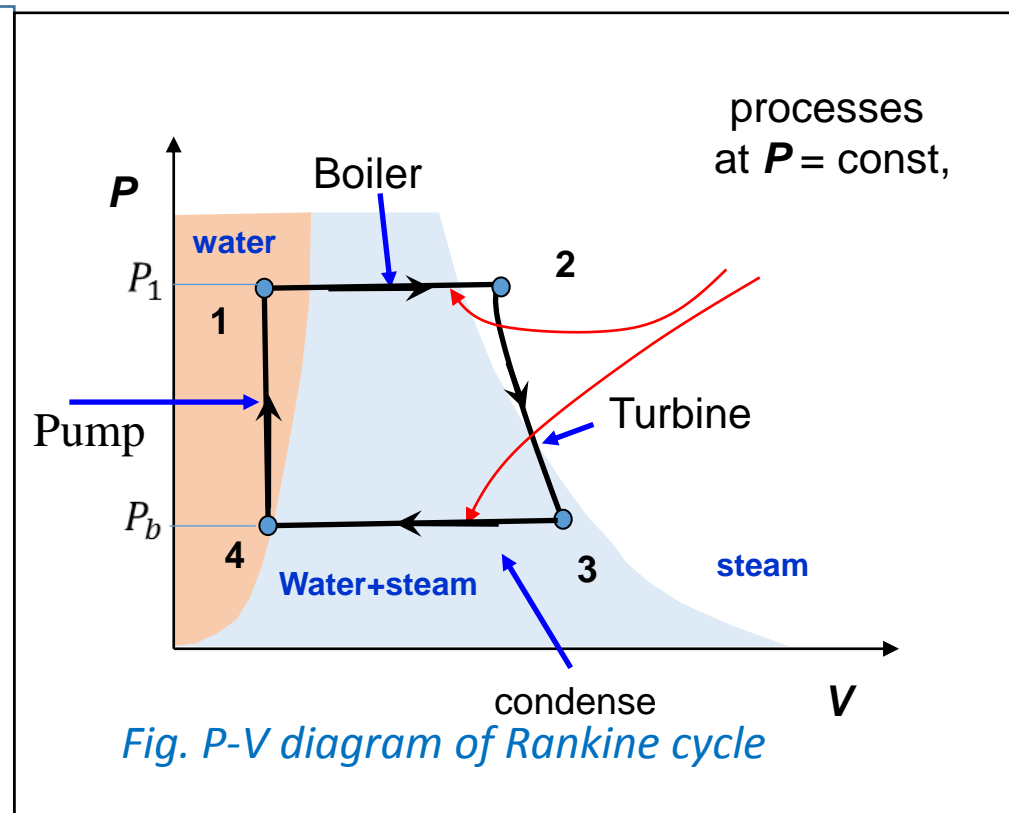
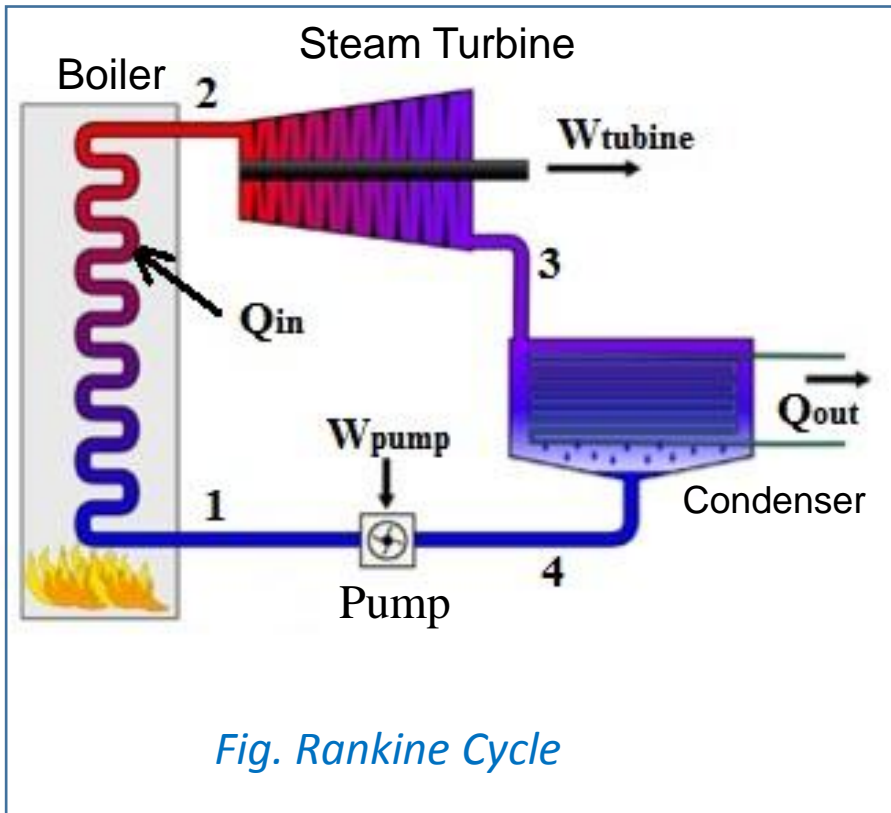
$$= 1 - \frac{\left(\frac{T_3/T_2}{(r/\rho)^{\gamma-1}} - \frac{1}{(r)^{\gamma-1}} \right)}{\gamma \left(\frac{T_3}{T_2} - 1 \right)}$$

$$= 1 - \frac{\left(\frac{\rho}{(r/\rho)^{\gamma-1}} - \frac{1}{(r)^{\gamma-1}} \right)}{\gamma(\rho - 1)} \quad (\text{from Eq.(23)})$$

$$= 1 - \frac{(\rho^\gamma - 1)}{\gamma(r)^{\gamma-1}(\rho - 1)} \quad \dots(26)$$

5.7 Rankine cycle

- The ideal Rankine cycle is a reversible cycle which used for steam power plants.
- Rankine cycle consist of **two constant pressure** and **two reversible adiabatic (isentropic)** processes. (SPSP)

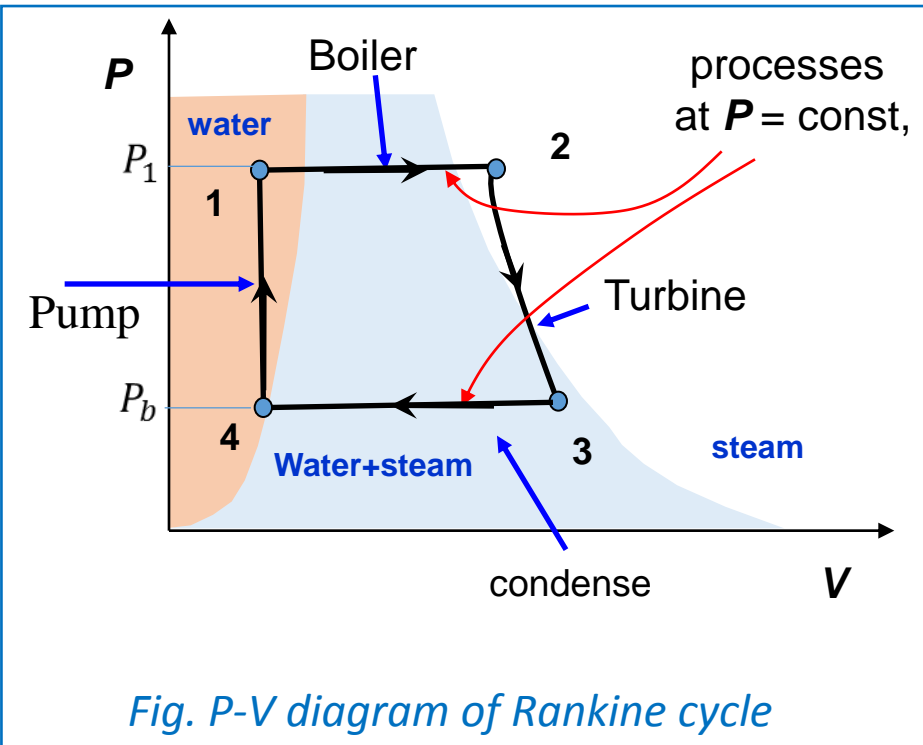


Main Components in Rankine Cycle

- 1) Steam Boiler
- 2) Steam Turbine
- 3) Condenser
- 4) Pump

- The working fluid is **steam**

5.7 Rankine cycle



(1-2) Process, Constant pressure heat supply in Boiler

- The feed water is converted into steam at constant pressure (P_1) in the boiler due to the heat supplied Q_{in} by burning of fuel (coal or oil)

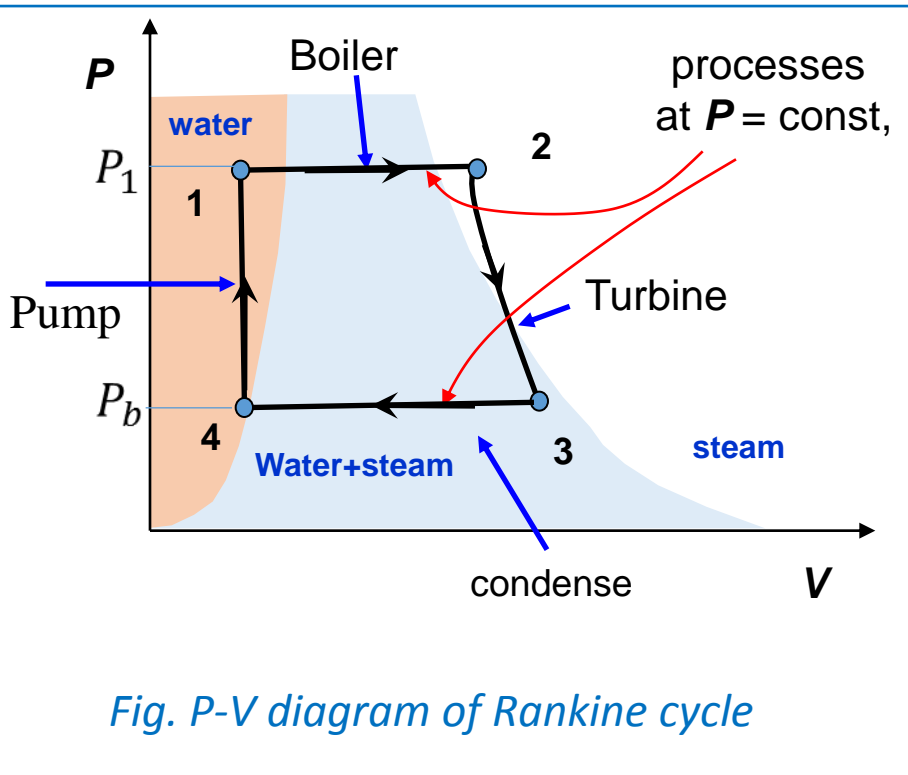
$$Q_{in} = (h_2 - h_1)$$

(2-3) Process, Revers adiabatic expansion in Steam Turbine

- High pressure and high temperature superheated steam generated in the boiler at P_1 and T_{sup1} is supplied to the steam turbine.
- This steam expand reversible adiabatically in the steam turbine up to condenser pressure.
- Due to expansion of steam, turbine develops mechanical work

$$W_T = (h_2 - h_3)$$

5.7 Rankine cycle



(3-4) Process, Constant pressure heat rejection in Condenser

- The exhaust steam is condensed at constant pressure (P_b) in condenser by circulating water in the tubes.
- The steam is converted into saturated water called condensate.
- Rejected heat $Q_{\text{out}} = (h_4 - h_3)$

(4-1) Process, Pump

- The condensate at condenser pressure, P_b is pumped with the help of a feed pump. It raised the pressure of condensate called feed water of the boiler pressure P_1 and work done

$$W_p = h_1 - h_4 = \int_{P_b}^{P_1} V_f dp = V_f(P_1 - P_b)$$

5.7 Rankine cycle

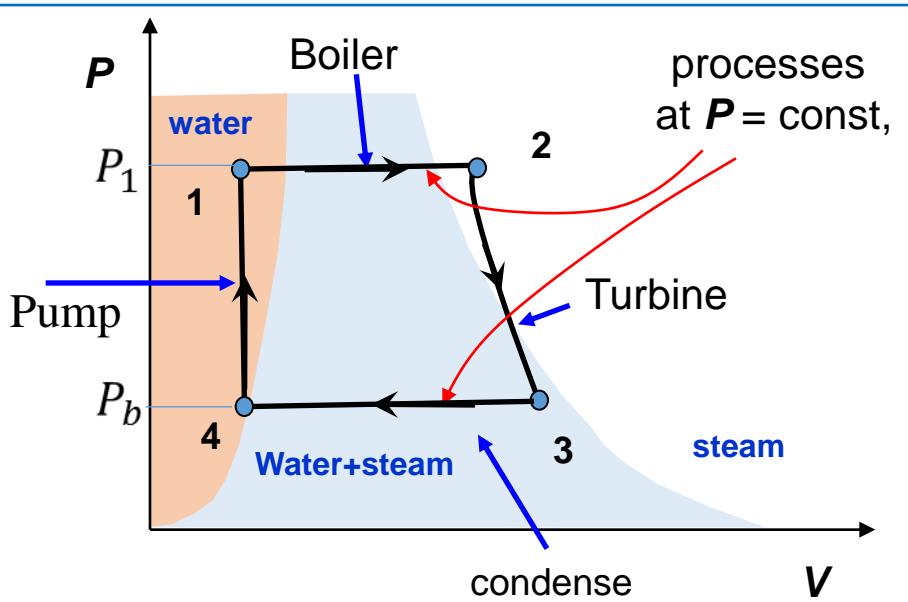


Fig. P-V diagram of Rankine cycle

Rankine cycle efficiency

$$\eta_{Rankine} = \frac{\text{Net Workdone}}{\text{Heat Supplied}}$$

$$= \frac{W_T - W_P}{Q_{in}}$$

$$= \frac{(h_2 - h_3) - (h_1 - h_4)}{(h_2 - h_1)}$$

Thank You...