INTERNAL COMBUSTION ENGINE

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TECHNICAL COLLEGE / KIRKUK

FUEL AND ENERGY ENGINEERING DEPT

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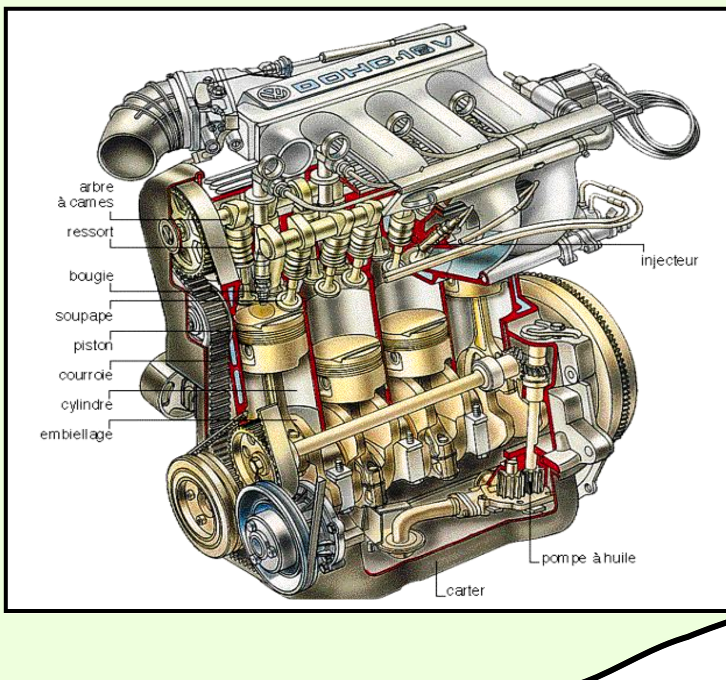


Internal Combustion Engines

Heat Engines :

A heat engine is a device which convert the chemical energy of the fuel to thermal energy and uses this energy to produce the mechanical work .

Heat engines are divided into two broad classes :

1- External combustion Engines : E.C.E

In an E.C.E the products of combustion of air and fuel transfer heat to a second fluid which is the working fluid of the cycle , as in the case of a steam turbine or steam engine .

2- Internal combustion Engines : I.C.E

In an internal combustion engine the product of the combustion are directly motive fluid , petrol and diesel engines , winkle engine , and the open cycle gas turbine are also (I.C.E) .

The main advantages of I.C over E.C :

1- Greater mechanical simplicity
2- Lower ratio of weight and bulk to output due to absence of auxiliary apparatus
3- Lower first cost
4- Higher overall efficiency
5- Less requirements of water for dissipation of energy through cooling system .

Reciprocating Engines:

1- Gasoline engine:

Essential Parts:-

As in figure (1)

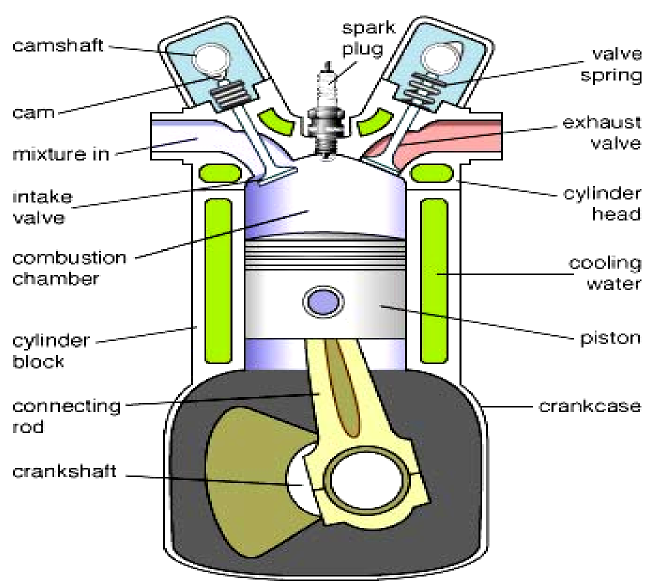


fig. (1)

2-Diesel Engine :

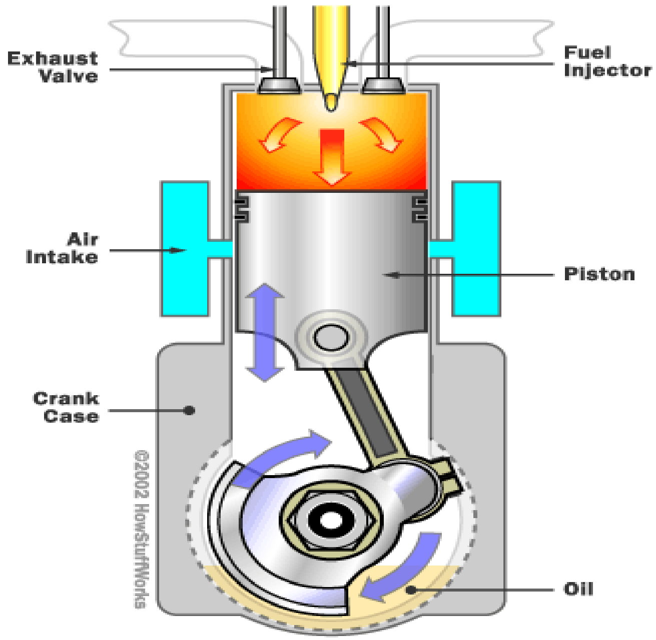


fig. (2)

Technical Assembly:

Cubic capacity or Engine capacity = Ec = Vd * Z

Where

Vd or Vs = displacement volume = swept volume

& Z= number of cylinders

Vd = $\frac{\pi}{4} * (B)^2 * S$

B=Cylinder Bore &

S =(stroke)

CR = rc = (compression ratio)
Vc = clearance volume
CR = V $_{total}$ / Vc

CR = (Vd + Vc / Vc)

CR = 1 + (Vd / Vc)

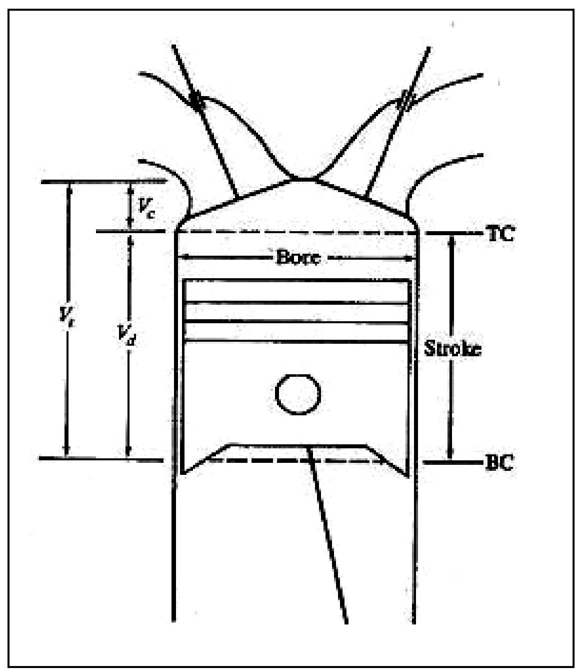


fig. (3)

TDC : Top Dead Center
BDC : Bottom Dead Center

P –V diagram for 4 – stroke cycle :

fig. (4)

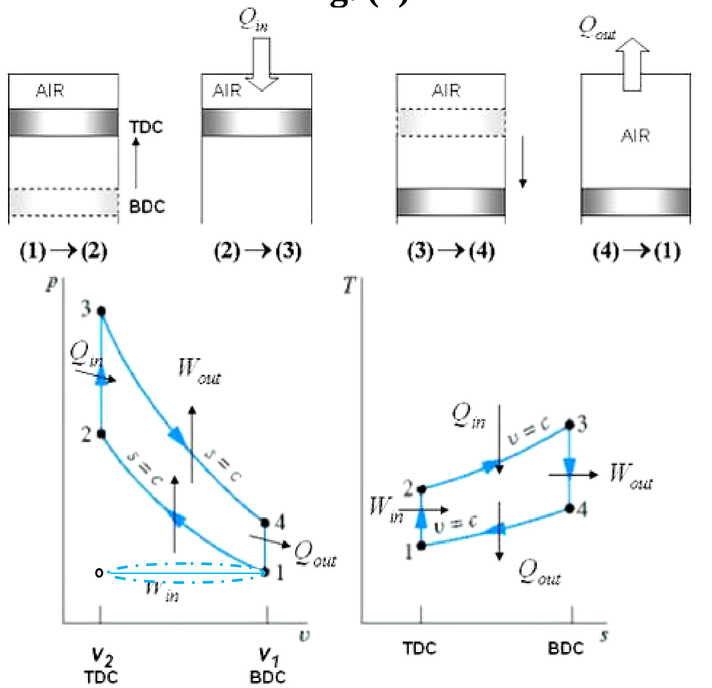
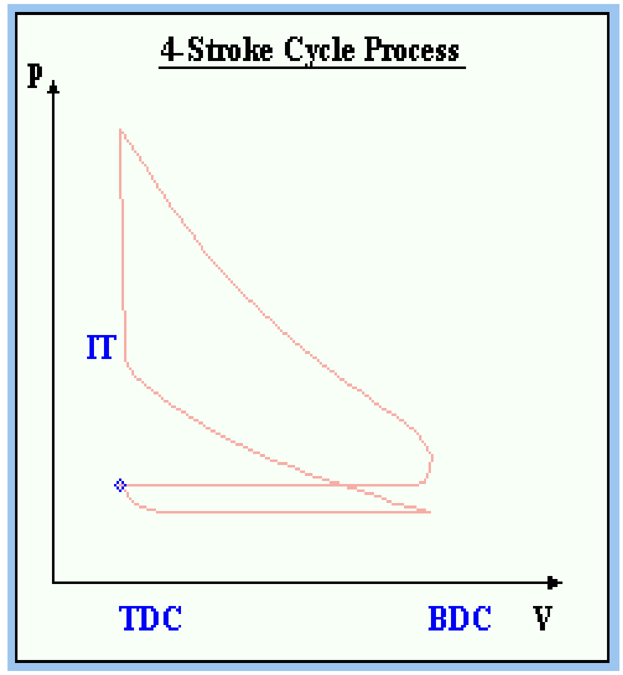


fig. (5)



4 – Stroke Cycle

1- Intake stroke : from position (0 – 1) in figure (4) fresh air mixed with fuel is drawn into cylinder .

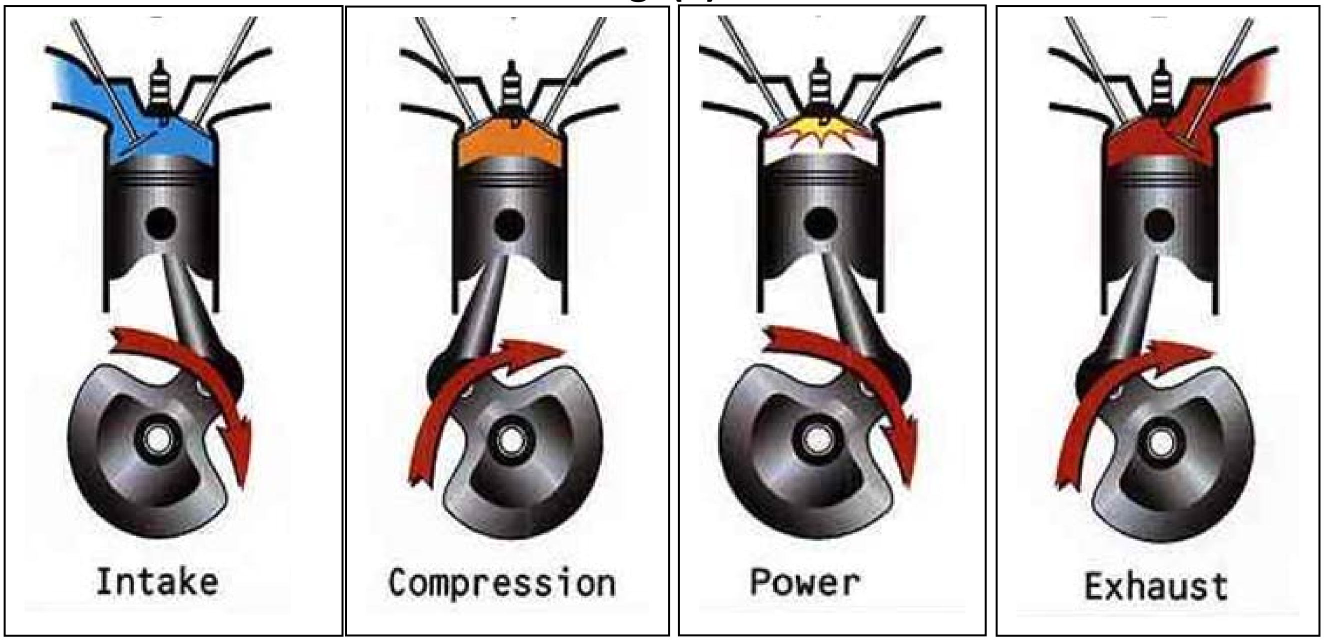
2- Compression stroke : the charge compressed from (1 – 2) just before the end of stroke the mixture ignited by spark plug converting chemical energy of the fuel into sensible energy producing a temperature rise of about 2000 ℃ and the pressure also considerably increased .

3- Power stroke : power is obtained during the stroke (3 – 4) both pressure and temperature decrease during the expansion .

4- Exhaust stroke : in this stroke the piston sweeps out the burning gases from the cylinder (4 – 0) .

* each cylinder in a 4- stroke complete the above operation in two revolution .

fig. (6)



(0 – 180) (180 – 360) (360 – 540) (540 – 720)

Example : Engine has **6 cylinders** of **82.55 mm Bore** and **79.5 mm stroke** . **Compression ratio is 7.8** , determine the cubic capacity of the engine and clearance volume of each cylinder ?

Solution :-

Vd = π / 4 $(D)^2 * S$

Vd = π / 4 $(82.55/1000)^2 *$ (79.5 / 1000)

$Vd = 0.000425\, m^3$

$Cubic\ capacity = engine\ capacity = Ec = Vd * Z$

Ec = 0.000425 $*$ 6

$Ec = 0.00255 \ litter$ & $CR = V \ total / Vc$

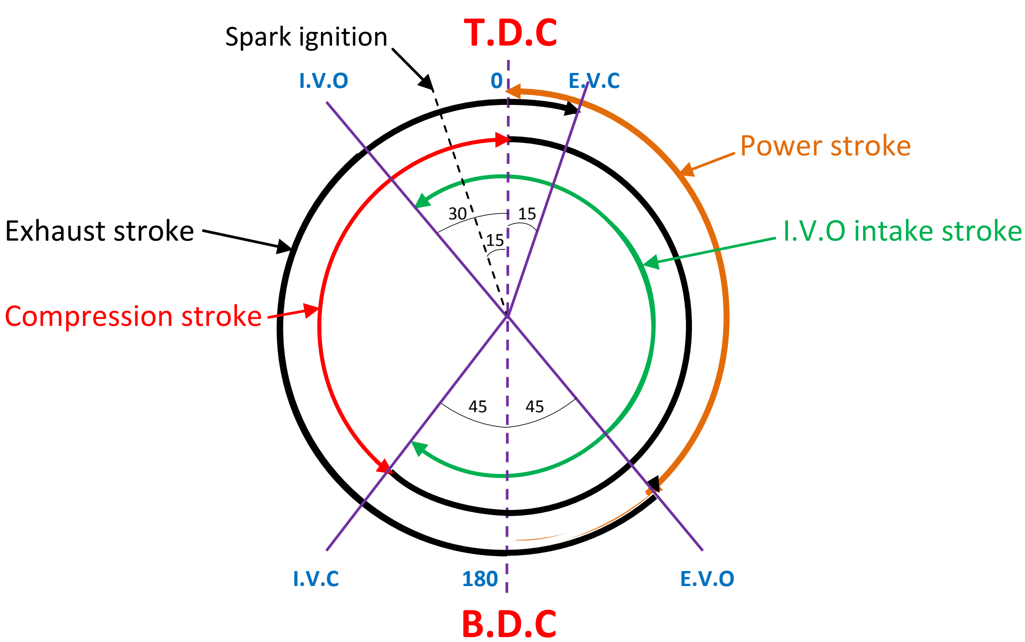
CR = (Vd + Vc)/ Vc CR = 1 + (Vd / Vc)

7.8 = 1 + (0.000425 / Vc) $Vc = 0.0000625 \, m^3$

Actual timing for stroke petrol engine :

Valve timing is the regulation of the point in the cycle at which the valve are set to open and close .

In an ideal cycle inlet and outlet valves open and close at (Dead centers) , but in actual cycle they open and close before and after dead center as explained below :



I : intake , **V** : valve

O : open , **E** : Exhaust

*** Intake valve remained open until 255° .**

There are two factors : One mechanical and other dynamics for outlet valves timing .

From the theoretical valve timing :

1- Mechanical factor : the poppet valves of the reciprocating engine are opened and closed by cam mechanism the clearance between cam , tappet and valve must be slowly taken up and valve slowly lifted (if noise and wear to be avoided) .

For the same reasons the valve cannot be closed suddenly . As a result the opening of the valve must be commence a head of time at which it is fully opened (before centers) .

2- Dynamic factor : besides mechanical factor of opening and closing of valves the actual valve timing is set to taking in consideration the dynamic factor effects of gas flow .

Intake valve timing :

Intake valve opens $(10-15)^{\circ}$ before (T.D.C) on the exhaust stroke to insure that the valve will be fully open and the fresh charge starting to flow into the cylinder . as sure as possible after (T.D.C) intake valve should close relatively early after (B.D.C) , (10° after B.D.C) for low speed engines and (60° B.D.C) for high speed engines .

Exhaust valve timing :

Exhaust valve set to open before (B.D.C) about (25° for low speed engines and 55° for high speed engines) .

If the (E.V) did not start to open until (B.D.C) the pressure inside the cylinder will be considerably above atmospheric pressure during the first portion of the exhaust gasses .But opening the (E.V) earlier reduces the pressure near the end of the stroke . However the overall efficiency of the engine will decreases .

	4 – stroke	2 - stroke
1	1 cycle ➔ 2 revolution or 1 power stroke	1 cycle ➔ 1 revolution or 1 power stroke
2	Turing moment is not uniform heavier fly wheel is needed	Turing moment is uniform light fly wheel is needed
3	For the same power the engine is heavy and bulk	For the same power engine is light and compact
4	Lesser cooling and lubricating required lesser ratio of wear and tear	Greater cooling and lubricating greater rate of tear and wear
5	Containing valve and valve	No valves but only parts

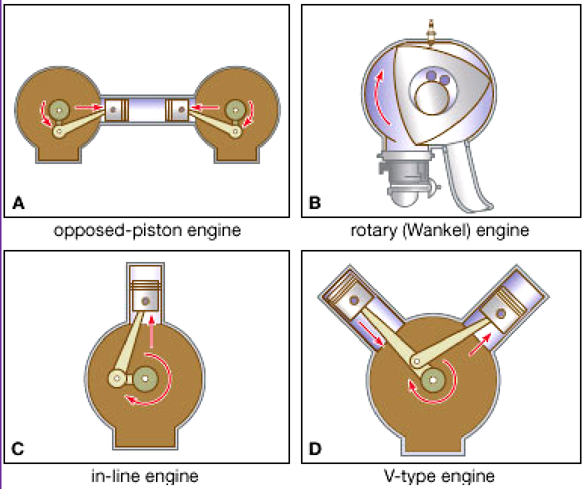
	mechanism	
6	Higher initial cost	Cheaper initial cost
7	η Vol more due to more time of induction	η Vol less due to less time of induction
8	η Thermal higher	η Thermal lower
9	Using in important engine generator , tractor	Using when lowest compact light

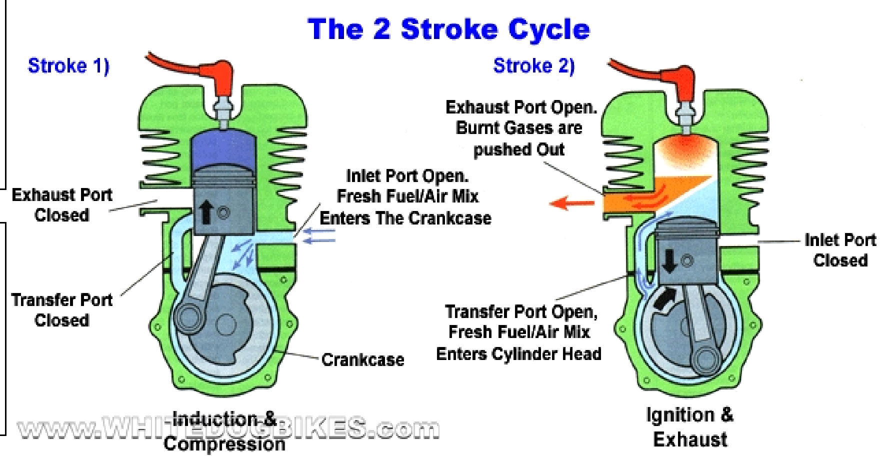
Fundamental difference between
(SI : spark ignition) and **(CI : compression ignition)** engines :

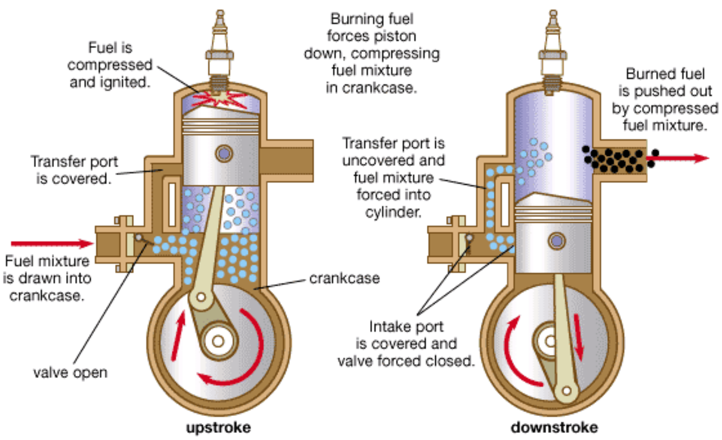
	SI engine	**CI engine**
1	Basic cycle :Based on Otto cycle	Based on Diesel cycle
2	Full : petrol (gasoline) high self ignition temperature	Diesel oil low self ignition temperature desirable
3	Introduction of fuel : fuel and air introduced as a gaseous mixture in suction stroke . carburetor is necessary , throttle controls the quantity of the mixture	Fuel is injected into the cylinder by injection pump and nozzles
4	Ignition : requires spark plug	Ignition system and spark is eliminated
5	Compression ratio 6 – 10.5	14 – 22
6	Speed : higher max , revolution	Lower max , revolution
7	Weight light	Weight heavy
8	η Max is lower	η Max is higher

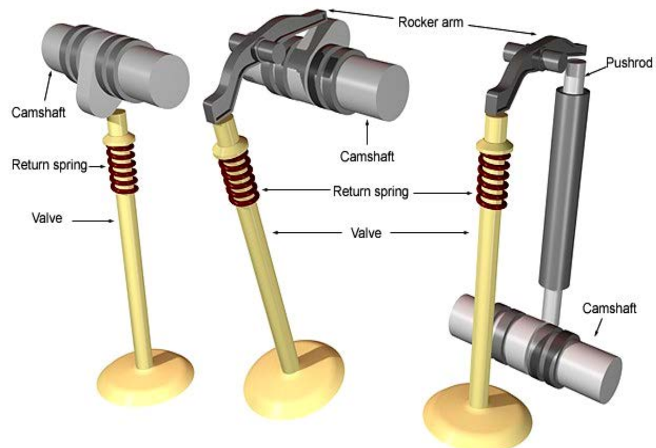
Engine classification by :

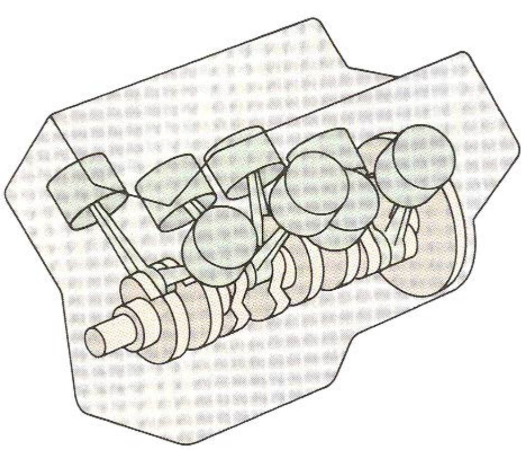
1	Type of ignition	Spark ignition Compression ignition
2	Engine cycle	2- stroke cycle 4- stroke cycle
3	Valve location	Valve in head Valve in block Valve in head and block
4	Basic design	Reciprocating Rotary wankel
5	Position and number of cylinder	Single cylinder In line V-engine Opposed cylinder engine Opposed piston engine W-engine Radial engine
6	Air intake process	Naturally aspirated Super charged Turbo charged
7	Method of fuel input for SI engine	Carbureted Multi point part fuel injection Throttle body fuel injection
8	Type of cooling	Air cooling Liquid cooling , water cooling

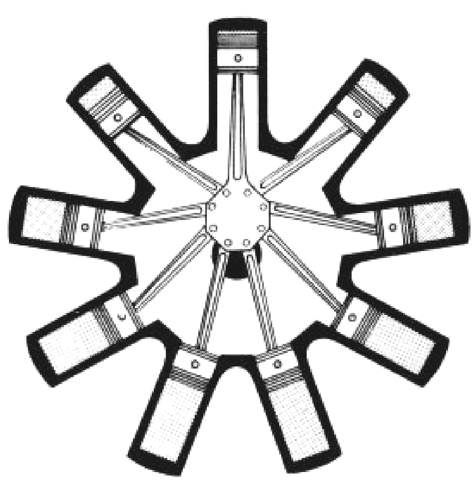

A
opposed-piston engine
B
rotary (Wankel) engine
C
in-line engine
D
V-type engine


The 2 Stroke Cycle
Stroke 1)
Stroke 2)
Exhaust Port Closed
Transfer Port Closed
Inlet Port Open. Fresh Fuel/Air Mix Enters The Crankcase
Crankcase
Induction & Compression
www.WHITEDOGBIKES.com
Exhaust Port Open. Burnt Gases are pushed Out
Inlet Port Closed
Transfer Port Open, Fresh Fuel/Air Mix Enters Cylinder Head
Ignition & Exhaust


Fuel is compressed and ignited.
Transfer port is covered.
Fuel mixture is drawn into crankcase.
valve open
Burning fuel forces piston down, compressing fuel mixture in crankcase.
Transfer port is uncovered and fuel mixture forced into cylinder.
crankcase
Intake port is covered and valve forced closed.
Burned fuel is pushed out by compressed fuel mixture.
upstroke
downstroke


Camshaft
Return spring
Valve
Rocker arm
Camshaft
Return spring
Valve
Pushrod
Camshaft





Operating characteristics :

S = 2a

$vp = 2sN = \frac{m}{min}$, $vp = \frac{2sN}{60} = \frac{m}{sec}$

vp : piston velocity (r.p.m)

displacement volume = vd = vs = $\frac{\pi}{4} B^2 * s$

Compression ratio :

Cr = rc = V total / Vc

(which is the ratio of the total volume to clearuce volume of the cylinder)

Cr = Vs + Vc / Vc

Cr = 1 + VS / Vc

Work (W) : is the force acting through a distance (J , kJ) .

$W = \int f.dx = \int P.A.dx = \int P.dv = P.(v1 - v2)$ the area under the curve

W° = is the work done per unit time (J / sec) ➔ W, (kJ / sec) ➔ KW

length	m
mass	kg
time	sec

Area = m^2

Volume = m^3

N = mass * acceleration

Kg = $\frac{m}{sec^2}$ = N

Velocity = $\frac{m}{s}$

Type of work :

1- indicated work (wi)

2- brake work (wb)

3- fraction work (wf)

Wb = wi – wf

Power= $\boldsymbol{W^{\circ}} = \boldsymbol{2\pi NT}$ (kJ / min) , (J / min)

Power :

1- Indicate power (I.P) : is the rate of work transfer between the gas in the cylinder , and the piston and can be derived from the indicated work .

$$I.P = \frac{imep * A * S * N * Z}{60 * n}$$

imep : indicated mean effective pressure (kpa)

N : engine speed (r.p.m)

Z : number of cylinder

$A * S = Vd =$ displacement of one cylinder where :

A = area of the cylinder

n = 1 for two stroke and n = 2 for 4 – stroke engines

2- Brake power (B.P) : power available at the engine crankshaft is defined as the (brake work) = $w \cdot b$

B.p = $wb = \frac{bmep*A*S*N*Z}{60*n}$ where bmep : brake mean effective pressure

3- Friction power (F.P) : is the power required to overcome friction .

$$F.P = \frac{Fmep * A * S * N * Z}{60 * n}$$

fmep : fraction mean effective pressure & F.P = I.P – B.P

Efficiency : $\eta = \frac{output}{input}$

1- mechanical efficiency = η_m

$$\eta_m = \frac{B.P\ (kw)}{I.P\ (kw)} = (\ \ )\ \%$$

2- indicate thermal efficiency = η_{ith} :

$$\eta_{ith} = \frac{I.P\ (w^{\circ} = \frac{KJ}{sec})}{m^{\circ} f\ \left(\frac{kg}{sec}\right) * QH.v\left(\frac{kJ}{kg}\right)} = (\ )\%$$

$m^{\circ} f$: mass of fuel / sec ➔ fuel consumption

$Q_{H.v}$: heating valve of the fuel

η_{bth} = brake thermal efficiency

$$\eta_{bth} = \frac{B.P}{m^{\circ} f * QH.v} = (\ \ )\%$$

$\eta_m = \eta_{bth} / \eta_{ith}$

Fuel consumption :

$$\frac{cm^3}{min}, \frac{liter}{min}, \frac{g}{sec}, \frac{kg}{min}, \frac{kg}{hr}$$

Specific fuel consumption = $\frac{f.c}{power}$

$$\text{b.s.f.c} = \frac{m^{\circ} f}{B.power\ (kw)}$$

$$\text{i.s.f.c} = \frac{m^{\cdot} f\ (\frac{kg}{hr})}{i.power\ (kw)} = \frac{kg}{kw\ .hr}$$

$$\frac{\frac{B.P}{m^{\cdot} * QH.v}}{\frac{I.P}{m^{\cdot} f * QH.v}} = \frac{B.P}{I.P} = \eta_m$$

$$m^{\circ} f = \frac{mass}{time}, \frac{kg}{sec}, \frac{kg}{hr}$$

Example : A four cylinder , two stroke cycle diesel engine with (10.9 cm) bore and (12.6 cm) stroke produces (88 kw) of brake power at (2000 r.p.m) compression ratio is (rc = 18 : 1) calculate :

1- Engine displacement (cm^3. L)

2- Brake mean effective pressure (kpa)

3- Torque (*N.M*)

4- Clearance volume of one cylinder (cm^3)

Solution :

1) $\boldsymbol{Vs = A * L}$

$$Vs = \frac{\pi}{4}\, d^2 * S$$

$$Vs = \frac{3.14}{4} * (10.9)^2 * 12.6$$

***Vs* = 1175 cm^3**

***Vs* = 1.175 liter**

2) $\boldsymbol{B.p = \frac{bmep * A * S * N * Z}{60 * n}}$

$$88 = \frac{bmep * 4 * 2000 * \frac{\pi}{4} * (0.109)^2 * 0.126}{60 * 1}$$

Bmep = 5280 / 9.5 = 555.8 kpa

3) $\boldsymbol{B.p = \frac{2\pi NT}{60}}$

$$88 = \frac{2 * 3.14 * 2000 * T}{60}$$

T = 5280000 / 12560

T = 420.4 *N.M*

4) CR = 1 + Vd / Vc

18 = 1 + 1175 / Vc

Vc = 1175 / 17

Vc = 69.18 cm^3

Example : A 4 cylinder , 2.4 liter engine operates on a four stroke cycle at (3200 r.p.m) the compression ratio is (9.4 : 1) the connect rod length (r = 18 cm) and the bore and stroke are related as (S = 1.06 B) calculate :

1- Clearance volume of on cylinder in cm^3 , L and in^3

2- Bore and stroke in cm and in

3- volume flow rate of the engine

4- Average piston speed in m / sec and ft / sec

Solution :

1) $Ec = Vd * Z$

Vd = E.C / Z

Vd = 0.0024 / 4

Vd = 0.0006 m^3

CR = 1 + Vd / Vc

9.4 = 1 + 0.0006 / Vc

8.4 = 0.0006 / Vc

Vc = 0.00007143 m^3

Vc = 71.43 cm^3 ($1\ m^3 = 1000000\ cm^3$)

Vc = 0.071 liter ($1\ m^3 = 1000\ liter$)

Vc = 4.36 in^3 (1 in^3 = 16.39 cm^3)

2) $\boldsymbol{Vs = A * L}$

$$Vs = \frac{\pi}{4}\, d^2 * S$$

$$0.0006 = \frac{3.14}{4} * \; B^2 * 1.06\,B$$

$$B^3 = \frac{0.0006}{0.8321}$$

***B* = 0.089 m**

***B* = 8.9 cm**

***B* = 3.5 in**

S = 1.06 * 0.089 = 0.094 m

S = 9.4 cm

3) $\boldsymbol{v^{\cdot} = \frac{z * N * A * L}{60 * n}}$

$$v^{\cdot} = \frac{4 * 3200 * \frac{\pi}{4} B^2 * S}{60 * 2}$$

v˙ = 0.062 $\boldsymbol{m^3/sec}$

4) Average piston speed = $\boldsymbol{\frac{2Ns}{60}}$

Average piston speed = $\frac{2 * 3000 * \frac{0.094}{100}}{60}$

Average piston speed = 0.094 m / sec

Example : A pickup truck has a V6 , 4 – stroke , SI engine operating at (2400 r.p.m).The piston speed is (7.5 m / s) and the compression ratio is (rc = 10.2 : 1) , b.m.e.p is (540 KN / m^2) and mechanical efficiency (ηm = 0.62) . If the bore and stroke relatives (S = 0.92 B) calculate :

1- Stroke length (cm)
2- Total displacement of the engine (liter)
3- Brake power (KW)
4- Indicate power (KW)
5- Clearance volume of one cylinder

Solution :

1) VP = 2NS / 60

$7.5 = \frac{2*2400*S}{60}$

S = 0.09375 m

S = 9.3 cm

S = 0.92 B

B = S / 0.92

B = 9.3 / 0.92

B = 10.1 cm

2) Vd = $\frac{\pi}{4} * B^2 * S$

Vd = $\frac{\pi}{4} * (10.1)^2 * 9.3$

Vd = 744.7 cm^3

Vd = 0.7447 liter

$Ec = Vd * Z$

Ec = 0.7447 * 6

Ec = 4.4682 liter

---

3) B.P = $\frac{b.m.e.p*S*A*N*Z}{n*60}$

B.P = $\frac{540*0.0045*2400}{60*2}$

B.P = 48.6 KW

4) ηm = B.P / I.P

I.P = 48.6 / 0.62

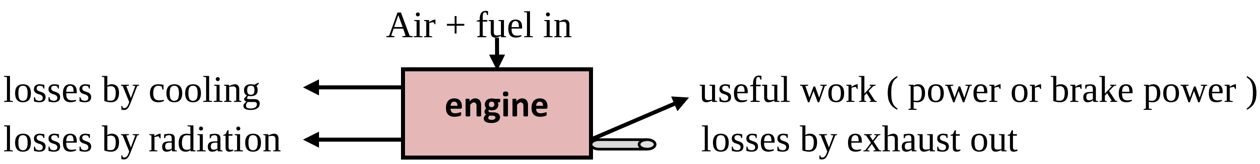
I.P = 78.3 KW

5) Cr = 1 + Vd / Vc

10.2 = 1 + 0.00074 / Vc

Vc = 0.000081 m^3

ENERGY BALANCE OR HEAT BALANCE OF THE ENGINE



1) Calculating total energy that enter the engine :

$Q^{\circ}_{total} = (m^{\circ}f \; \frac{kg}{hr}) * Q_{H.v} (\frac{kJ}{kg}) = \frac{kJ}{hr} \; , \frac{kJ}{min} \; , \frac{kJ}{sec}$ (KW)

2) Calculating the useful energy (Brake power) as :

$$B.p = \frac{2\pi NT}{60} \; or \; B.p = \frac{b.m.e.p * A * s * N * Z}{60 * n} = KW$$

3) Calculating the energy loss (energy dissipated) by cooling system as :

$Q^{\cdot}_{water} = m^{\cdot}_{w} * CPW * \Delta T$

$$m^{\circ} = mass\ flue\ rate(\frac{kg}{sec, min, hr})$$

CPW = specific heat

ΔT = (T out – T in)

4) Calculating the energy loss by exhaust gasses as :

$Q^{\circ}a = m^{\circ} * CPa * \Delta Ta \quad kw = \frac{kJ}{sec}$

---

5) Calculating the energy losses by radiation as :

$Q^{\circ}_{rad} = Q^{\circ}_{total} - (Q^{\circ}_{BP} + Q^{\circ}_{w} + Q^{\circ}_{a})$ BP = Br

As a percentage of the total energy

$\% QB = \frac{QBP}{Q \cdot total} * 100 \%$

$\% Q^{\circ}w = \frac{Q^{\circ}w}{Q^{\circ}total} * 100 \%$

$\% Q^{\circ}air = \frac{Q^{\circ}air}{Q^{\circ}total} * 100 \%$

$\% Q^{\circ}rad = 100 - (\% Q^{\circ}_{Bp} + \% Q^{\circ}_{w} + \% Q^{\circ}_{air})$

Air standard cycles

Air standard cycle assumptions :

1) The working fluid in the cylinder is treated as air (perfect gas)

2) We are dealing with closed system (m = constant)

3) The combustion process is replaced with a heat addition (Q_{add})

4) The exhaust process is replaced with a head rejection (D_{rej})

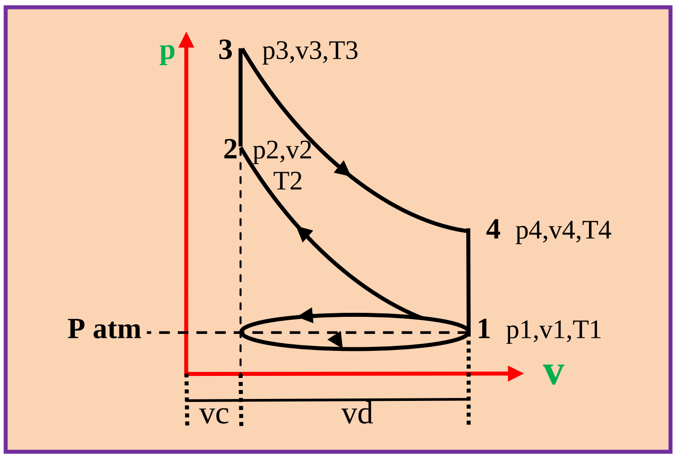
5) Specific heats are constant with temperature (cv.cp)

6) All process are reversible

1- otto cycle (constant volume cycle)

The idealized approximation of the spark ignition (S.I) engine is the air standard otto cycle .

Otto cycle is composed of four following process :



1) process 1-2 isentropic compression , the piston moves from B.D.C to T.D.C and the gas is compressed

Isentropically ($pv^{\gamma} = c$)

$$p_1 v_1^{\gamma} = p_2 v_2^{\gamma}$$

$\boldsymbol{\gamma} = \frac{cp}{cv}$ ➔ isentropic

$P_1V_1 = MRT_1$
$P_2V_2 = MRT_2$ } for one point

$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2}$ } for two point

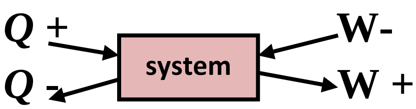
$$p_1 v_1^{\gamma} = p_2 v_2^{\gamma}$$

$$\frac{p_2}{p_1} = (\frac{v_1}{v_2})^{\gamma} = \frac{p_2}{p_1}(rc)^{\gamma} \rightarrow p_2 = p_1(rc)^{\gamma}$$

V_1 = V total

V_2 = VC

$$rc = \frac{v_{total}}{vc} = (\frac{v_1}{v_2})$$



$$W_{1\text{-}2} = \frac{p_1 v_1 - p_2 v_2}{\gamma - 1} = \frac{MRT_1 - MRT_2}{\gamma - 1} = \frac{mR(T_1 - T_2)}{\gamma - 1}$$

$Q_{1\text{-}2} = 0$

$T_2 = T_1(\frac{v_1}{v_2})^{\gamma - 1}$

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

2) Process 2-3 heat added at constant volume while the piston at T.D.C kept at rest

$V_2 = V_3$ = VC

W(2-3) = 0

Heat addition = $Q_{add2\text{-}3} = m * cv * (T_3 - T_2)$

Q_{add} = mf(mass of fuel) * $Q_{H.v} * \eta_c$

$Q_{H.v}$ = low heating volume

η_c = combustion efficiency

3) process 3-4 isentropic expansion the piston returns to B.D.C , gas expand isentropically

$(pv^{\gamma} = c)$, positive (W. D) is taken from the gas .

$P_3V_3^{\gamma} = P_4V_4^{\gamma}$, $TV^{\gamma-1} = C$

(V3 = V2) , (V4 = V1)

$p_4 = p_3(\frac{v_3}{v_4})^{\gamma} = p_3(\frac{v_2}{v_1})^{\gamma} = p_2(\frac{1}{rc})^{\gamma}$

$T_4 = T_3(\frac{1}{rc})^{\gamma-1}$

$Q_{3\text{-}4} = 0$

$W_{(3\text{-}4)} = \frac{p_3v_3 - p_4v_4}{\gamma-1} = \frac{MR(T_3-T_4)}{\gamma-1}$

R = specific gas constant
R_o = G = universal gas constant

$8.314\frac{KJ}{Kg.Kmol.K}$

R = CP – CV

$\gamma = \frac{CP}{CV}$

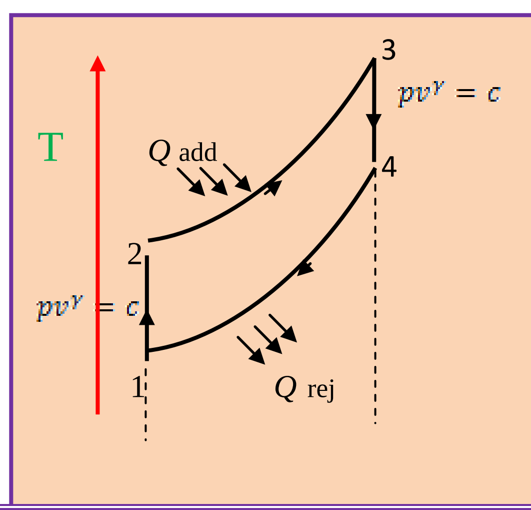
4) process 4-1 , heat is rejected at constant volume until the initial condition is attained while the piston is kept at rest

$V_4 = V_1$, $\frac{P}{T} = C$

$\frac{P_4V_4}{T_4} = \frac{P_1V_1}{T_1}$

$\frac{P_4}{T_4} = \frac{P_1}{T_1}$

$W_{(4\text{-}1)} = 0$



$Q_{rej\ 4\text{-}1} = mcv\ (T_1 - T_2)$

$S_1 = S_2$ $S_3 = S_4$ S

T – S diagram of otto cycle

The efficiency of otto cycle

$$\eta_{otto} = \frac{W\ net}{Q\ add} = \frac{Q\ add - Q\ rej}{Q\ add}$$

$$\eta\ otto = 1 - \frac{Q\ rej}{Q\ add}$$

$Q_{\ add} = mcv\ (T_3 - T_2)$

$Q_{\ rej} = mcv\ (T_4 - T_1)$

$$\eta_{otto} = 1 - \frac{\cancel{mcv}\ (T_4 - T_1)}{\cancel{mcv}\ (T_3 - T_2)}$$

$$\eta_{otto} = 1 - \frac{(T_4 - T_1)}{T_3 - T_2}$$

$$\eta\ otto = 1 - \frac{T1\ (\frac{T4}{T1} - 1)}{T2\ (\frac{T3}{T2} - 1)}$$

since the process 1-2 and 3-4 are isentropic ($TV^{\gamma-1} = C$)

$\frac{T_1}{T_2} = (\frac{V_2}{V_1})^{\gamma-1}\ and\ \frac{T_4}{T_3} = (\frac{V_3}{V_4})^{\gamma-1}$, because $V_1 = V_4$ and $V_2 = V_3$

$$\therefore \frac{T_1}{T_2} = \frac{T_4}{T_3} \rightarrow \frac{T_3}{T_2} = \frac{T_4}{T_1}$$

$$\therefore \eta_{otto} = 1 - \frac{T_1[T_4(T_1 - 1)]}{T_2[T_3(T_2 - 1)]}$$

η otto = $1 - \frac{T_1}{T_2}$

$\frac{T_1}{T_2} = (\frac{V_2}{V_1})^{\gamma-1}$

ηotto = 1- $(\frac{1}{rc})^{\gamma-1}$

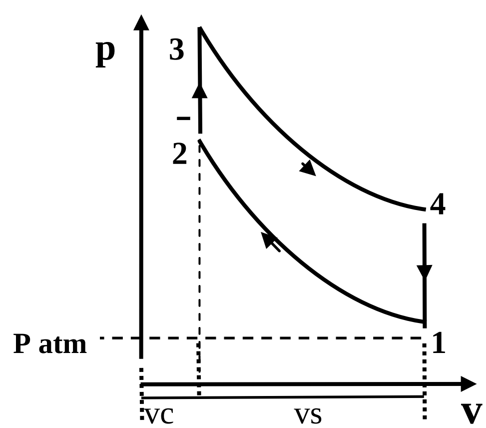
Example : In otto air standard cycle has compression ratio of (8 : 1) , at the start of compression process the temperature is (300 K) and pressure is 1 bar . Heat is supplied at a rate of (1350 KJ / Kg of air) . **Determine :**

1- Thermal efficiency
2- Net work
3- Pressure and temperature at each point in the cycle .
[take cp = 1.005 KJ / Kg . K , cv = 0.714 KJ / Kg . K]

Solution :

1- ηotto = $\frac{Q\,add - Q\,rej}{Q\,add}$ ➔ (1)

or ηotto = 1- $(\frac{1}{rc})^{\gamma-1}$



$$\gamma = \frac{CP}{CV} = \frac{1.005\frac{KJ}{Kg.K}}{0.714\frac{KJ}{Kg.K}} = 1.4$$

η otto = 1- $(\frac{1}{rc})^{1.4-1}$

ηotto = 1- $(\frac{1}{8})^{1.4-1}$

ηotto = 0.564 * 100 **= 56.4 %**

2- from equ. (1)

$$0.564 = \frac{1350 - Qrej}{1350}$$

Q_{rej} = 588.5 KJ / Kg of air

*** Q_{add} – Q_{rej} = net work**

$\eta_{otto} = \frac{Net\ work}{Qadd}$ → $0.564 = \frac{Net\ work}{1350\ KJ/Kg}$

Net work = 7614.4 KJ / Kg

3- At Point 1 :

T_1 = 300 K

P_1 = 1 bar

Point 2 :

Process 1-2 isentropic

$p_2 = p_1 (\ rc\ )^{\gamma}$

P_2 = 1 bar $(\ 8\ )^{1.4}$

P_2 = 18.38 bar

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

$T_2 = 300\ (\ 8\ )^{1.4-1}$

T_2 = 689.2 K

Point 3 :

Process 2-3 constant volume { W = 0 }

Q_{add} = 1350 KJ / Kg of air

Q_{add} = mcv (T_3 – T_2)

* For 1Kg (m = 1)

$Q_{add} = cv\ (T_3 - T_2)$

$1350 = 0.714 * (T_3 - 689.2)$

$T_3 = 2577.3$ K

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

$\frac{18.36}{689.2} = \frac{P3}{2577.3}$ ➔ **$P_3 = 68.73$ bar**

Point 4 :

Process 3-4 isentropic ($P_a V_a^{\gamma} = P_b V_b^{\gamma}$)

$$P_3 V_3^{\gamma} = P_4 V_4^{\gamma}$$

$$P_4 = P_3 (\frac{V_3}{V_4})^{\gamma} \quad \{ V_3 = V_2 \ , \ V_4 = V_1 \}$$

$$P_4 = 68.73\ (\frac{1}{rc})^{\gamma}$$

$$P_4 = 68.73\ (\frac{1}{8})^{1.4}$$

$P_4 = 3.74$ bar

$$T_3 V_3^{\gamma-1} = T_4 V_4^{\gamma-1}$$

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

$$T_4 = T_3\ (\frac{1}{rc})^{\gamma-1}$$

$$T_4 = 25.773\ (\frac{1}{8})^{1.4-1}$$

$T_4 = 1121.8$ K

2- Diesel cycle (constant pressure cycle)

The air standard diesel is the ideal approximate of the compression ignition engine.

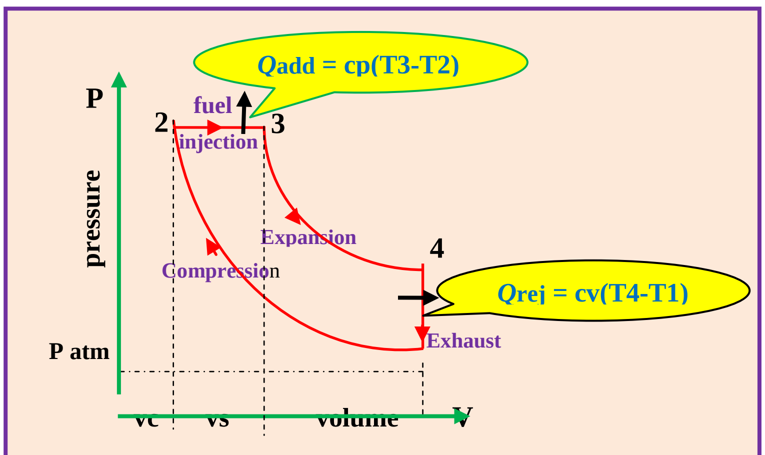
1) process 1-2 isentropic process (compression)

$p1v1^{\gamma} = p2v2^{\gamma}$ ➔ $P_2 = P_1(\frac{v_1}{v_2})^{\gamma}$

$T_2 = T_1(\frac{v1}{v2})^{\gamma}$

$W_{1-2} = \frac{p_1v_1 - p_2v_2}{\gamma - 1}$

$Q_{1-2} = 0$

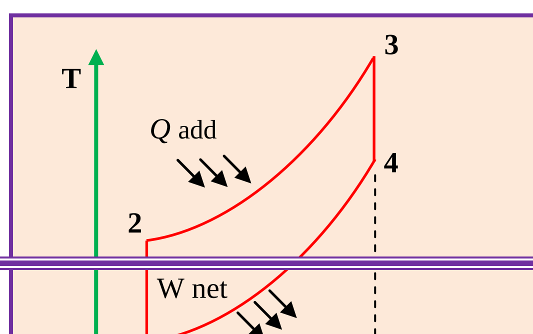


P – V diagram of the cut off volume

2) process 2-3 heat added at constant pressure while the piston is moving (the volume is increasing from $V_2 - V_3$ Diesel cycle .

The volume V_3 is called (cut off volume) and point 3 is called (cut off volume) therefore cut off volume is defined as the volume at which the heat addition is stopped $P_2 = P_3$ ➔ p = constant $\frac{P_2V_2}{T_2} = \frac{P_3V_3}{T_3}$

$\frac{V_2}{T_2} = \frac{V_3}{T_3}$ ➔ $\frac{T_3}{T_2} = \frac{V_3}{V_2}$



$\frac{V_3}{V_2} = cut\ off\ ratio$

Cut off ratio = r off = $\mathcal{P} = \frac{V_3}{V_2} = \frac{T_3}{T_2}$

Heat added = $Q_{2\text{-}3} = m * cp * T_3 - T_2$

$Q_{2\text{-}3} = m * Q_{H.v} * \eta_c$

$W_{2\text{-}3} = \int_{v2}^{v3} p.dv = p * (v_3 - v_2)$

Cut off ratio (r off) : is the ratio between cut off volume to the minimum volume in the cycle (r off = $\frac{V_3}{V_2}$)

---

3) process 3-4 isentropic expansion the ratio of the maximum volume to the cut off volume is called expansion ratio (re)and equal re = $\frac{V_4}{V_3}$, $V_4 = V_1$

4) process 4-1 constant volume process $Q_{rej} = m\ cv\ (T_4 - T_1)$

Dividing compression ratio to cut off ratio

$$\frac{rc}{r\ off} = \frac{\frac{v1}{v2}}{\frac{v3}{v2}} = \frac{v_1}{v_2} * \frac{v_2}{v_3} = \frac{v_1}{v_3}\ , v_4 = v_1$$

$$\therefore\ \frac{rc}{r\ off}\ \frac{v_4}{v_3} = re$$

$$re = \frac{rc}{r\ off}$$

$$\eta_{th\ diesel} = \frac{rc}{Q\ add}$$

$$\eta_{th\ diesel} = \frac{w\ net}{q\ add}$$

$$w = \frac{KJ}{Kg} = \frac{p_1 v_1 - p_2 v_2}{\gamma - 1}$$

$$\frac{Q\ add - Q\ rej}{Q\ add} = 1 - \frac{Q\ rej}{Q\ add}$$

$Q_{rej} = mcv\,(T_4 - T_1)$

$Q_{add} = mcp\,(T_3 - T_2)$

$$\therefore Diesel = 1 - \frac{mcv\,(T_4 - T_1)}{mcp\,(T_3 - T_2)}$$

$$\eta_{Diesel} = 1 - \frac{(T_4 - T_1)}{\gamma(T_3 - T_2)}$$

1) from isentropic process 1-2

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = (rc)^{\gamma-1}$$

$$\therefore \boldsymbol{T_2 = T_1 (rc)^{\gamma-1}}$$

---

2) from process 2-3 (p = constant)

$$\frac{T_3}{T_2} = \frac{V_3}{V_2} = r\,off$$

$$\frac{T_3}{T_2} = r\,off$$

$$\therefore \boldsymbol{T_3 = T_2 * r\,off}$$

3) from process 3-4

$$\frac{T_3}{T_4} = \left(\frac{v_4}{v_3}\right)^{\gamma-1}$$

$$T_3 = T_4\,(re)^{\gamma-1}$$

$$T_4 = \frac{T_3}{(re)^{\gamma-1}} = \frac{T_1 (rc)^{\gamma-1} * r\,off}{(re)^{\gamma-1}}$$

$$rc = re * r\,off$$

$$\therefore T_4 = \frac{T_1\,(re)^{\gamma-1}}{re^{\gamma-1}} = T_1\, r\,off^{\gamma}$$

η

$$\text{Diesel} = 1 - \frac{(T_1 * roff^{\gamma} - T_1)}{\gamma(T_1 * rc^{\gamma-1} * roff - T_1 rc^{\gamma-1})}$$

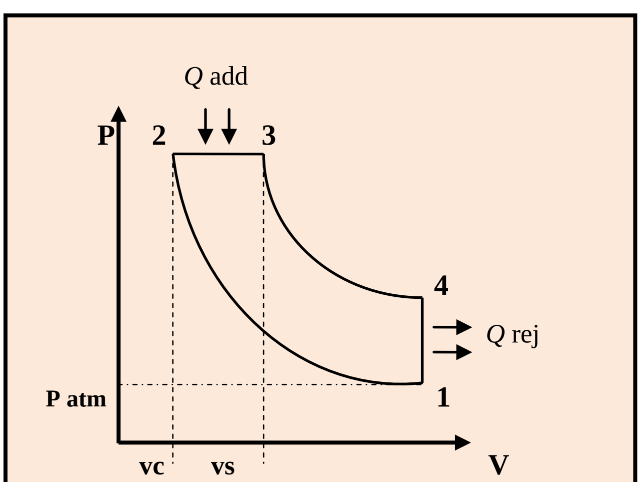
$$\eta_{Diesel} = 1 - \frac{\cancel{T_1}(roff^{\gamma} - 1)}{\gamma \cancel{T_1} rc^{\gamma-1}(roff - 1)}$$

$$\boldsymbol{\eta_{Diesel} = 1 - \frac{1}{rc^{\gamma-1}} - \frac{roff^{\gamma} - 1}{\gamma(roff - 1)}}$$

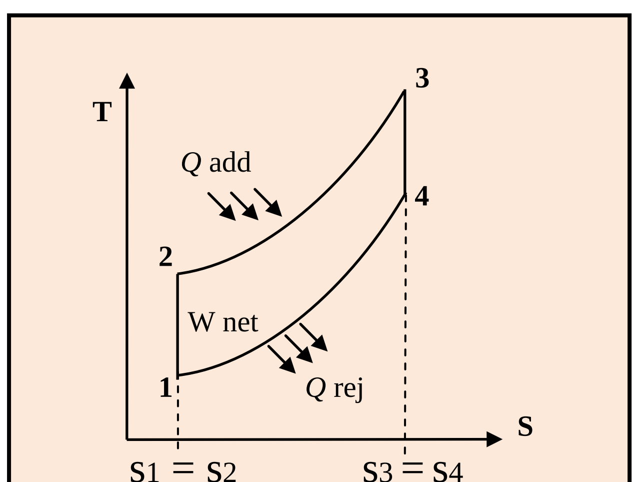
Example : An constant pressure heat addition air standard cycle of a (CR = 11) heat is added at the rate off (1500 KJ/Kg) and the atmospheric conditions are (1 bar) and (35 ℃) . Show the cycle on both P-V and T-S diagram and **calculation :**

1- The temperature and pressure at each point in the cycle .
2- The thermal efficiency .
3- The mean effective pressure .
[take CP = 1.005 KJ / Kg K **,** CV = 0.714 KJ / Kg . K **]**

Solution :



P – V diagram of the cut off volume



T – S diagram of diesel cycle

$$\gamma = \frac{CP}{CV} = \frac{1.005\ \frac{KJ}{Kg.K}}{0.714\ \frac{KJ}{Kg.K}} = \mathbf{1.4}$$

$$P_2 = P_1\ (\frac{V_1}{V_2})^{\gamma} = P_1(rc)^{\gamma} = 100 * (\ 17\ )^{1.4} = 5279.9\ Kpa = \mathbf{52.8\ bar}$$

Pressure is constant **$P_2 = P_3 = 52.8$ bar**

$$T_2 = T_1(rc)^{\gamma-1} = 308 * (\ 17\ )^{0.4} = 956.6\ K = T2$$

At (2-3) process pressure is constant

$$\therefore P_2 = P_3$$

Q add = cp (T3-T2)

1500 = 1.005 (T_3 - 956.6)

T_3 = 2449.14 K

$$P_1V_1 = RT_1 = V_1 = \frac{RT_1}{P_1} = \frac{0.287*308}{100} = \mathbf{0.8839\ m^3} \ / \ \mathbf{Kg}$$

$$rc = \frac{V_1}{V_2} = V_2 = \frac{V_1}{rc} = \frac{0.8839}{17} = \mathbf{0.0519\ m^3/kg}$$

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

$$V_3 = V_2 * \frac{T_3}{T_2} = 0.0519 * \frac{244913}{956.6}$$

V_3 = 0.133 m^3/kg

$$P_4 = 5279.9 * (\frac{0.133}{0.8839})^{1.4} = 368.5\ kpa = 3.68\ bar$$

$$T_4 = T_3 \left(\frac{V_3}{V_4}\right)^{\gamma-1} = 2449.13 * \left(\frac{0.132}{0.8839}\right)^{0.4} = 1144.67\ K$$

Wnet = W2-3 + W 3-4 – W1-2

$W_{2\text{-}3} = P(V_3 – V_2) = 52.8 * (0.132 – 0.0519)$ **= 422.9 KJ/Kg**

$$W_{3\text{-}4} = \frac{R(T_3-T_4)}{\gamma-1} = \frac{0.287(2449.13-1144.67)}{1.4-1} = 935.9\ \text{KJ/Kg}$$

$$W_{1\text{-}2} = \frac{R(T_1-T_2)}{\gamma-1} = \frac{0.286(308-956.6)}{0.4} = -465.4\ \text{KJ/Kg}$$

$W_{net} = 422.9 + 935.9 – 465.4$ **= 893.4 KJ/Kg**

$$\eta_{Th\ otto} = \frac{Wnet}{q\ in} = \frac{893.4}{1500} = 0.5956 = 59.5\ \%$$

$$m.e.p = \frac{Wnet}{\Delta V} = \frac{893.4}{V1-V2} = \frac{893.4 * 10^{-2}}{0.8839-0.0519} = 10.73$$

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Q1 / solution :

n = 2 , Z = 4 , N = 300 r.p.m , $\dot{m} = 60\ g/sec$, $Q_{H.v}$ = 44 MJ/Kg ,
A/F = 14.6 : 1 , η_m = 0.85 , B = 87.5 mm , S = 92 mm , BP = 65 kw

1- Volumetric efficiency : $\eta_{vol} = \frac{\dot{m}\ actual}{\dot{m}\ theory}$

$$\dot{m} = 60\ \frac{g}{sec}$$

$\dot{m}_{theory} = \frac{pa*Vd*Z*N}{60*n}$ and at the atmospheric standard conditions

T = 25 + 273 = 298 K , P = 1.01325 bar , R = 0.287 K

$$\therefore pa = \frac{pa}{Ra * Ta}$$

$$pa = \frac{(1.01325 * 10^2)KN/m^2}{0.287\frac{KJ}{Kg.k} * 298\ K} = 1.184\ \frac{Kg}{m^3}$$

$$Vd = \frac{\pi}{4} * B^2 * S = \frac{\pi}{4}\left(\frac{87.5}{1000}\right)^2 * \left(\frac{92}{1000}\right) = 0.000553\ m^3$$

$$\therefore\ m^{\cdot}a_{\text{theory}} = \frac{1.084\ Kg/m^3 * 0.000553\ m^3 * 4 * 3000}{2*60} = \mathbf{0.06546\ Kg/sec}$$

$$\text{And}\ \eta vol. = \frac{m^{\cdot}a\ actual}{m^{\cdot}a\ theory} = \frac{\left(60\frac{g}{sec}\right)*\frac{1kg}{1000\,g}}{0.06546\frac{kg}{sec}} = 0.916 = 91.6\ \%$$

2- $\eta bth = \frac{BP}{m^{\cdot}f * QH.v}$, $BP = 65\ kw$, QH.V = 44 MJ/Kg = 44000 KJ/Kg

$$\frac{A}{F} = \frac{m^{\cdot}a}{m^{\cdot}f} \rightarrow 14.6 = \frac{\left(60\frac{g}{sec}\right)*\frac{1Kg}{1000g}}{m^{\cdot}f} \rightarrow m^{\cdot}f = 0.00411\frac{Kg}{sec}$$

$$\therefore \eta bth = \frac{65\ kw}{0.00411\frac{kg}{sec}*44000\frac{KJ}{Kg}} = 0.3594 = 35.94\ \%$$

3- $B.P = \frac{2\pi NT}{60} \rightarrow T = \frac{BP*60}{2\pi N} \rightarrow T = \frac{65*60}{2\pi*3000} = 0.207\ KN.m\ or\ 207\ N.m$

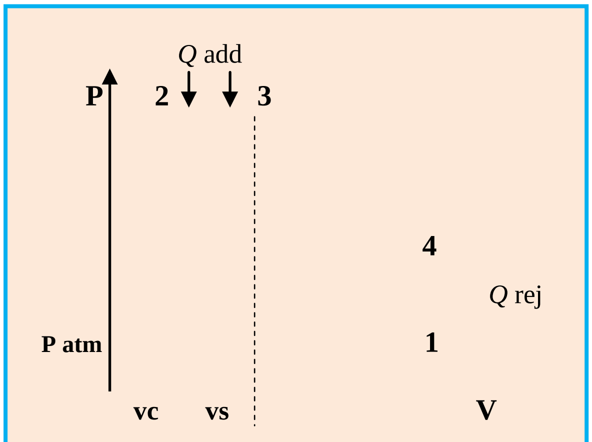
4- $\eta m = \frac{B.P}{I.P} \rightarrow 0.85 = \frac{65\ Kw}{I.P} \rightarrow I.P = \frac{65\ Kw}{0.85} = 76.47\ Kw$

5- $b.s.f.c = \frac{F.c}{B.P} = \frac{m^{\cdot}f\left(\frac{kg}{hr}\right)}{B.P\ kw} = \frac{0.00411\frac{kg}{sec * \frac{3600\ sec}{1\ hr}}}{65\ kw} = 0.227\ \frac{Kg}{Kw.hr}$

Q2 / solution :

$P_1 = 98.5 KN/m^2$, T = 60 + 273 = 333 K , Pmax = $P_2 = P_3 = 4.5 * 10^3\ KN/m^2$

(diesel cycle) , qadd = 580 KJ/Kg , T at the end of compression = T2 = 619 + 273 = 892 K , and R = 0.287 KJ/Kg.K



P – V diagram of the cut off volume

1- *compression ratio* $= rc = \frac{V1}{V2} = \frac{v1}{v2}$

$\therefore$ from $P_1 V_1 = mRT1$

$$v_1 = \frac{RT1}{P_1} = \frac{0.287\frac{KJ}{Kg.K}*333K}{98.5\frac{KN}{m^2}} = 0.97\frac{m^3}{Kg}$$

And $v_2 = \frac{RT2}{P_2} = \frac{0.287*892}{4.5*10^3} = 0.0569\ \frac{m^3}{Kg}$

$\therefore rc = \frac{v_1}{v_2} = \frac{0.97\ m^3/Kg}{0.0569\ m^3/Kg} = 17$

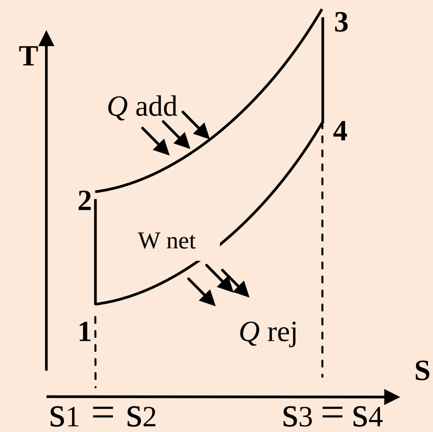
2- *specific heat ratio* $= \frac{CP}{CV} = \gamma$

from $P_1 V_1^{\gamma} = P_2 V_2^{\gamma}$

$\frac{P_2}{P_1} = (\frac{V_1}{V_2})^{\gamma}$ ➔ $\frac{P_2}{P_1} = (rc)^{\gamma} = \frac{4500\ KN/m^2}{98.5\ KN/m^2} = (\ 17\ )^{\gamma}$

Taken (Ln) for both sides yield :

Ln (45.68) = γ ln (17) ➔ $\gamma = \frac{\ln(45.68)}{\ln(17)} = \frac{3.82}{2.833} = 1.348$



T – S diagram of diesel cycle

3- Net work = W1-2 + W2-3 + W3-4

W1-2 = $\frac{P1V1^{\gamma} - P2V2^{\gamma}}{\gamma - 1} = \frac{(98.5*0.97) - (4500*0.0569)}{1.348 - 1} = -461.22$ KJ/Kg

$R = CP - CV$ …. a

$\gamma = \frac{CP}{CV}$ ➔ $CP = \gamma * CV$ ➔ $CP = 1.348 * CV$ …. b sub. in a

$R = 1.348 - CV$ ➔ 0.348 = 1.348 – CV ➔ CV = 0.824 sub. in b ➔ CP = 1.348 * 0.824 = 1.11 $\frac{KJ}{Kg.K}$

W1-2 = P * ($v_3 - v_2$) , qadd = 1Kg * CP KJ/Kg.K * (T3 – T2) K

$q$add $= 580\ \frac{KJ}{Kg} = 1.11 * (T3 - 892)$ ➔ T3 = 1414 K

$\frac{v_2}{T2} = \frac{v_3}{T3}$ ➔ $\frac{v_3}{v_2} = \frac{T3}{T2} = roff = \frac{1414}{892} = 1.585$

$\therefore v_3 = v_2 * roff = 0.0569 * 1.585 = 0.0902\ m^3/Kg$

$\therefore W$2-3 = $4500\ KN/m^2 * (0.0902 - 0.0569) = 150\ KJ/Kg$

W3-4 = $\frac{P_3 V_3 - P_4 V_4}{\gamma - 1} = \frac{(4500*0.0902) - (183*0.97)}{1.348 - 1} = \frac{656KJ}{Kg}$, $\therefore W$net $= -461.22 + 150 + 656 = 344.82\ \frac{KJ}{KG}$

4- η th = $\frac{Wnet}{Qadd} = \frac{344.82\ KJ/Kg}{580\ KJ/Kg} = 0.594 = 59.4\ \%$

Home works :

1/ A constriction vehicle has a diesel engine with weight of (13.5 cm) bore and (20 cm) stroke operating on a four stroke cycle . It delivers (114 kw) as a brake power at (1000 r.p.m) with mechanical efficiency of (60%) and fuel consumption of (14 kg / hr) . **calculate :**

1- Total engine displacement (engine capacity) (liter)

2- Brake mean effective pressure (KN / m^2)

3- Torque at 1000 r.p.m *(K.N.M)*

4- Indicated power (KW)

5- Indicated specific fuel consumption (Kg / Kw . hr)

2/ A 4 cylinder , two stroke diesel engine with (10 cm) bore and (11 cm) stroke produces (75 kw) of a brake power at (1500 r.p.m) compression ratio is (15) and mechanical efficiency is (90 %) **. calculate :**

1- B.m.e.b

2- Torque

3- Clearance volume of one cylinder

4- I.P and i.m.e.p

3/ A single-cylinder Air Standard Otto engine has a compression ratio of 8.5 and a peak temperature of 3500°F at ambient conditions of 80°F and one atmosphere . **Determine** the cycle efficiency, maximum cylinder pressure and mean effective pressure .

4/ A single-cylinder four-stroke-cycle spark-ignition engine operating at 3500 rpm has a brake mean effective pressure of 1800 kPa and a displacement of 400 cm^3 , Atmospheric conditions are 101kPa and 27°C .

(a) If the stroke is 6 cm, what is the bore ?

(b) What is the brake power ?

(c) If the mass air-fuel ratio is 16 and the fuel flow rate is 0.00065 kg/s, what is the volumetric efficiency ?

5/ A six-cylinder engine with a compression ratio of 11 runs at 3200 rpm and 80°F and 14.7 psia . Each cylinder has a bore of 3 inches, a stroke of 3.25 inches, and a volumetric efficiency of 0.85. Assume an Air Standard four-stroke Otto cycle with stoichiometric octane as fuel . Assume that the energy release from the fuel is equally divided between internal energy increase in cylinder gases and cylinder wall heat loss . **What** are the cylinder mean effective pressures and the engine horsepower and specific fuel consumption? Assume a heating value of 20,600 Btu/lbm

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6/ An Otto engine takes in an air-fuel mixture at 80°F and standard atmosphere pressure . It has acompression ratio of 8. Using Air Standard cycle analysis, a heating value of 20,425 Btu/lbm , and A/F = 15, **determine :**

(a) The temperature and pressure at the end of compression, after combustion , and at the end of the power stroke .

(b) The net work per pound of working fluid .

(c) The thermal efficiency.

7/ A single-cylinder four-stroke-cycle spark-ignition engine has a BSFC of 0.4 kg/kW-hr and a volumetric efficiency of 78% at a speed of 45 rps .The bore is 6 cm and the stroke is 8.5 cm . **What** is the fuel flow rate , fuel-air ratio , and brake torque if the brake power output is 6 kW with ambient conditions of 100 kPa and 22°C ?

Contents :-