UNIVERSITE PIERRE & MARIE CURIE
LA SCIENCE A PARIS

Introduction aux moteurs thermiques

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Université Pierre et Marie Curie

Turbines à Vapeur

250 MW à 2,5 GW
Centrales électriques
η = 30 à 40 %
machines lourdes

Turbines à gaz

Jusqu'à 1 MW
η = 20 à 30 %
machines légères 0,95 à 1,4 Kg/KW

Diesel stationnaire

Jusqu'à 35 MW
η = 50%
machines lourdes 12 à 50 Kg/KW

Diesel véhicule

η = 40%
Ferroviaire : 150 à 3000 KW
6 à 18 Kg/KW

Naval : 12 à 50 Kg/KW

Poids lourds, automobile : 75 à 400 KW
5 à 7 Kg/KW

Essence

1 à 500 KW
η = 30%
0,9 à 6 Kg/KW

Turbo-Réacteur

Jusqu'à 350 tonnes de poussée (200 MW)
η = 25%
Machines légères 0,05 Kg/KW

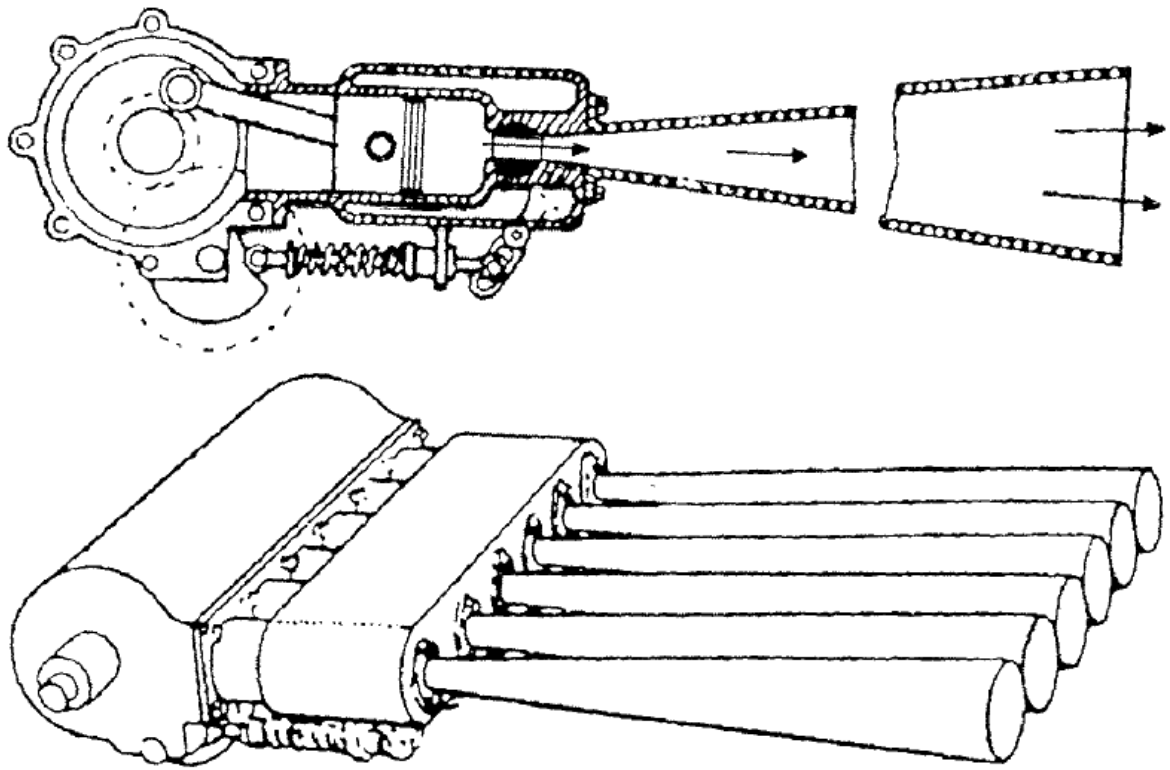
- Puissance utile.

$$P_v = (C_R M_v g + \tfrac{1}{2} \rho_a C_D A_v V_v^2) \cdot V_v$$

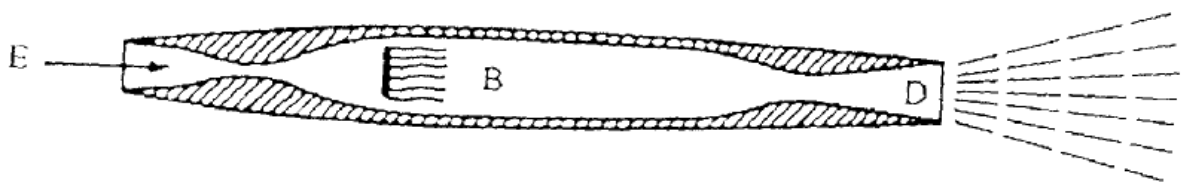
C_R = coefficient de roulement (0.012 - 0.015)
M_v = masse vehicule
g = accélération pesanteur
ρ_a = masse. Vol. air
C_D = coefficient de traînée (0.3 - 0.5)
A_v = aire frontale vehicule
V_v = vitesse vehicule

* 90 km/hr ~ 5-6 kW (7-8 HP) !

Architecture



Lodin's 1908

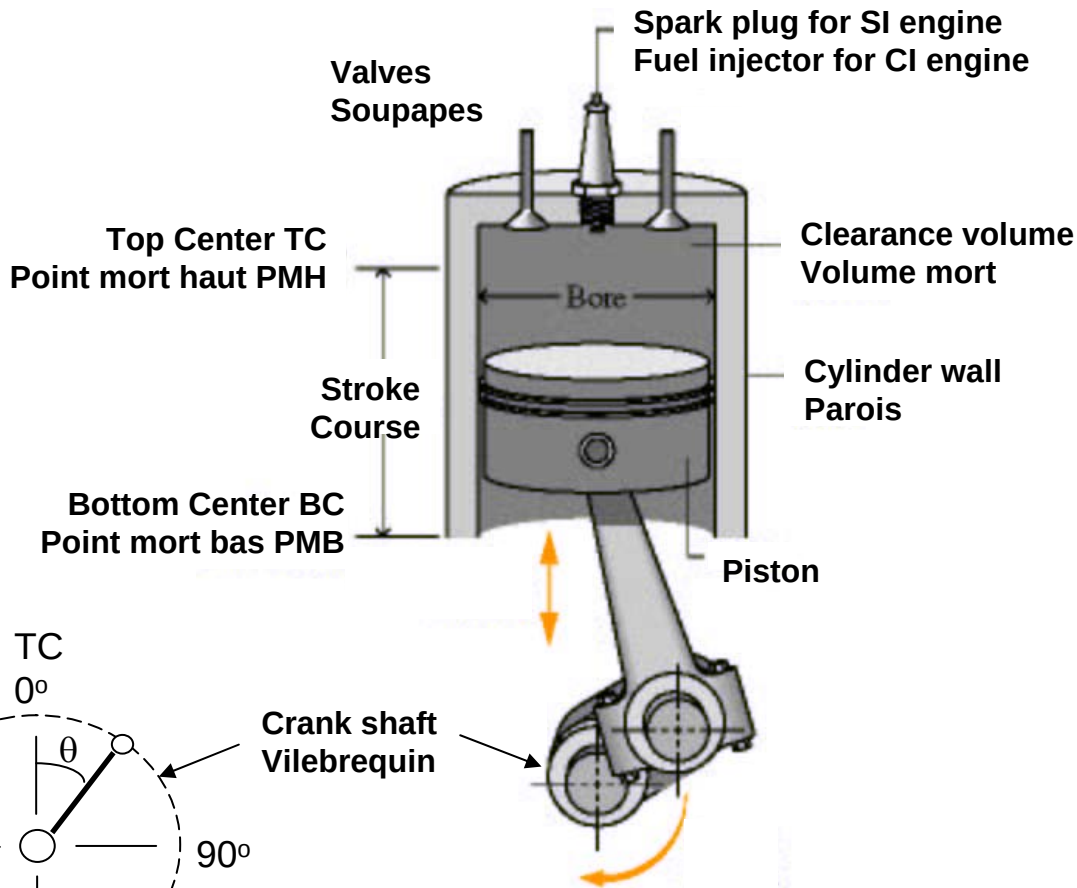


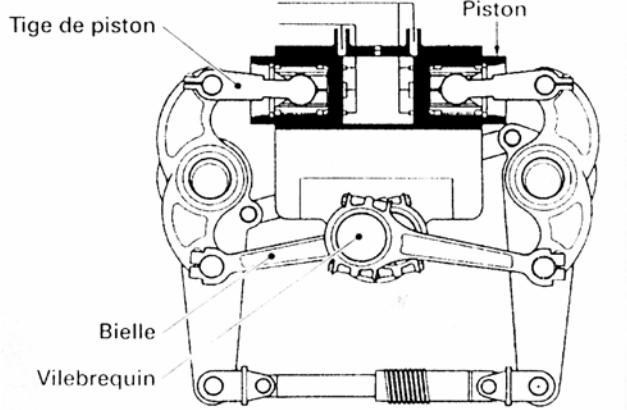
Lodin's 1913

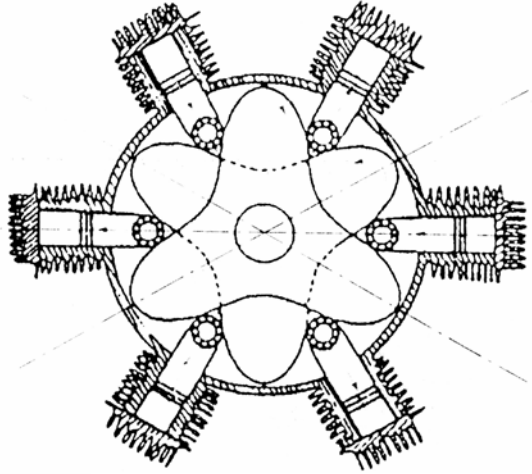
Système bielle-vilebrequin

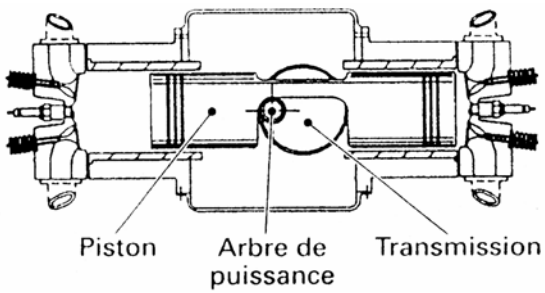
$$\text{time} = \frac{\text{crank angles}}{\text{crank speed}}$$

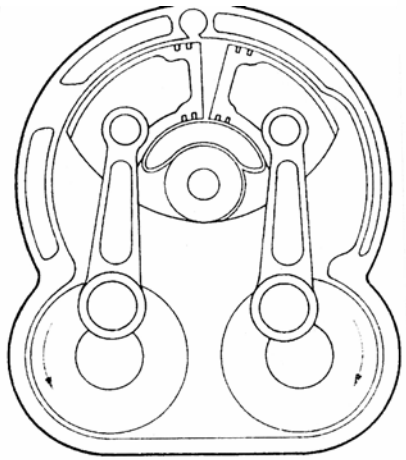
$$= CA \cdot \frac{s}{rev} \cdot \frac{1\,rev}{360\,CA}$$

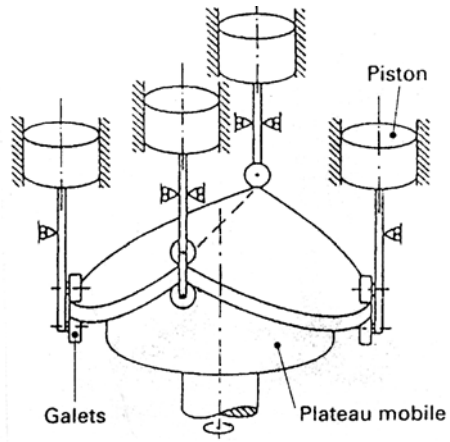


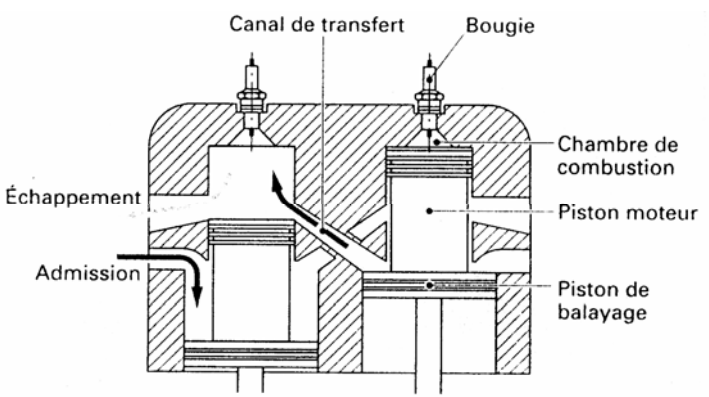

Tige de piston
Piston
Bielle
Vilebrequin

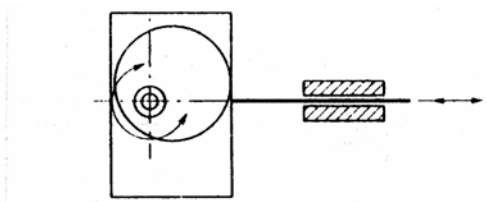


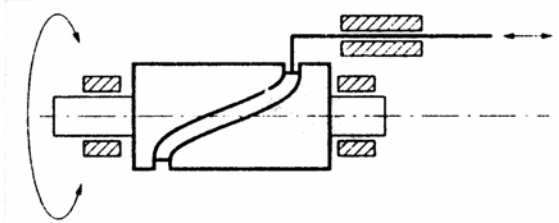

Piston
Arbre de puissance
Transmission

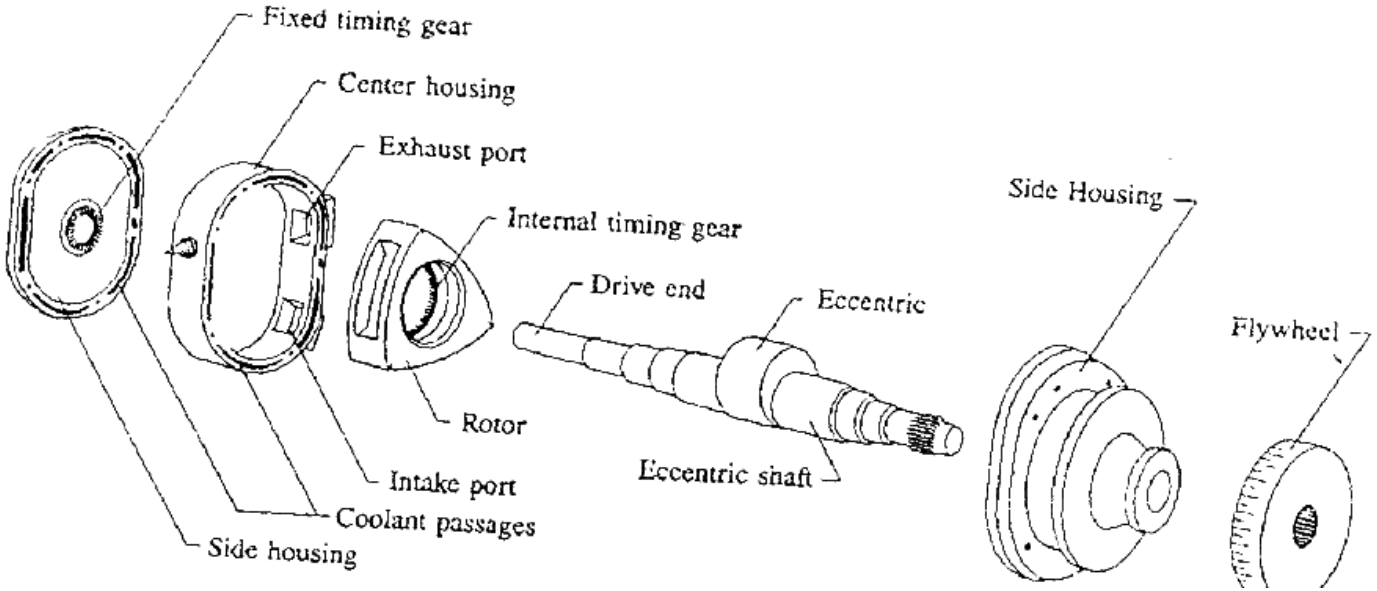


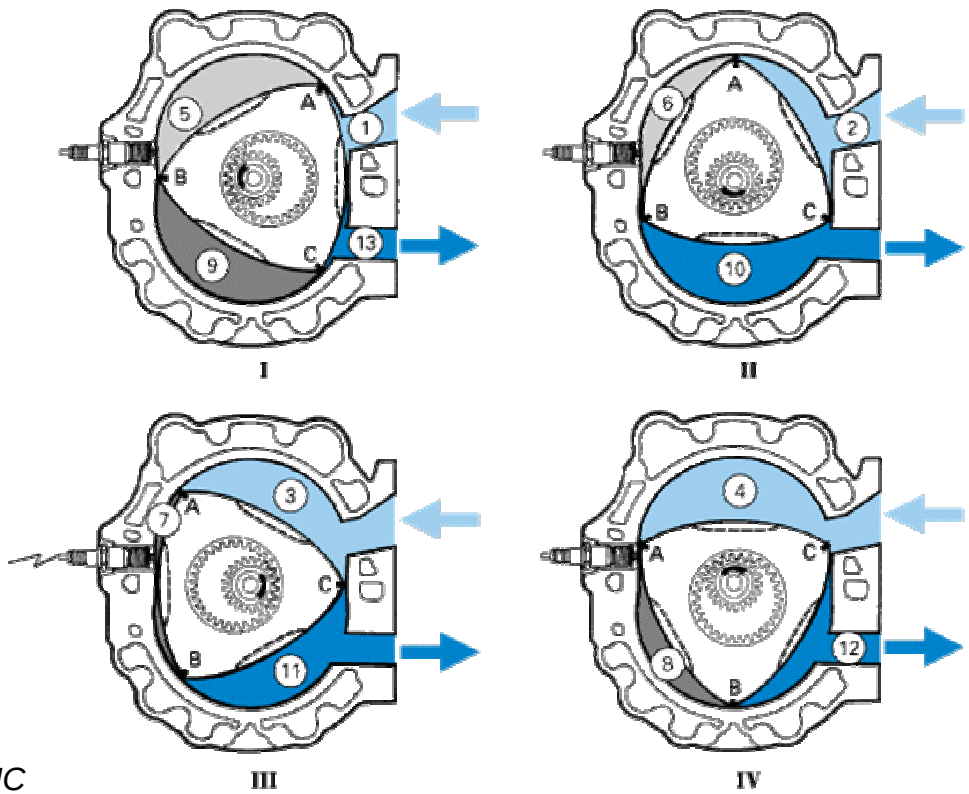

Piston
Galets
Plateau mobile

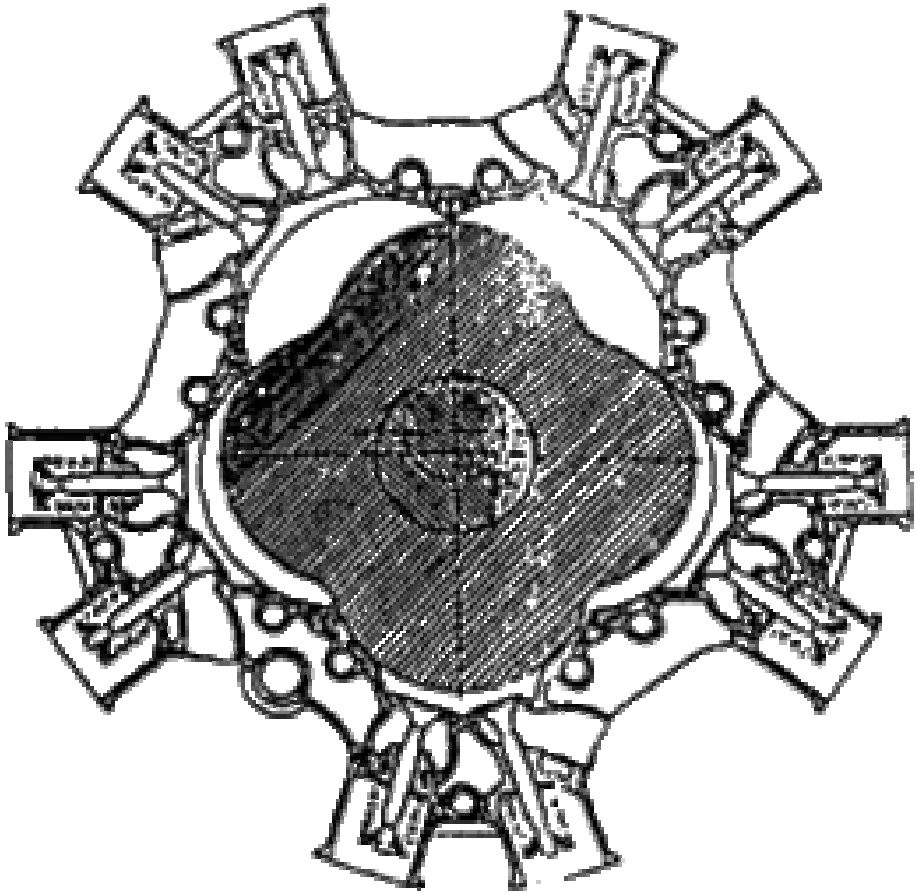

Canal de transfert
Bougie
Chambre de combustion
Échappement
Piston moteur
Admission
Piston de balayage

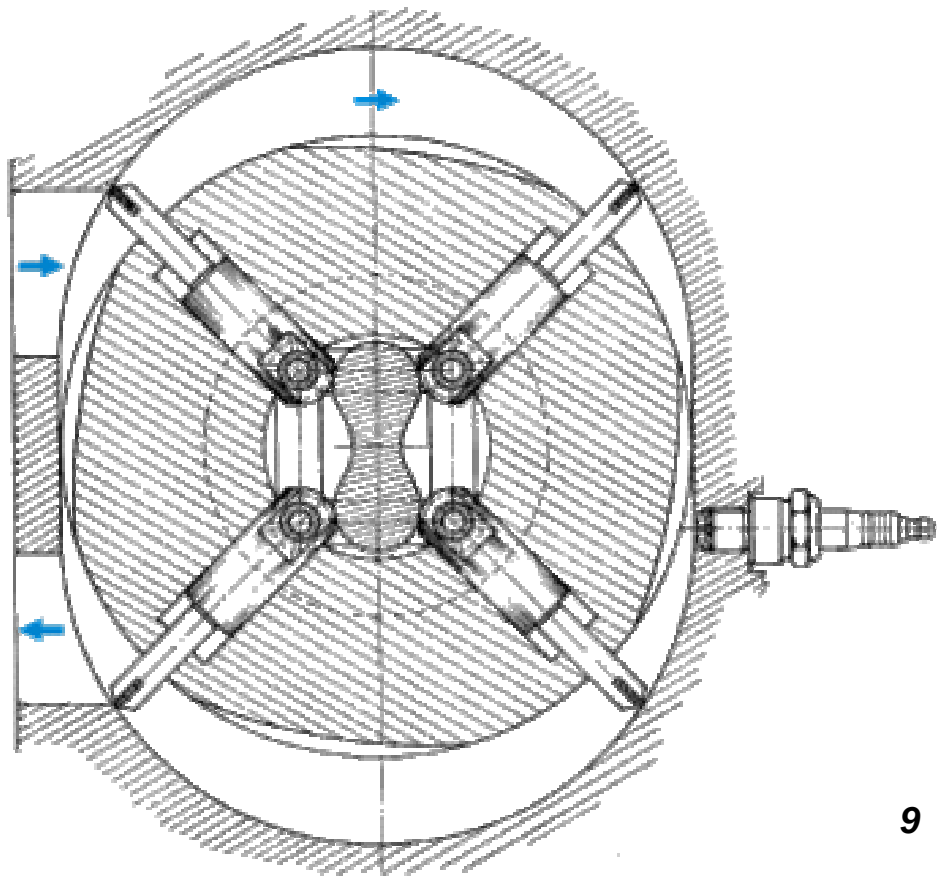




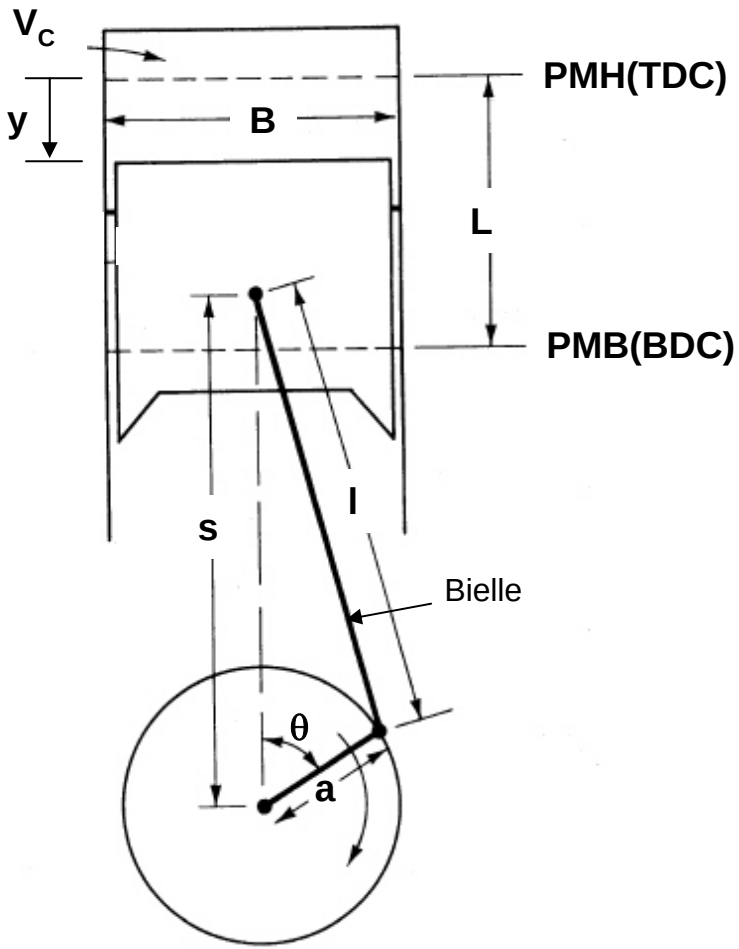

Fixed timing gear
Center housing
Exhaust port
Internal timing gear
Drive end
Eccentric
Side Housing
Flywheel
Rotor
Intake port
Eccentric shaft
Coolant passages
Side housing


I
II
III
IV





Système bielle-manivelle



Très souvent B ~ L

(“moteur carré”)

Elongation du piston : y = l + a - s

$$s = a\cos\theta + \left(l^2 - a^2\sin^2\theta\right)^{1/2}$$

Au point mort haut (*s*= *l*+*a*), le volume cylindre est minimum: volume mort V_c

En fonction du degré vilebrequin :

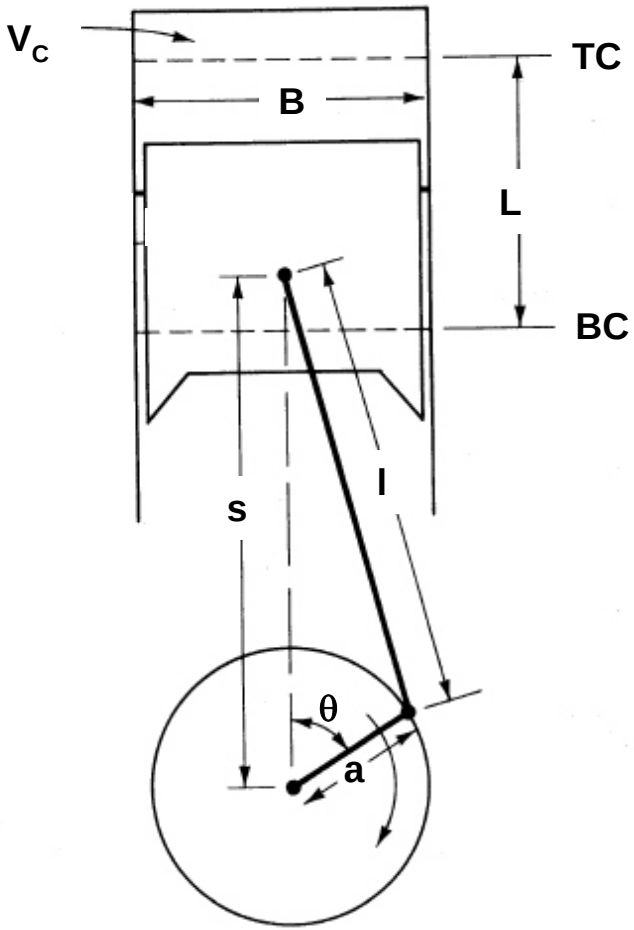
$$V = V_c + A_c y = V_c + \frac{\pi B^2}{4}(l + a - s)$$

Volume balayé ou cylindrée :

$$V_d = \frac{\pi B^2}{4} L$$

Rapport volumétrique:

$$r_c = \frac{V_{BC}}{V_{TC}} = \frac{V_c + V_d}{V_c}$$



$$s = a\cos\theta + \left(l^2 - a^2\sin^2\theta\right)^{1/2}$$

Vitesse moyenne et instantanée du piston:

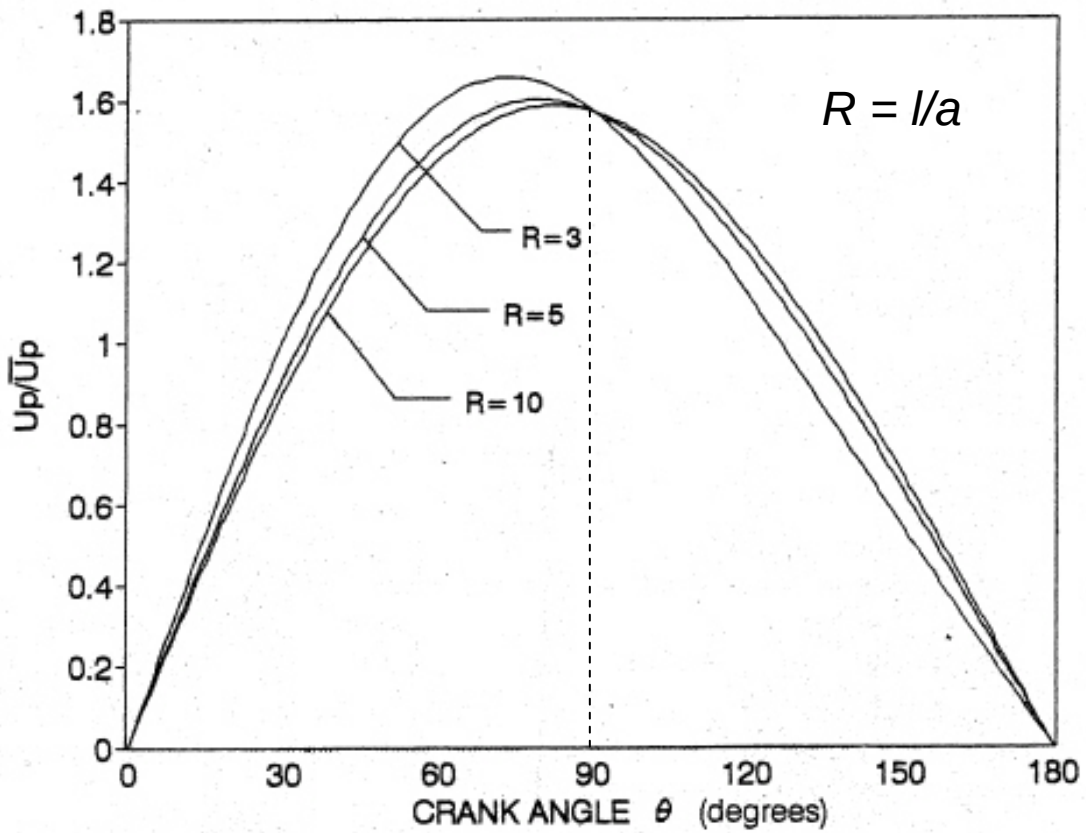
$$\overline{U}_p = 2LN$$

$$U_p = \frac{ds}{dt}$$

Avec N vitesse de rotation en tr/s

$$\frac{U_p}{\overline{U}_p} = \frac{\pi}{2}\sin\theta\left[1 + \frac{\cos\theta}{\left((l/a)^2 - \sin^2\theta\right)^{1/2}}\right]$$

Vitesse Piston – Rapport bielle/course



Acceleration

Elongation du Piston : $$s = a\cos\theta + l\left(1-\left(\frac{a}{l}\right)^2 \sin^2\theta\right)^{1/2}$$

Pour la plupart des moteurs modernes $(a/l)^2 \sim 1/9$

Approx : $(1-\varepsilon)^{1/2} \sim 1-(\varepsilon/2)$ et comme $\theta = \omega t$

$$s = a\cos\omega t + \left(1-\frac{a^2}{2l}\sin^2\omega t\right)$$

$$\sin^2\omega t = (1-\cos 2\omega t)/2$$

$$s = a\cos\omega t + \left(1-\frac{a^2}{4l}(1-\cos 2\omega t)\right)$$

$$\boxed{\frac{d^2 s}{dt^2} = a\omega^2\left(\cos\omega t + \frac{a}{l}\cos 2\omega t\right)}$$

Forces d'Inertie Piston

$$-m\frac{d^2s}{dt^2} = -am\omega^2\left(\cos\omega t + \frac{a}{l}\cos 2\omega t\right)$$

- Maximum au PMH, $\theta = \omega t = 0 \rightarrow F = -am\omega^2$
- Pour une bielle très longue $(a/l) << 1$ le deuxième terme disparaît
- Annulation des forces possible sur moteurs, 6 et 8 en-ligne et V-12 , V-16

Principes de fonctionnement

Four stroke Spark Ignition (SI) Engine

Stroke 1: Fuel-air mixture introduced into cylinder through intake valve

Stroke 2: Fuel-air mixture compressed

Stroke 3: Combustion (roughly constant volume) occurs and product gases expand doing work

Stroke 4: Product gases pushed out of the cylinder through the exhaust valve

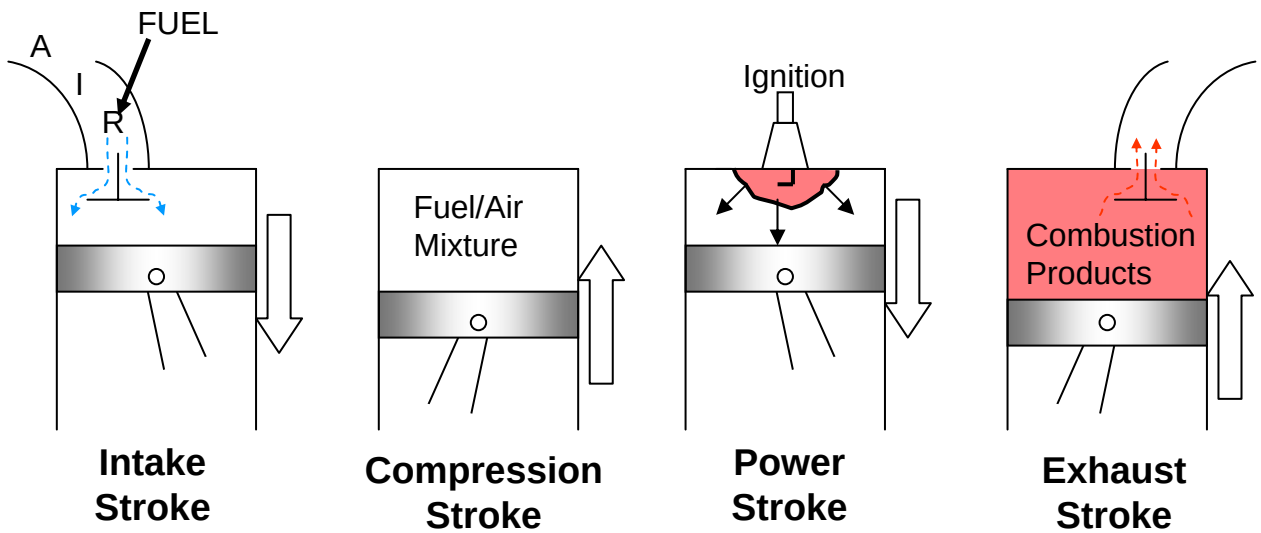
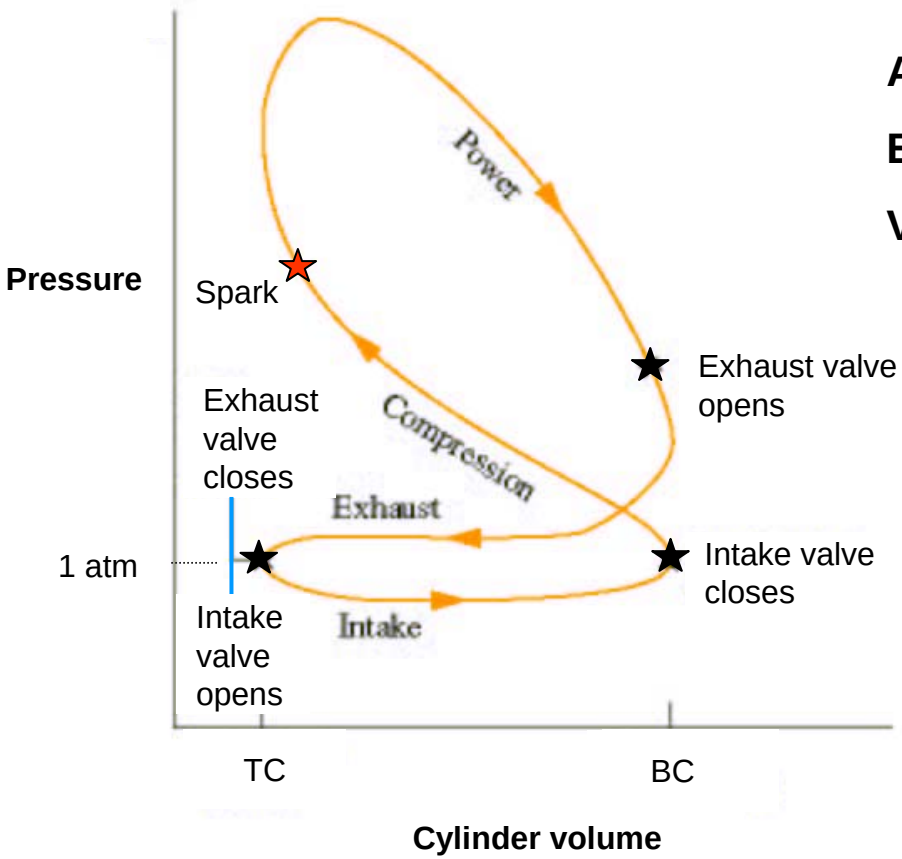


Diagramme Pression-Volume moteur à allumage commandé 4 temps (4-stroke SI engine)

Un cycle moteur tous les deux tours vilebrequin

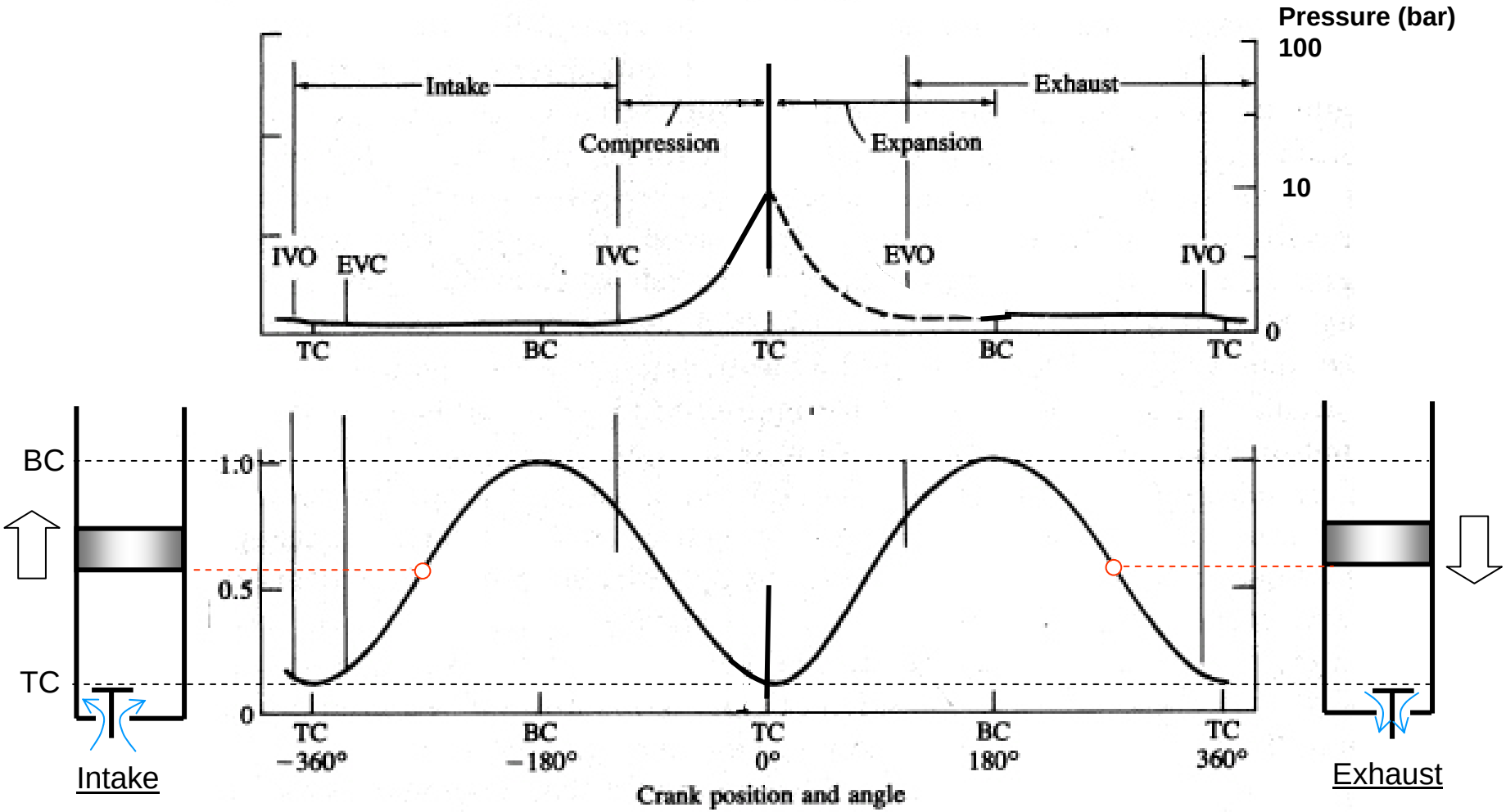


Admission : intake

Exhaust : échappement

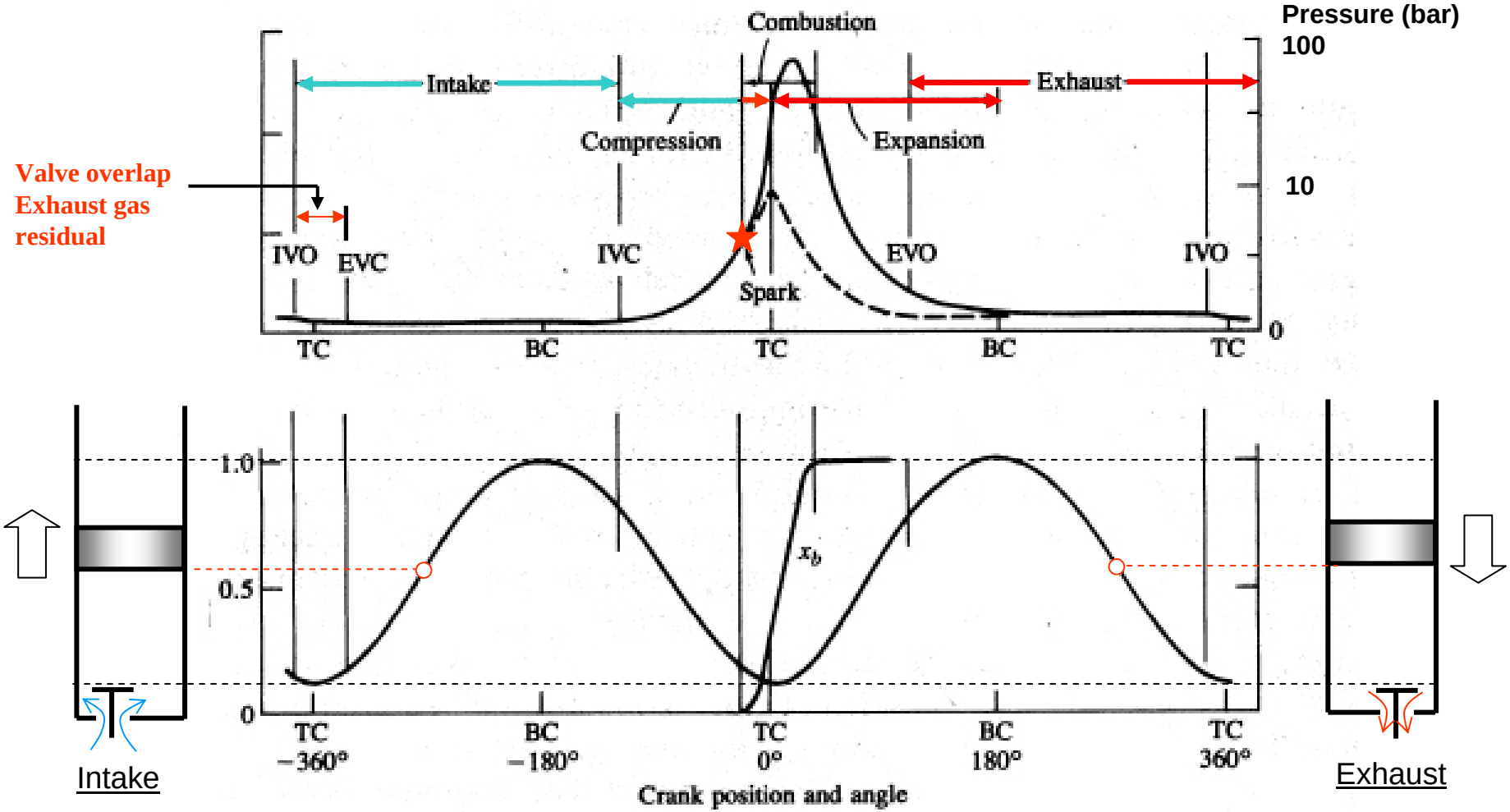
Valve : soupape

Motored Four-Stroke Engine



IVO - intake valve opens, IVC – intake valve closes
EVO – exhaust valve opens, EVC – exhaust valve opens
X_b – burned gas mole fraction

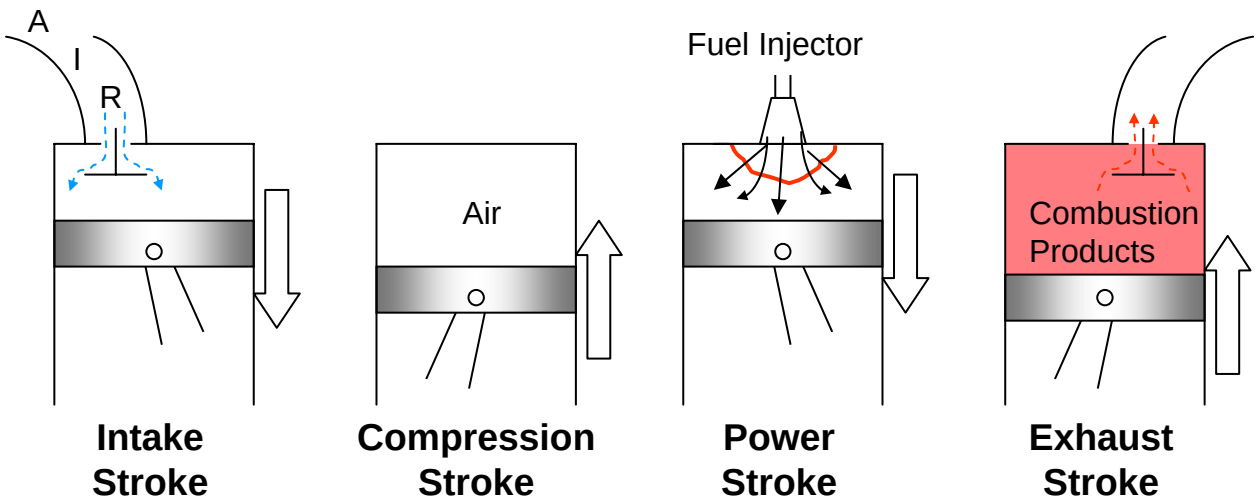
Four-Stroke SI Engine



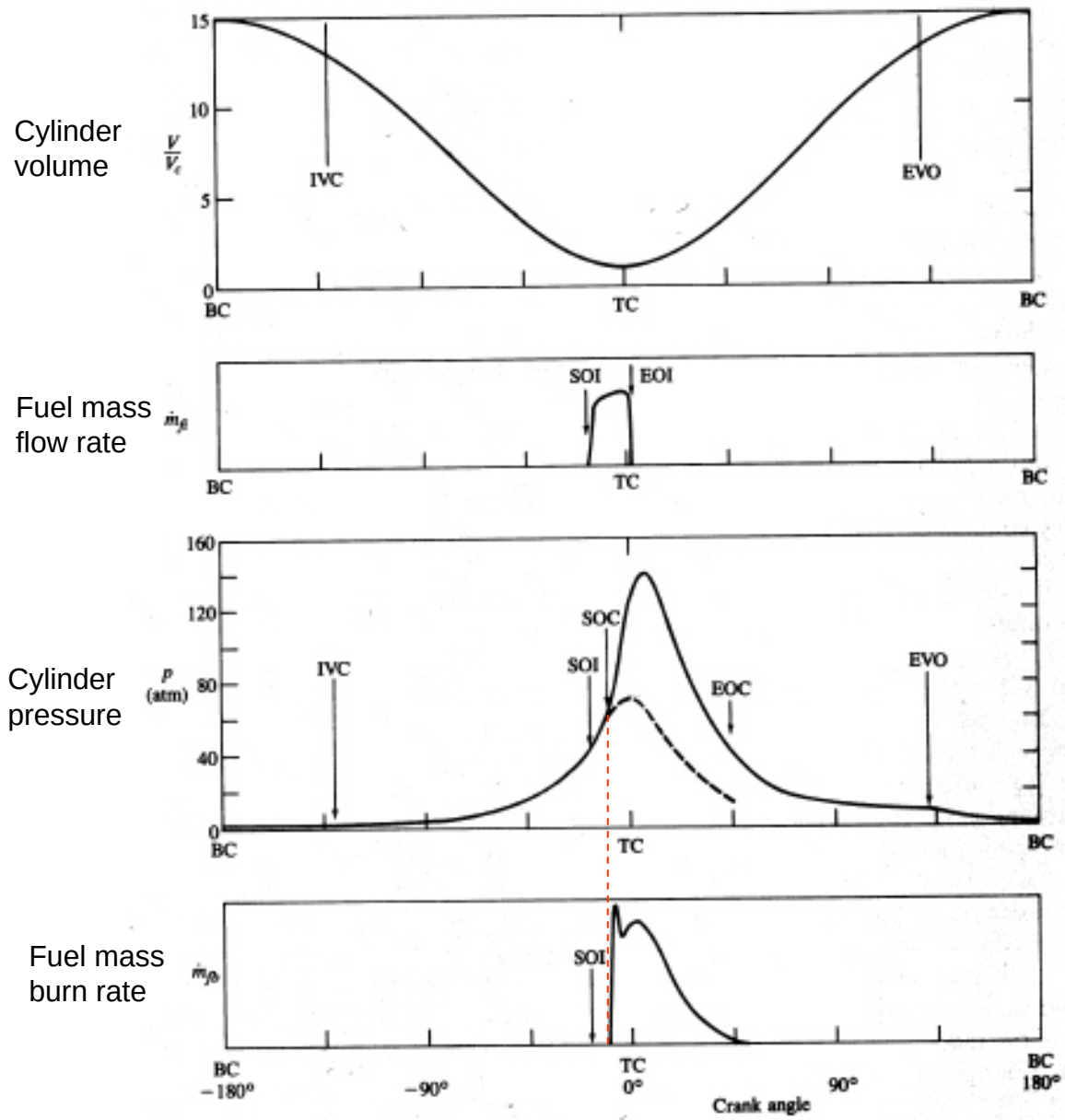
IVO - intake valve opens, IVC – intake valve closes
EVO – exhaust valve opens, EVC – exhaust valve opens
X_b – burned gas mole fraction

Four stroke Compression Ignition (CI) Engine

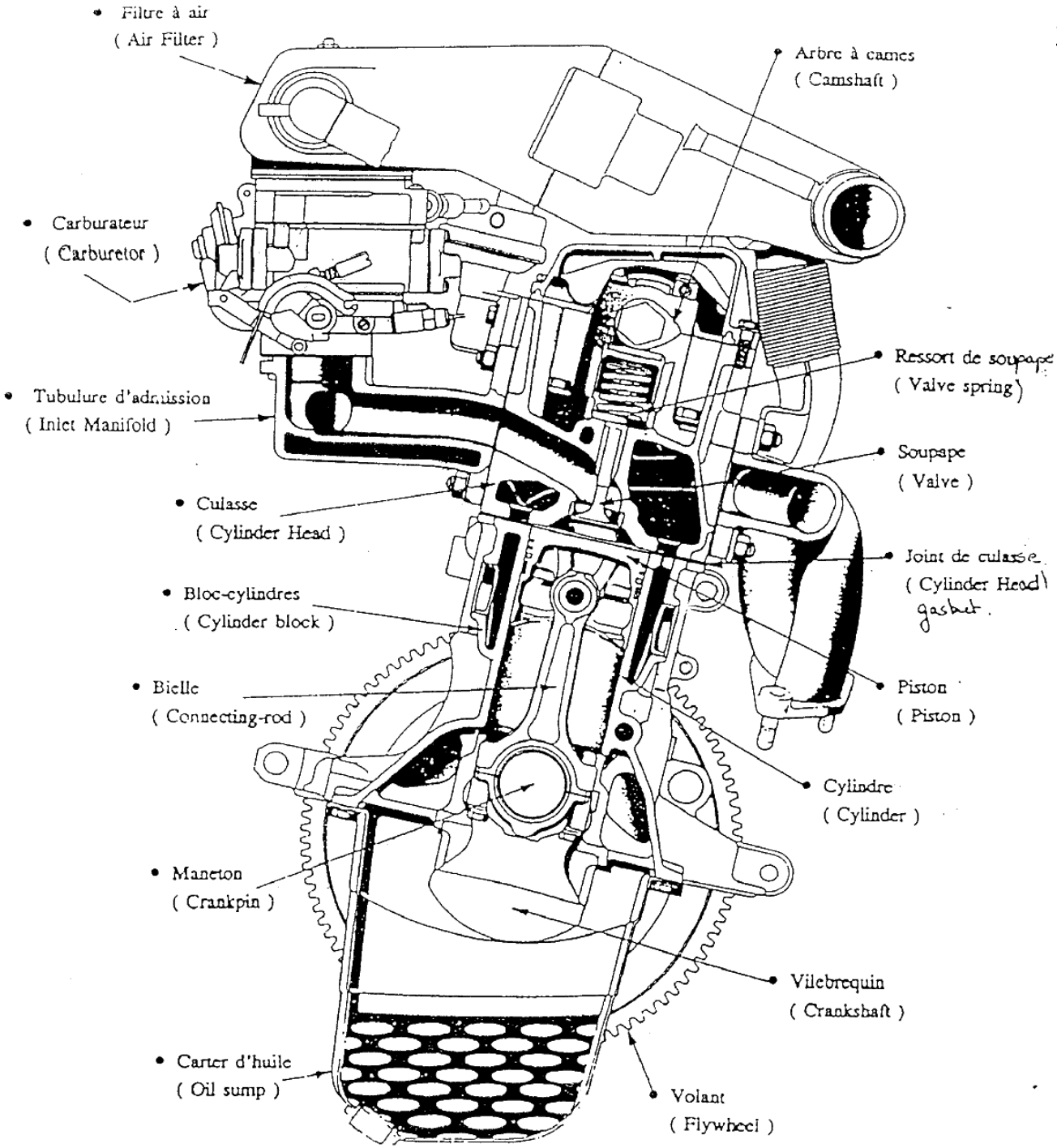
Stroke 1: Air is introduced into cylinder through intake valve
Stroke 2: Air is compressed
Stroke 3: Combustion (roughly constant pressure) occurs and product gases expand doing work
Stroke 4: Product gases pushed out of the cylinder through the exhaust valve



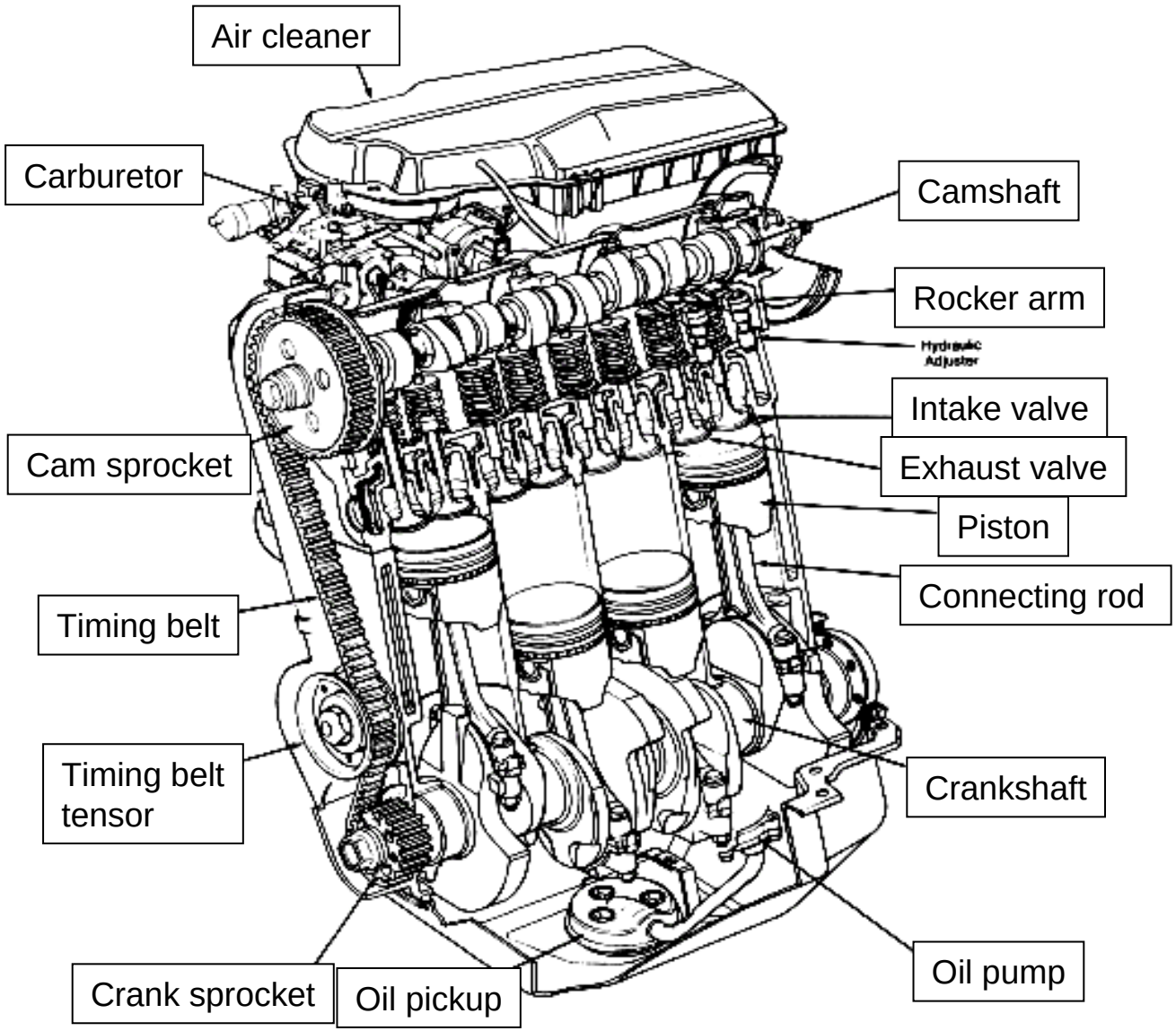
Four-Stroke CI Engine



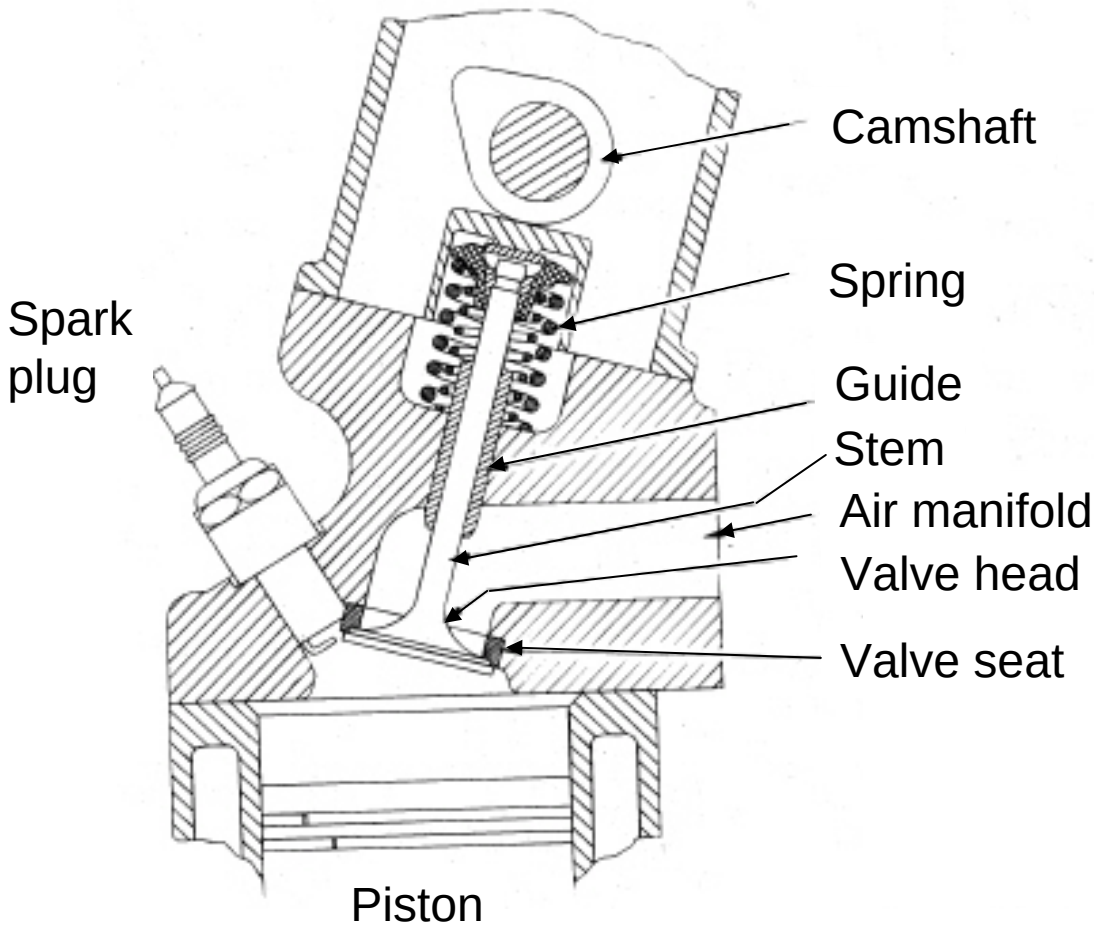
SOI – start of injection
EOI – end of injection
SOC – start of combustion
EOC – end of combustion


Filtre à air
(Air Filter)
Arbre à cames
(Camshaft)
Carburateur
(Carburetor)
Ressort de soupape
(Valve spring)
Tubulure d'admission
(Inlet Manifold)
Soupape
(Valve)
Culasse
(Cylinder Head)
Joint de culasse
(Cylinder Head gasket)
Bloc-cylindres
(Cylinder block)
Bielle
(Connecting-rod)
Piston
(Piston)
Cylindre
(Cylinder)
Maneton
(Crankpin)
Vilebrequin
(Crankshaft)
Carter d'huile
(Oil sump)
Volant
(Flywheel)

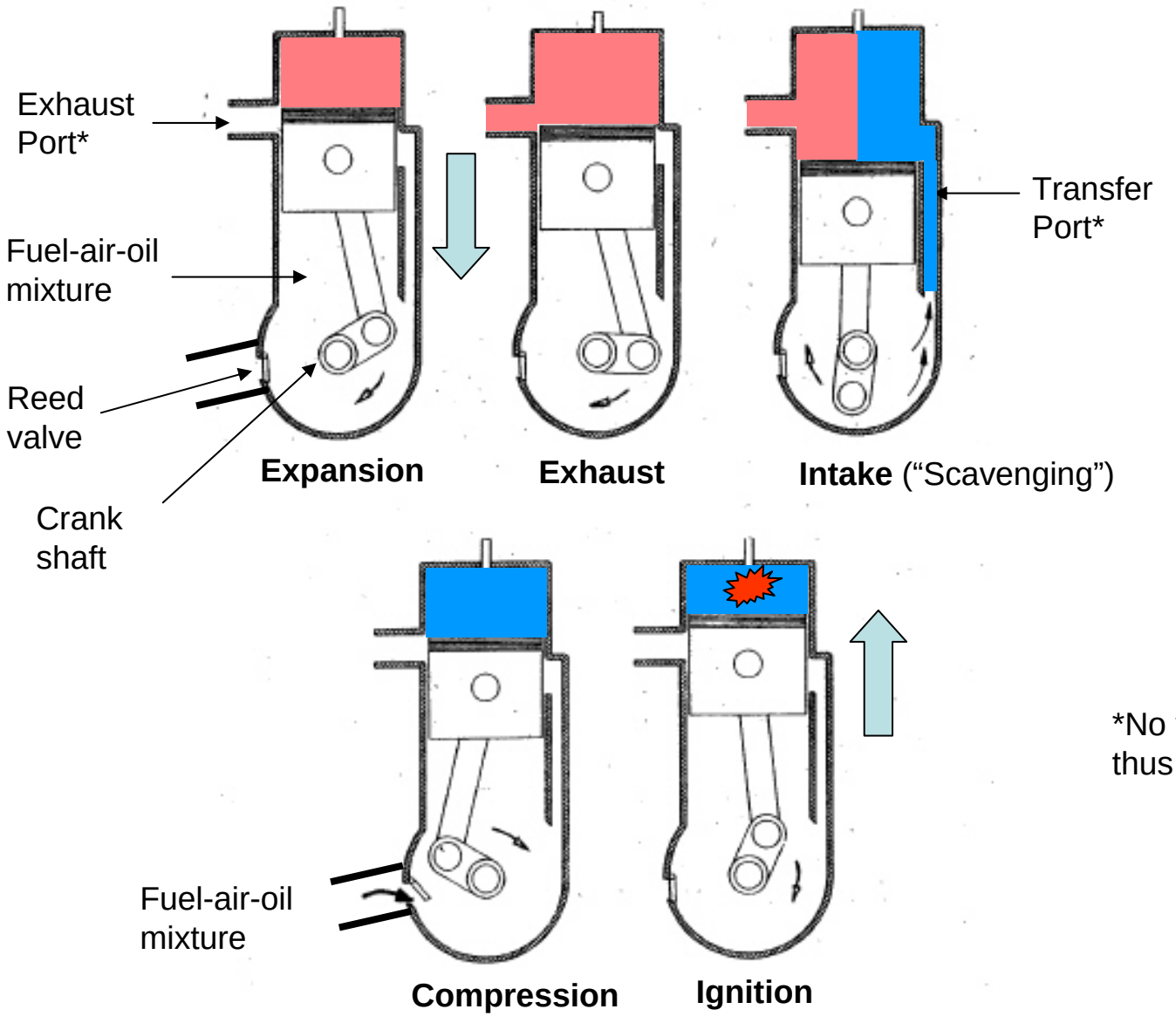
Engine Anatomy



Poppet Valve Actuation with Overhead Camshaft / Commande de soupape avec arbre à came en tête

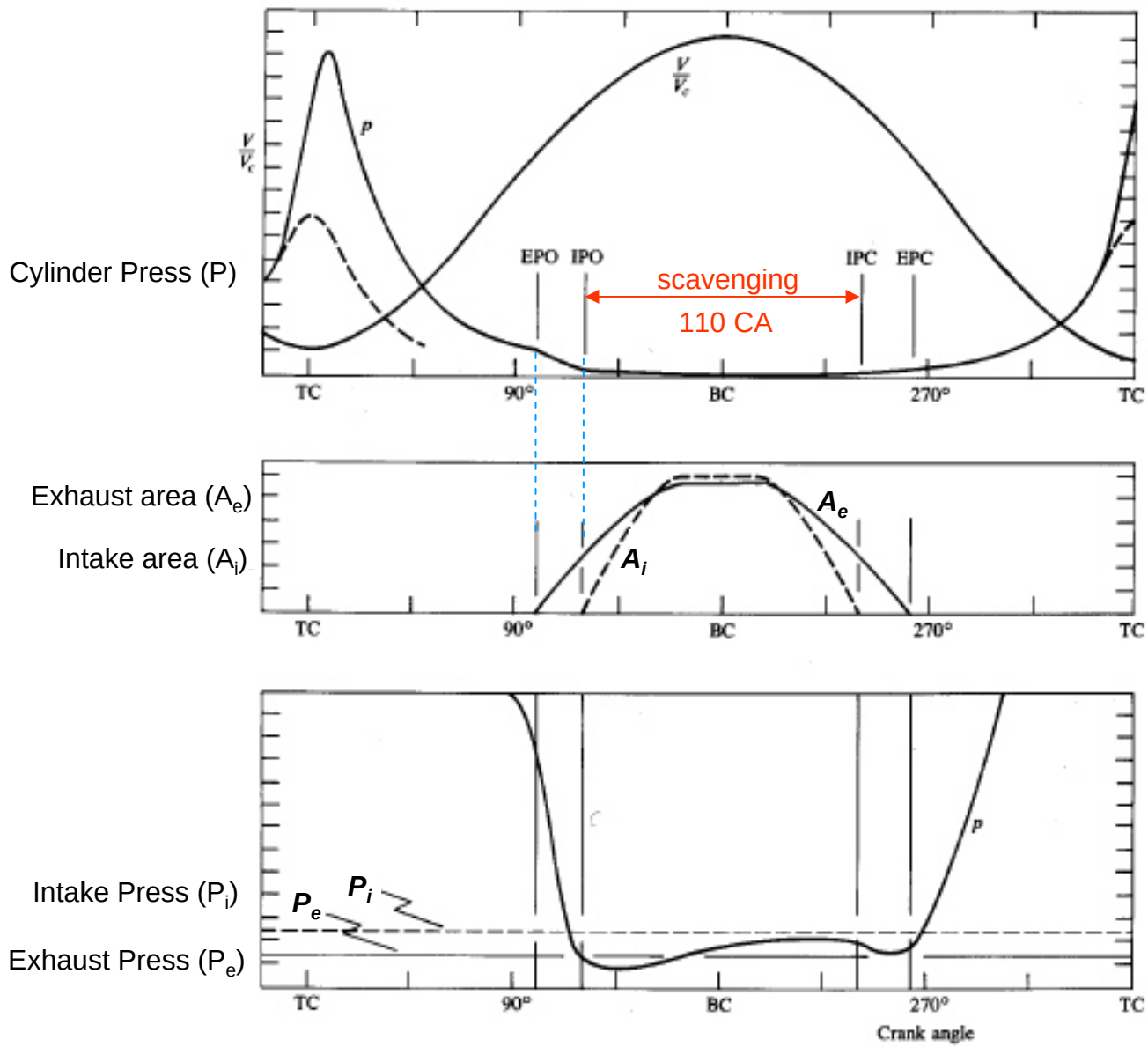


Two Stroke Spark Ignition Engine/ Moteur à allumage commandé 2 temps



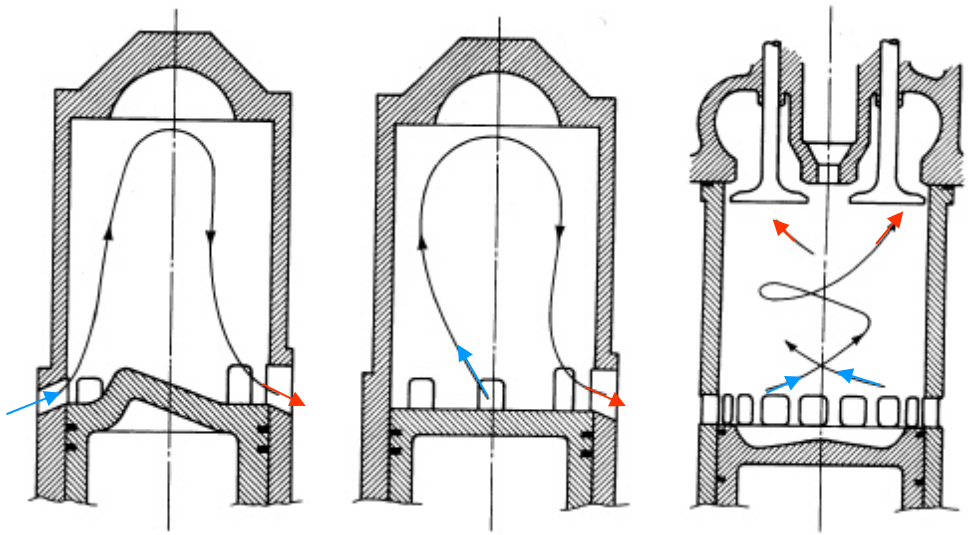
*No valves and thus no camshaft

Two-Stroke CI Engine

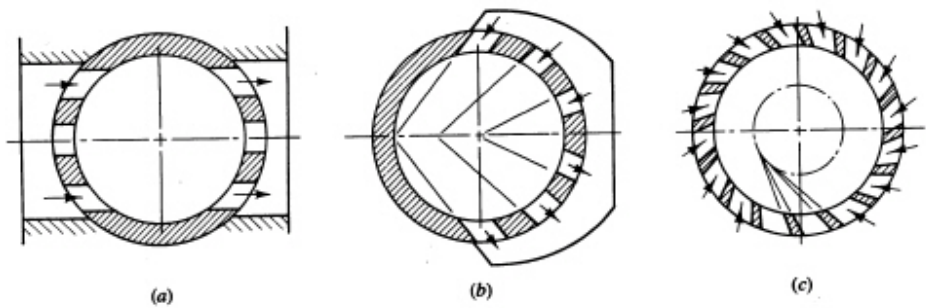


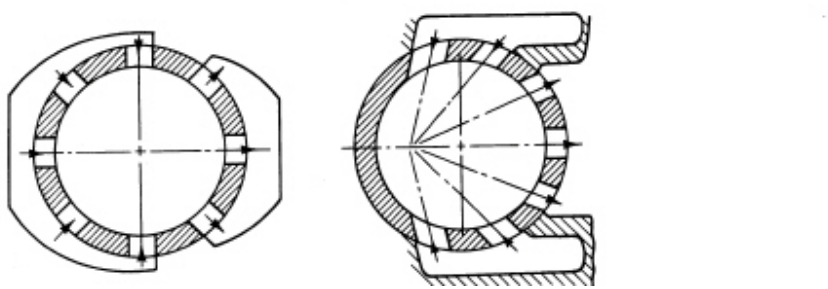
EPO – exhaust port open
EPC – exhaust port closed
IPO – intake port open
IPC – intake port closed

Scavenging in Two-Stroke Engine/ Balayage dans les moteurs 2 temps



Cross **Loop** **Uniflow**





Avantages du moteur 2 temps:

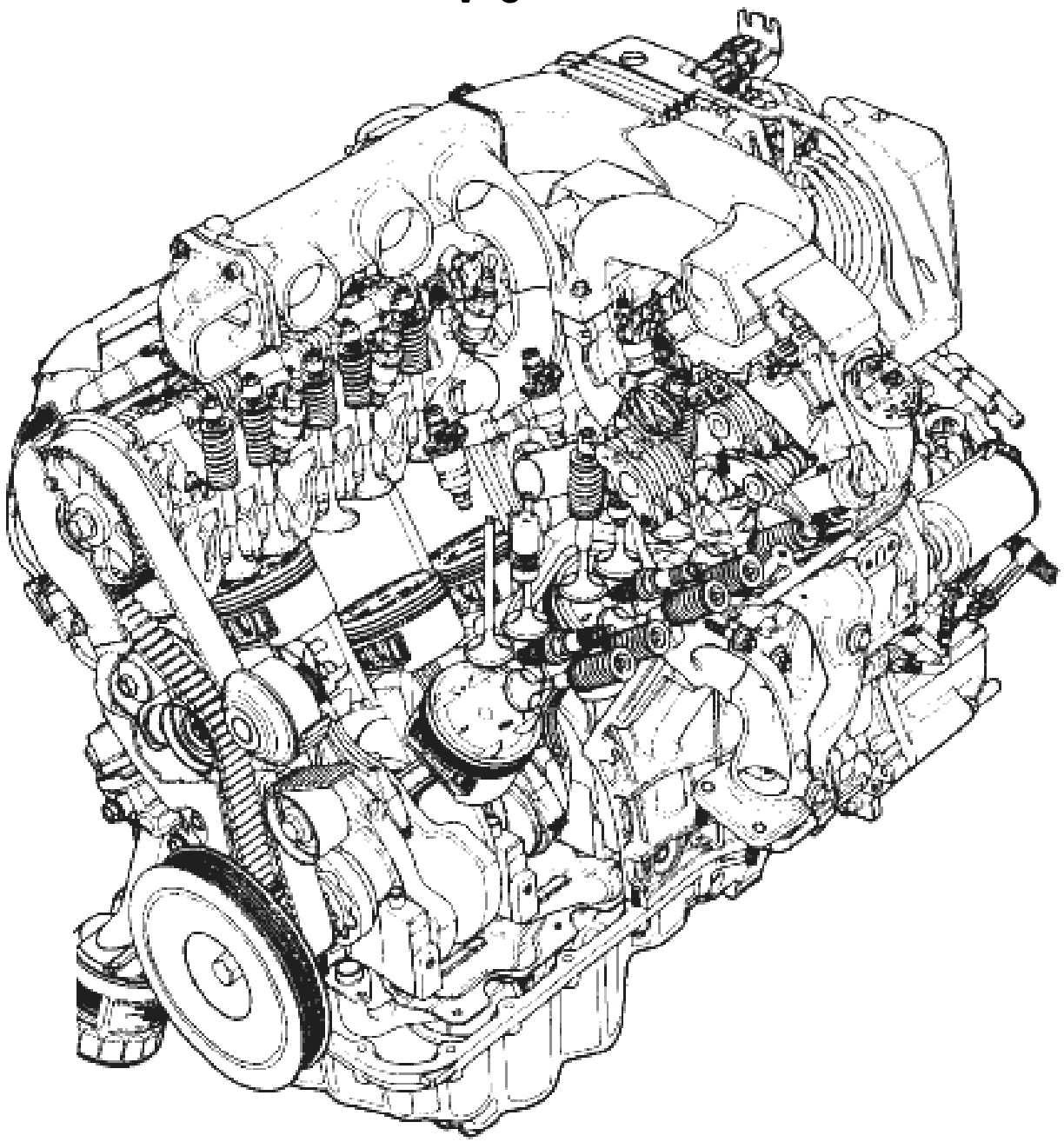
• Le rapport poids/puissance est plus avantageux qu'en 4 temps car chaque tour délivre de la puissance.
• Pas de soupapes, arbre à cames…

Moteurs bas prix, petits moteurs

Désavantages:

• Balayage incomplet (remplissage) ou excessif (pertes)
• Mélange huile/ combustible

V-6



Régulation de puissance

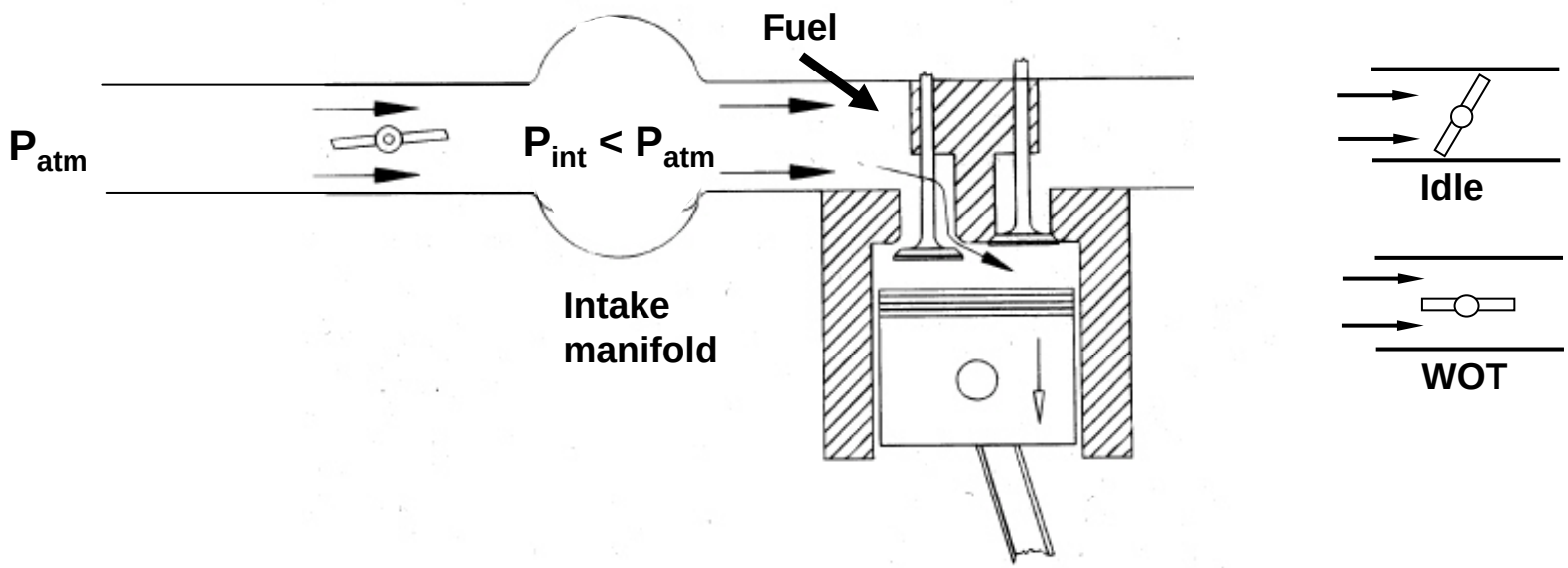
Régulation de puissance

• La combustion a lieu dans les zones de mélange stoechiométrique : rapport masse d'air sur masse de combustible ~ 15.

• La puissance dépend de la masse de combustible :

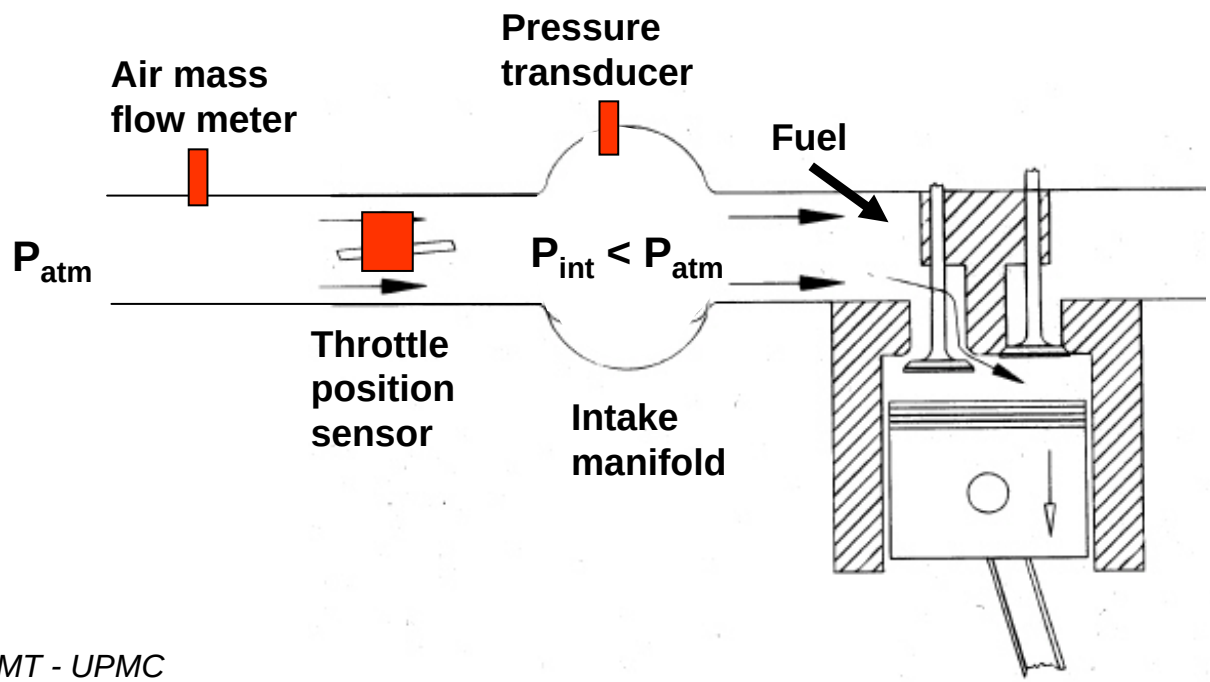
• En mélange homogène (richesse constante) il faut maintenir la proportion air/combustible -> Faire varier le débit d'air :

•Papillon des gaz : Maximum de pression admission (et de puissance) obtenu papillon ouvert (wide-open-throttle WOT), minimum au ralenti (idle)

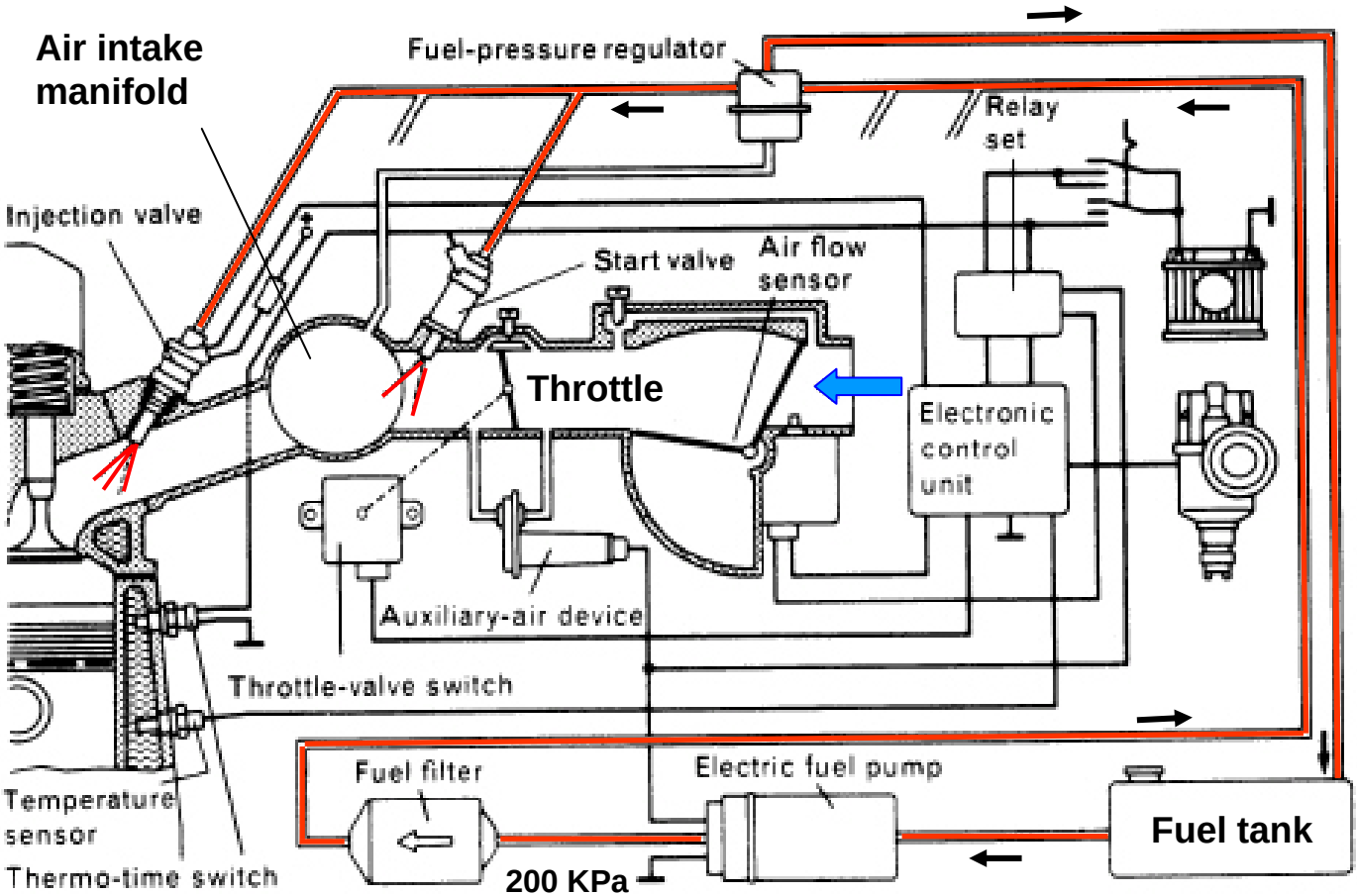


Estimation de la masse d'air

1) Pression collecteur / Manifold pressure
2) Débitmètre air / Air mass flow rate
3) Position papillon / Throttle position



Fuel Injection System

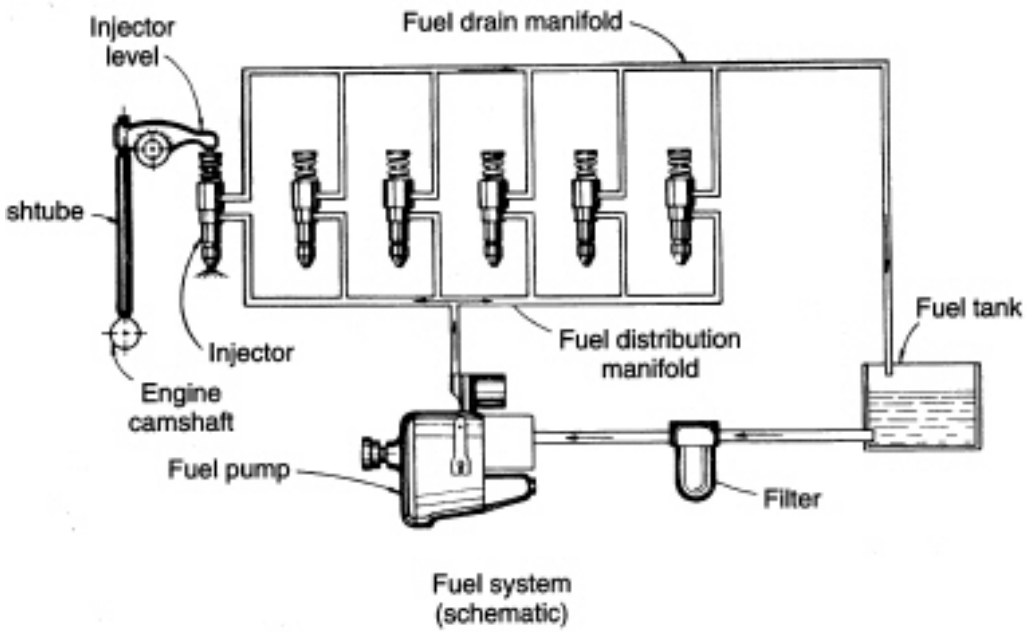


During start-up the components are cold so fuel evaporation is very slow, as a result additional fuel is added through a second injecting valve

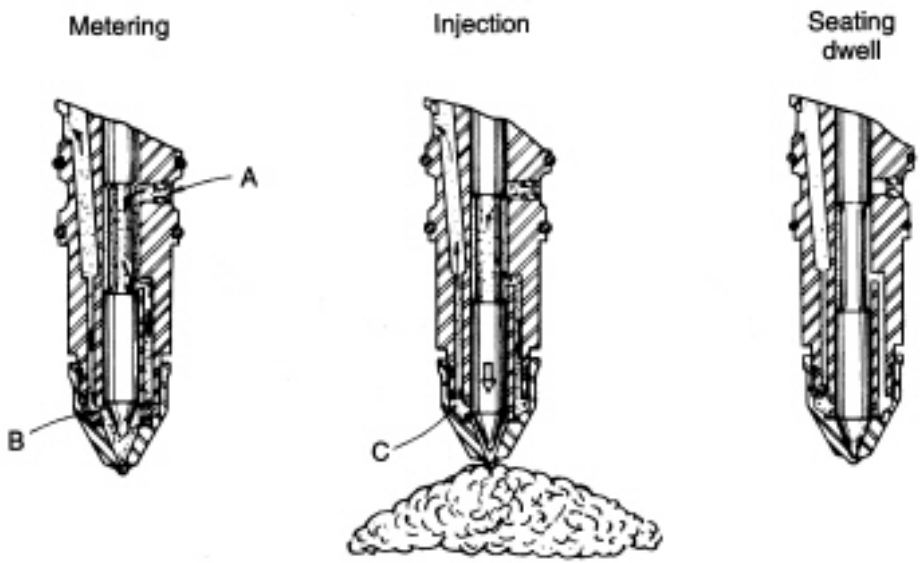
Régulation de puissance en mélange stratifié

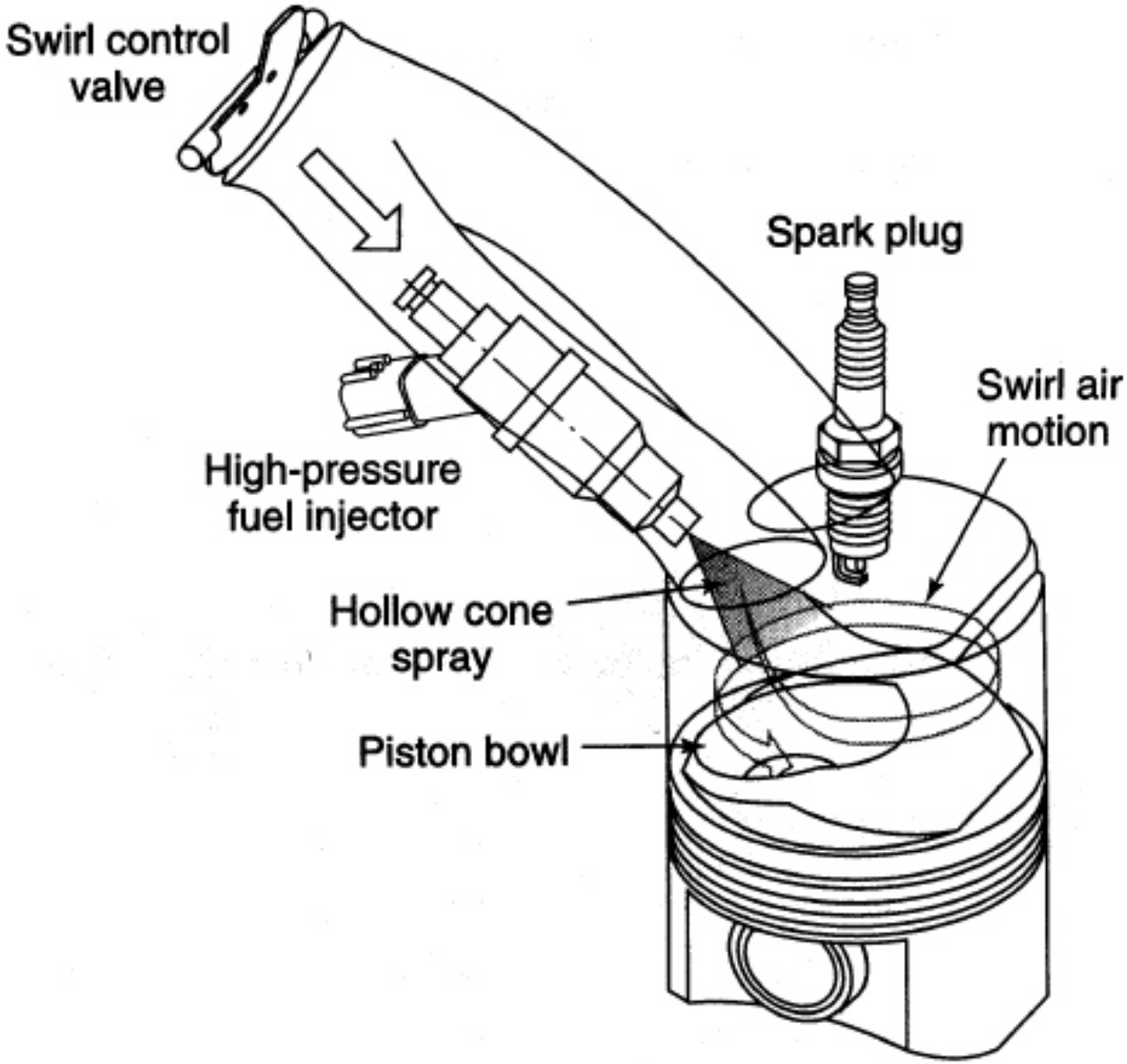
La quantité de combustible est changée indépendamment de la masse d'air : richesse variable

Moteurs Diesel
Moteurs GDI

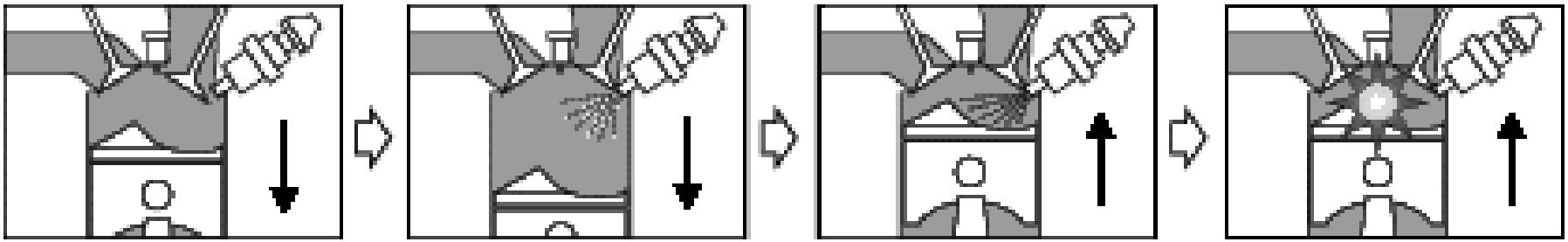


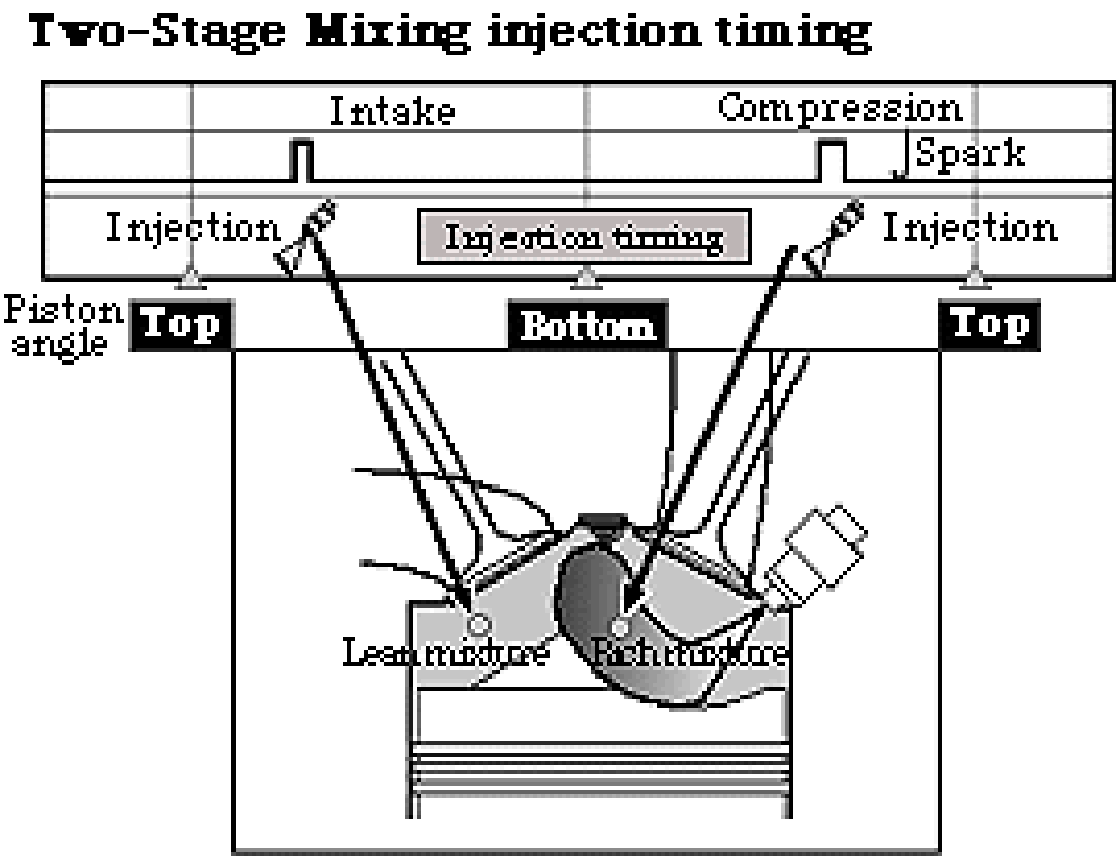
Fuel system (schematic)




Swirl control valve
Spark plug
Swirl air motion
High-pressure fuel injector
Hollow cone spray
Piston bowl

Mitsubishi Two-Stage Ignition GDI Engine





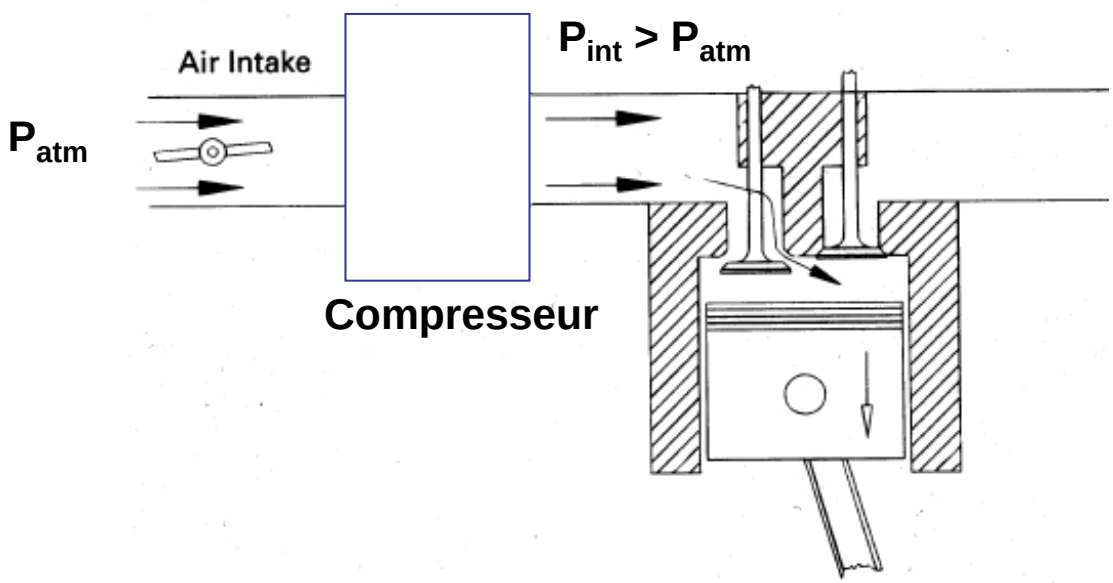
Autre Types d'allumage

- **Homogeneous Charge Compression Ignition (HCCI)**
- **Controlled Auto-Ignition (CAI)**
- **Dual - Fuel**

Suralimentation

Augmenter la puissance d'un moteur en augmentant la masse d'air admise (et donc la masse de combustible pouvant être brûlée), avec un compresseur à l'admission

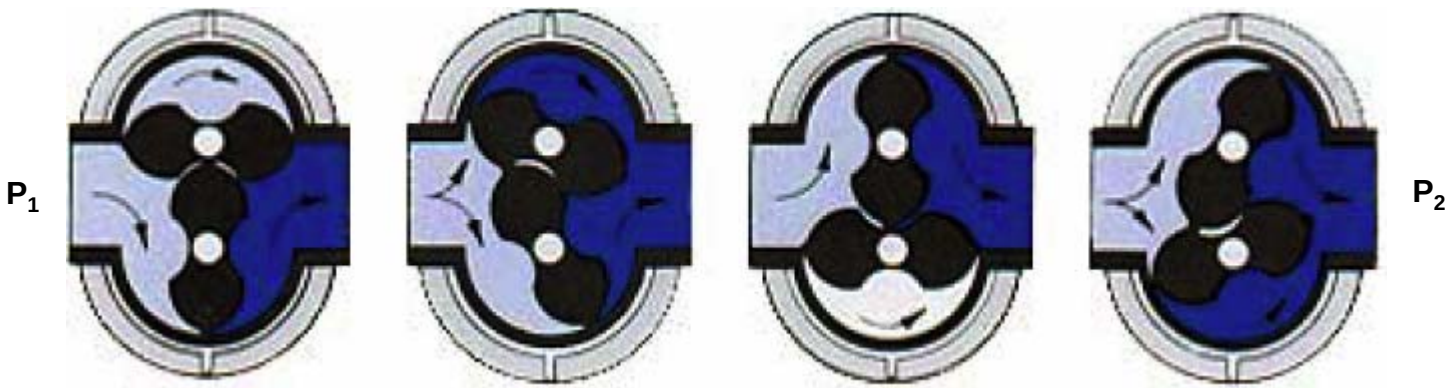
Pb. de Cliquetis (Knock) en essence



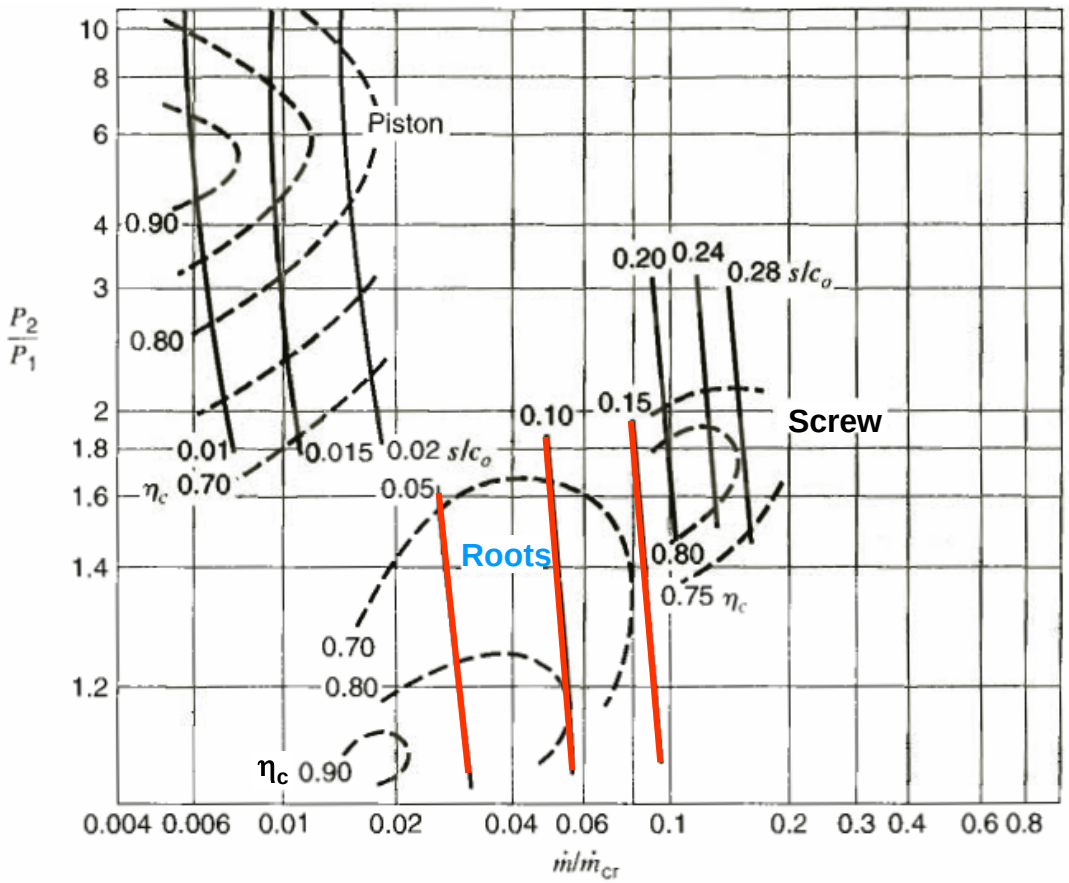
Positive Displacement Compressors/ Compresseurs Volumétriques

piston, Roots, screw (à vis)

Roots :



Performance of Positive Displacement Compressors



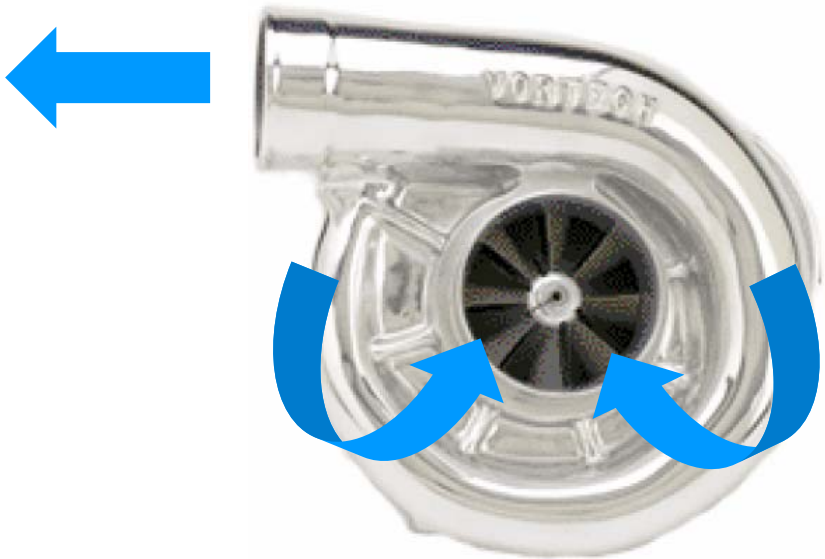
s/c_o = rotor tip Mach#
~ pump speed

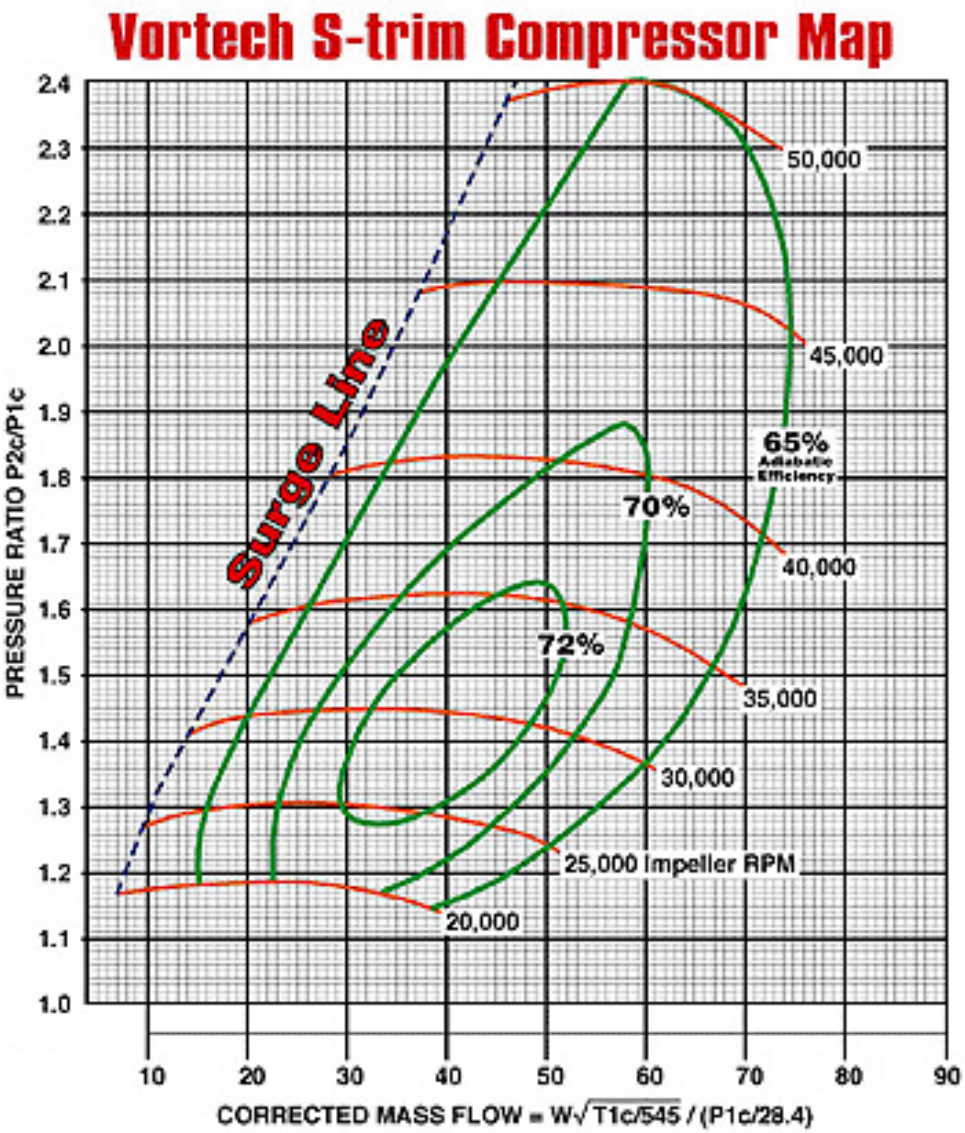
η_c = rendement isentropique compresseur

Les pertes représentent la chaleur cédée à l'air (baisse de densité)

Dynamic Compressors/
Compresseurs rotatifs

Compresseur centrifuge :

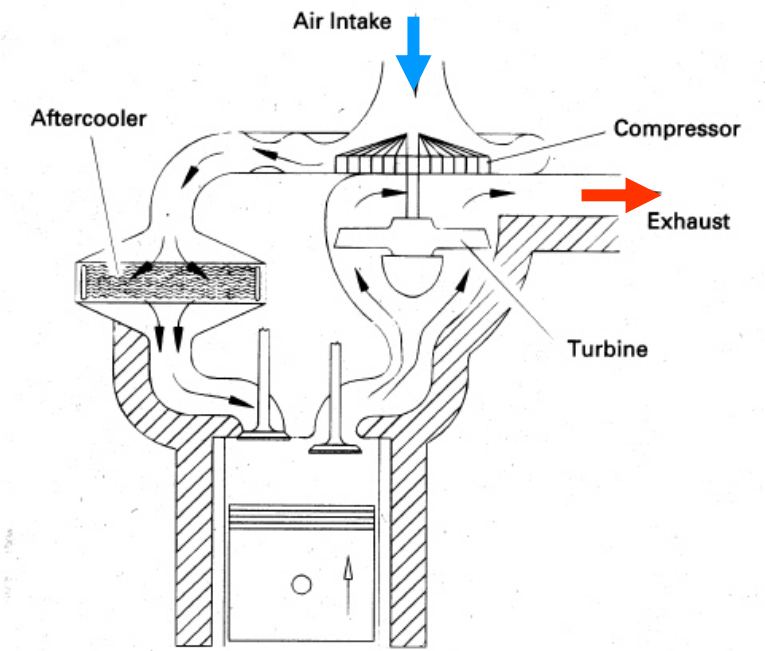




Surge line : limite de pompage

Débit d'air

Turbocompresseurs

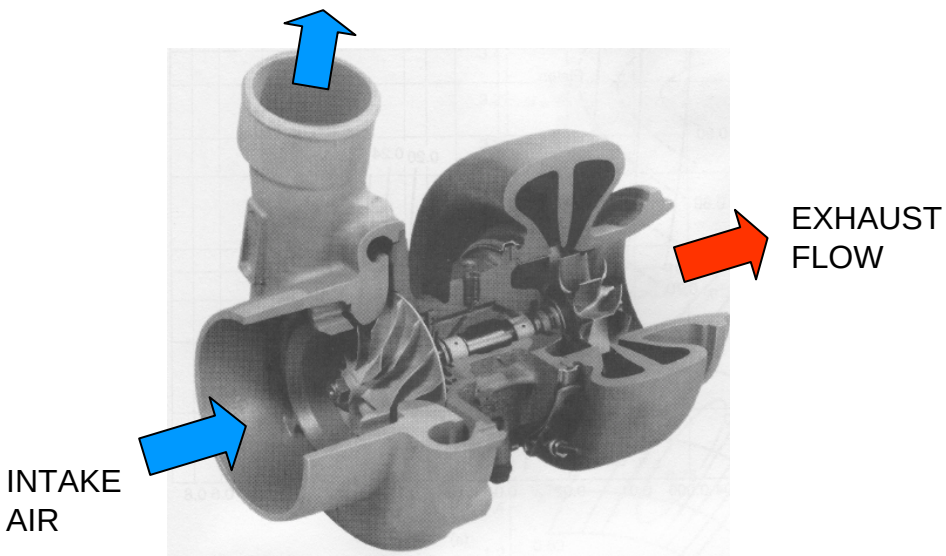


Petit ΔP turbine

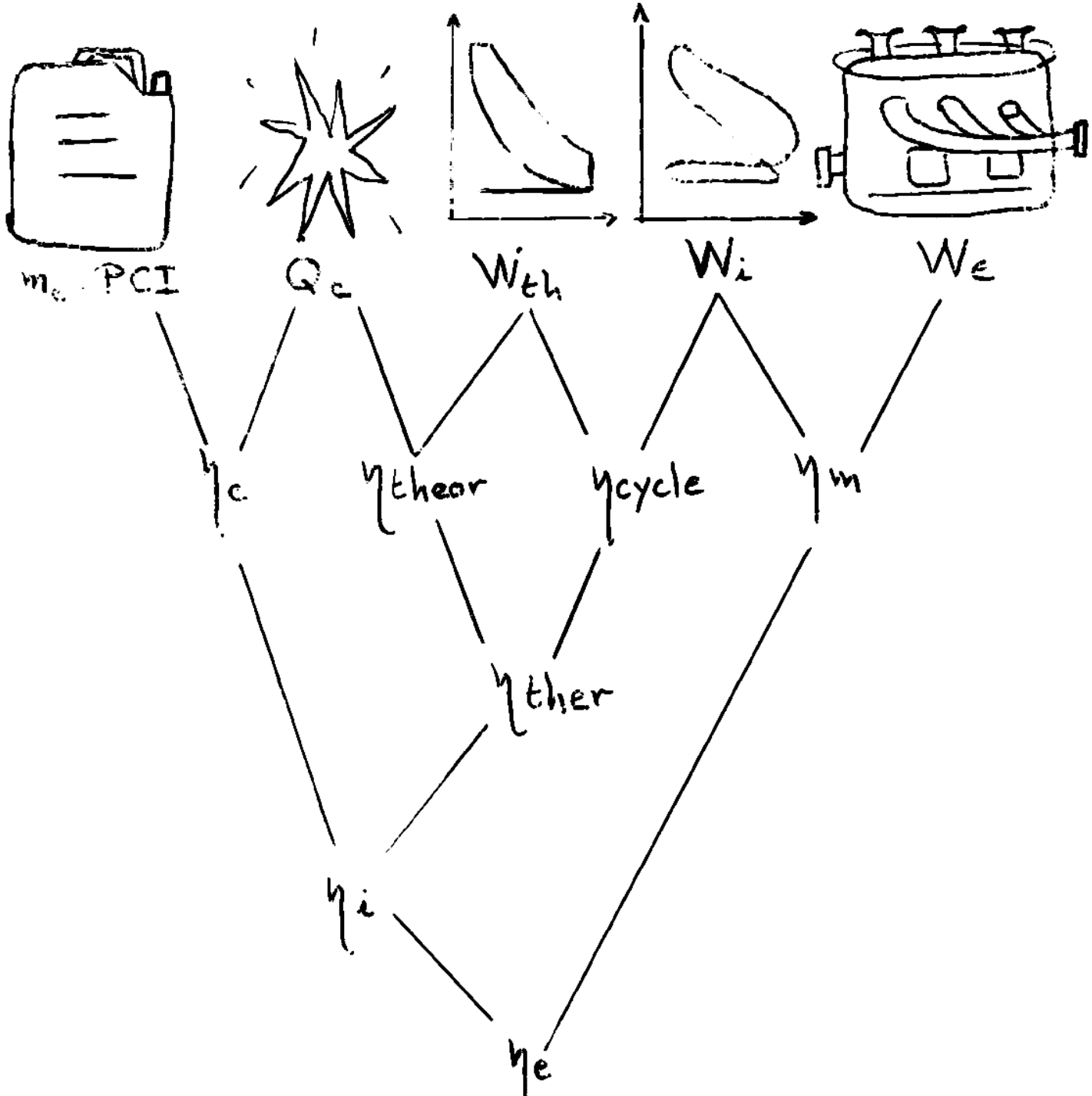
Vitesse rotation élevée (100k-200k tr/min) – endurance

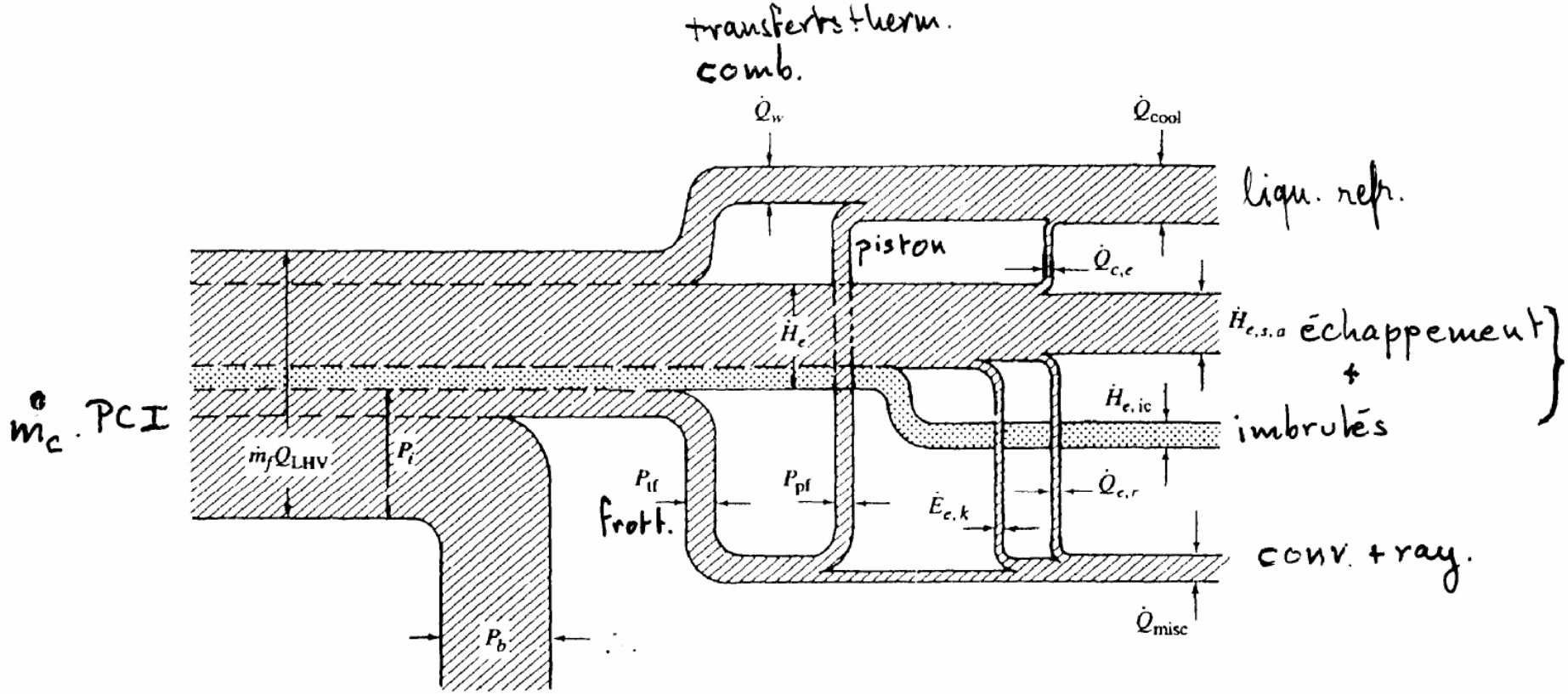
Inertie turbine - **Turbo lag**

Waste gate/blades (aubes fixes) / nozzle nécessaires pour contrôler le débit turbine



Rendements et facteurs de performance

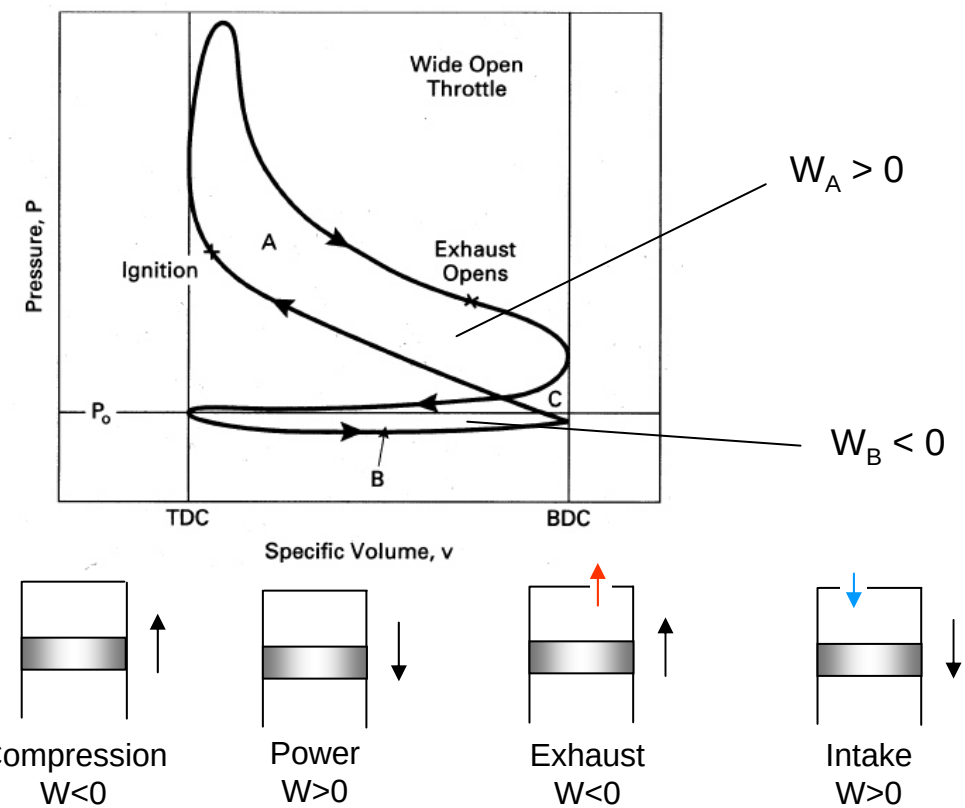

m_c PCI
Q_c
W_{th}
W_i
W_e
η_c
η_{thear}
η_{cycle}
η_m
η_{ther}
η_i
η_e



Energy flow diagram for IC engine. ($\dot{m}_f Q_{LHV}$) = fuel flow rate × lower heating value, $\dot{Q}_w$ = heat-transfer rate to combustion chamber wall, $\dot{H}_e$ = exhaust gas enthalpy flux, P_b = brake power, P_{tf} = total friction power, P_i = indicated power, P_{pf} = piston friction power, $\dot{Q}_{cool}$ = heat-rejection rate to coolant, $\dot{Q}_{c,e}$ = heat-transfer rate to coolant in exhaust ports, $\dot{H}_{e,s,a}$ = exhaust sensible enthalpy flux entering atmosphere, $\dot{H}_{e,ic}$ = exhaust chemical enthalpy flux due to incomplete combustion, $\dot{Q}_{e,r}$ = heat flux radiated from exhaust system, $\dot{E}_{e,k}$ = exhaust kinetic energy flux, $\dot{Q}_{misc}$ = sum of remaining energy fluxes and transfers.

Travail Indiqué

$$W_i = \oint P dV$$



Gross indicated work (Boucle HP) :

$$W_{i,g} = \textit{aire A} + \textit{aire C} \quad (>0)$$

Pump work (Boucle BP – pompage) :

$$W_p = \textit{aire B} + \textit{aire C} \quad (<0)$$

Net indicated work (Travail indiqué) :

$$W_{i,n} = W_{i,g} - W_p = \textit{aire A} - \textit{aire B}$$

Puissance Indiquée

$$\dot{W}_i = \frac{W_i N}{n_R} \qquad \frac{(kJ/cycle)(rev/s)}{rev/cycle}$$

avec N – vitesse rotation in rev/s

n_R – nombre de tours par cycle

= 2 en 4-temps W

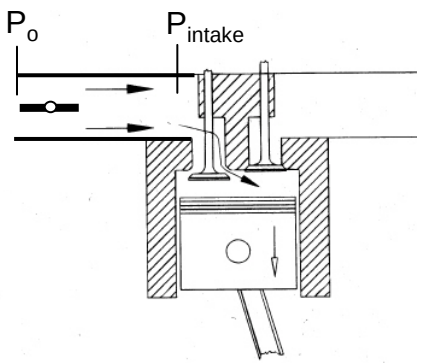
= 1 en 2-temps

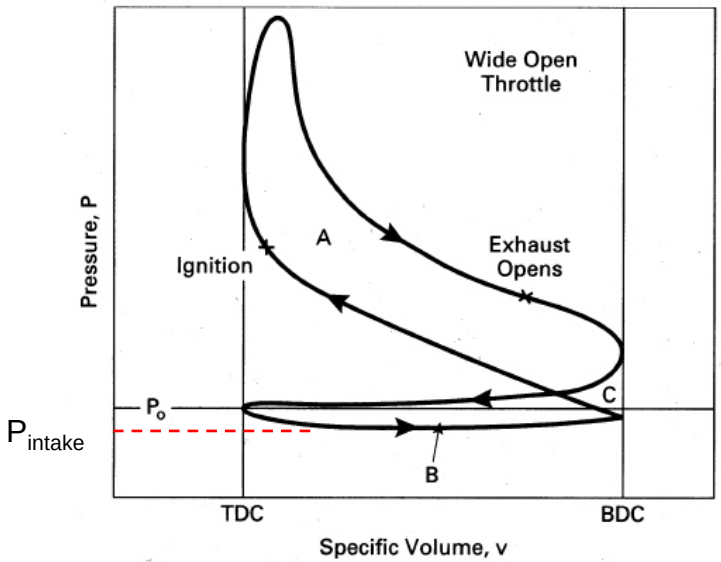
La Pi peut être augmentée :

- Taille du moteur, V_d
- « Taux de compression » , r_c
- Vitesse, N

Travail indiqué papillon ouvert

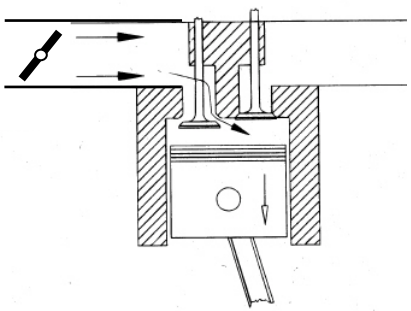
Légère dépression admission

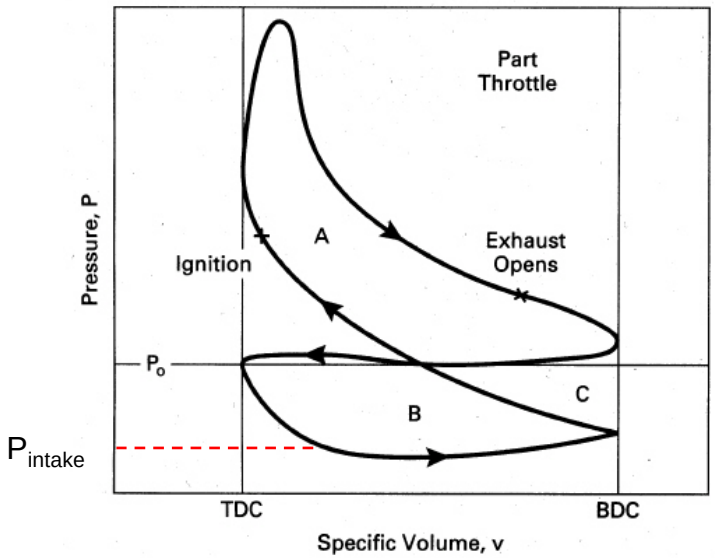




Travail indiqué papillon fermé

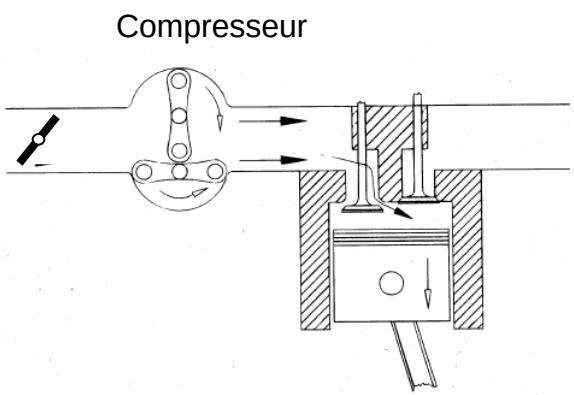
Dépression importante admission

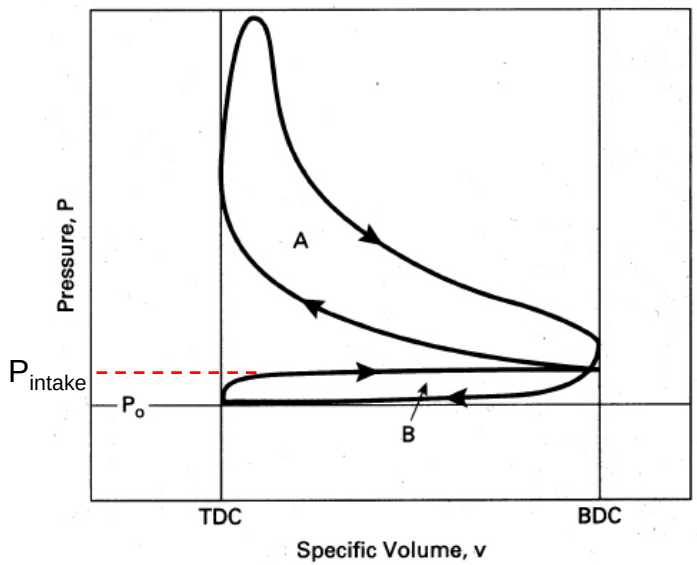




Travail indiqué en suralimentation

On peut obtenir des pressions admission supérieures aux pressions échappement, pompage positif





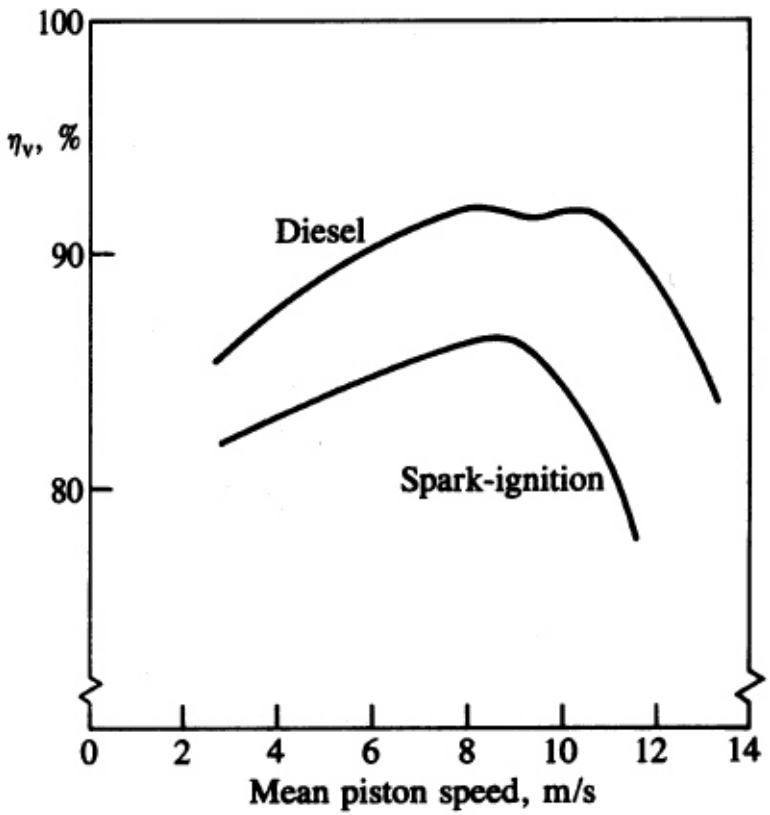
Rendement mécanique

$$\dot{W}_f = \dot{W}_{i,g} - \dot{W}_b$$

$$\eta_m = \frac{\dot{W}_b}{\dot{W}_{i,g}} = \frac{\dot{W}_{i,g} - \dot{W}_f}{\dot{W}_{i,g}} = 1 - \frac{\dot{W}_f}{\dot{W}_{i,g}}$$

Rendement de Remplissage

$$\eta_v = \frac{2m_a}{\rho_{a,o} V_d}$$



Dépend des facteurs:

i) Evaporation combustible
ii) Température du Mélange
iii) Pertes de charge
iv) Effets dynamiques des gaz
v) Synchro. soupapes

Ou vitesse moteur : $N = (S/2) \cdot \overline{U}_p$

$$P = \frac{\eta_c \cdot \eta_v \cdot N \cdot V_c \cdot PCI \cdot \rho_a \cdot (1/\lambda)}{n}$$

$$C = \frac{\eta_c \cdot \eta_v \cdot V_c \cdot PCI \cdot \rho_a \cdot (1/\lambda)}{2\pi \cdot n}$$

$$pme = \eta_c \cdot \eta_v \cdot PCI \cdot \rho_a \cdot (1/\lambda)$$

Pression moyenne indiquée

$P_i = pmi . V_c . n$

Pression moyenne effective

$P_e = pme . V_c . n$

$n = \frac{N}{2 \times 60}$: 4 temps

$n = \frac{N}{1 \times 60}$: 2 temps, si N en tr/min

pme : 3 bar (Endurance) → 21 bar (Puissance)

Cylindrée : Vc

Mono-cylindre → Multi-cylindre	
Simplicité	Prix
Grand alésage/course/encombrement	Faible alésage/course/encombrement
Faible vitesse	Grande vitesse

Vitesse moyenne de piston

$vmp = \frac{2CN}{60}$: 6 m/s pistons fonte

12 à 22 m/s pistons alliage léger

Rapport volumétrique

$\tau_v = \frac{V_m + V_c}{V_m}$: 10 à 11 en allumage commandé (limité par cliquetis, Pmax~70 bar)

18 à 22 en Diesel (limité par efforts, Pmax~150 bar)

Géométrie

C/d = 1 : moteur carré

<1 moteur course longue : lent

>1 moteur super carré : rapide

Mode d'injection

Fraction brûlée à volume constant : 75 % allumage commandé

25 % Diesel injection indirecte

30 % Diesel injection directe

TABLE 2.1
Typical design and operating data for internal combustion engines

	Operating cycle	Compression ratio	Bore, m	Stroke/ bore	Rated maximum: Speed, rev/min	Rated maximum: bmep, atm	Rated maximum: Power per unit volume kW/dm³	Weight/ power ratio, kg/kW	Approx. best bsfc, g/kW·h
Spark-ignition engines									
Small (e.g., motorcycles)	2S,4S	6–11	0.05–0.085	1.2–0.9	4500–7500	4–10	20–60	5.5–2.5	350
Passenger cars	4S	8–10	0.07–0.1	1.1–0.9	4500–6500	7–10	20–50	4–2	270
Trucks	4S	7–9	0.09–0.13	1.2–0.7	3600–5000	6.5–7	25–30	6.5–2.5	300
Large gas engines	2S,4S	8–12	0.22–0.45	1.1–1.4	300–900	6.8–12	3–7	23–35	200
Wankel engines	4S	≈ 9	0.57 dm³ per chamber		6000–8000	9.5–10.5	35–45	1.6–0.9	300
Diesel engines									
Passenger cars	4S	17–23	0.075–0.1	1.2–0.9	4000–5000	5–7.5	18–22	5–2.5	250
Trucks (NA)	4S	16–22	0.1–0.15	1.3–0.8	2100–4000	6–9	15–22	7–4	210
Trucks (TC)	4S	14–20	0.1–0.15	1.3–0.8	2100–4000	12–18	18–26	7–3.5	200
Locomotive, industrial, marine	4S,2S	12–18	0.15–0.4	1.1–1.3	425–1800	7–23	5–20	6–18	190
Large engines, marine and stationary	2S	10–12	0.4–1	1.2–3	110–400	9–17	2–8	12–50	180

Typical 1998 Passenger Car Engine Characteristics

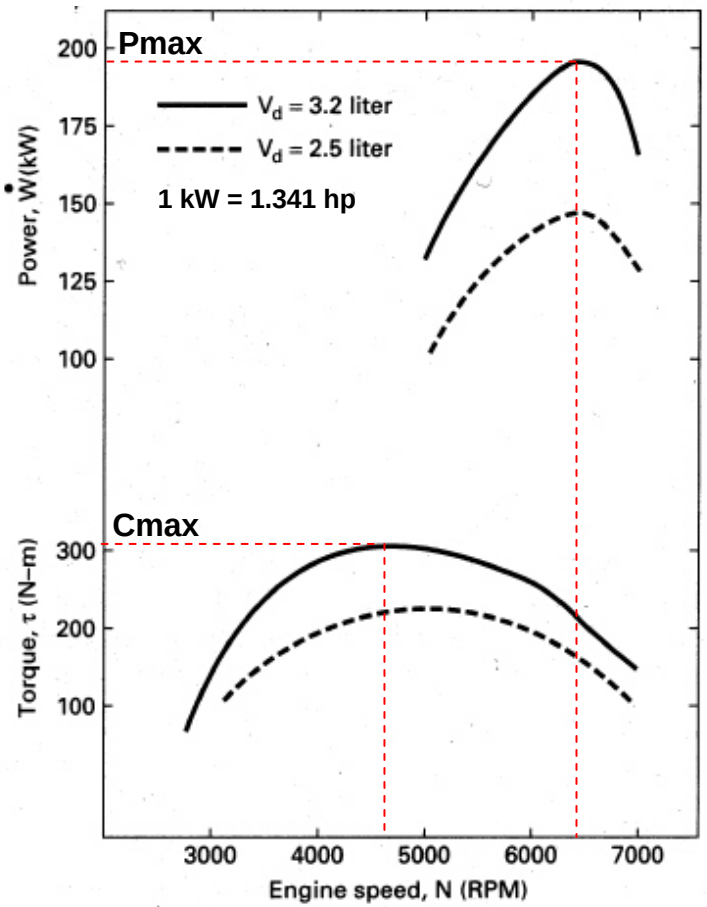
Vehicle	Engine type	Displ. (L)	Max Power (HP@rpm)	Max Torque (lb-ft@rpm)	BMEP at Max BT (bar)	BMEP at Rated BP (bar)
Mazda Protégé LX	L4	1.839	122@6000	117@4000	10.8	9.9
Honda Accord EX	L4	2.254	150@5700	152@4900	11.4	10.4
Mazda Millenia S	L4 Turbo	2.255	210@5300	210@3500	15.9	15.7
BMW 328i	L6	2.793	190@5300	206@3950	12.6	11.5
Ferrari F355 GTS	V8	3.496	375@8250	268@6000	13.1	11.6
Ferrari 456 GT	V12	5.474	436@6250	398@4500	12.4	11.4
Lamborghini Diablo VT	V12	5.707	492@7000	427@5200	12.7	11.0

Courbes de performances

Puissance et couple à pleine charge

$$\dot{W} \propto N \cdot W_{cycle}$$

$$T \propto W_{cycle}$$



La puissance passe par un maximum.
A grande vitesse la puissance diminue à cause des frottements

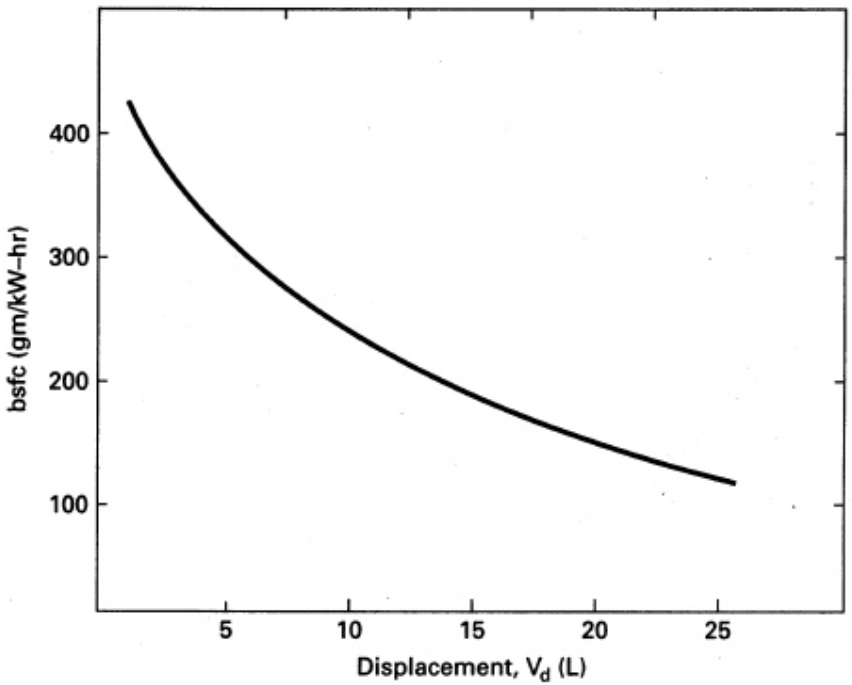
$$\dot{W}_b = \dot{W}_{i,g} - \dot{W}_f$$

Le couple passe par un maximum.

Le couple diminue:
- à faible vitesse à cause des pertes thermiques
- à grande vitesse à cause du remplissage

Consommation spécifique et taille moteur

• cse diminue avec la taille à cause de la diminution relative des pertes thermiques.

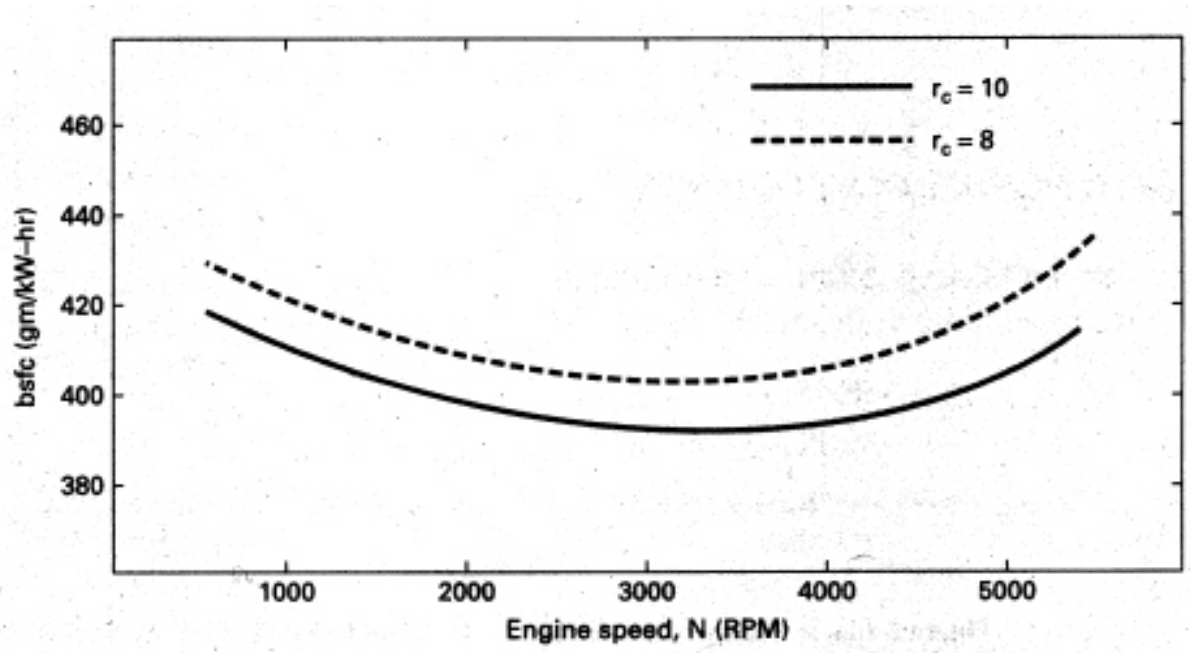


• Le rapport Surface-cylindre sur volume-cylindre augmente avec l'alésage.

$$\frac{cylinder\ surface\ area}{cylinder\ volume} = \frac{2\pi rL}{\pi r^2 L} \propto \frac{1}{r}$$

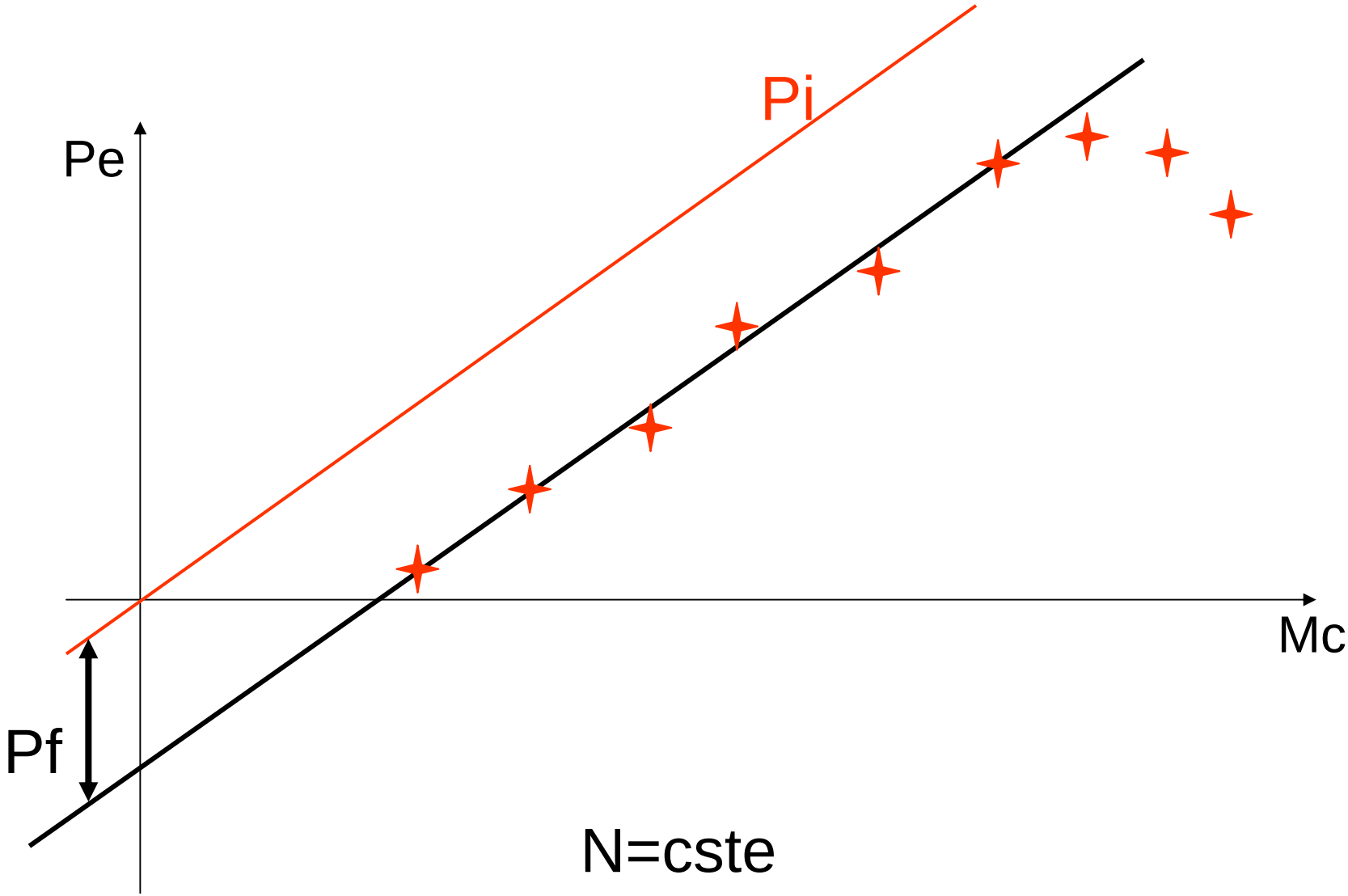
Cse et vitesse

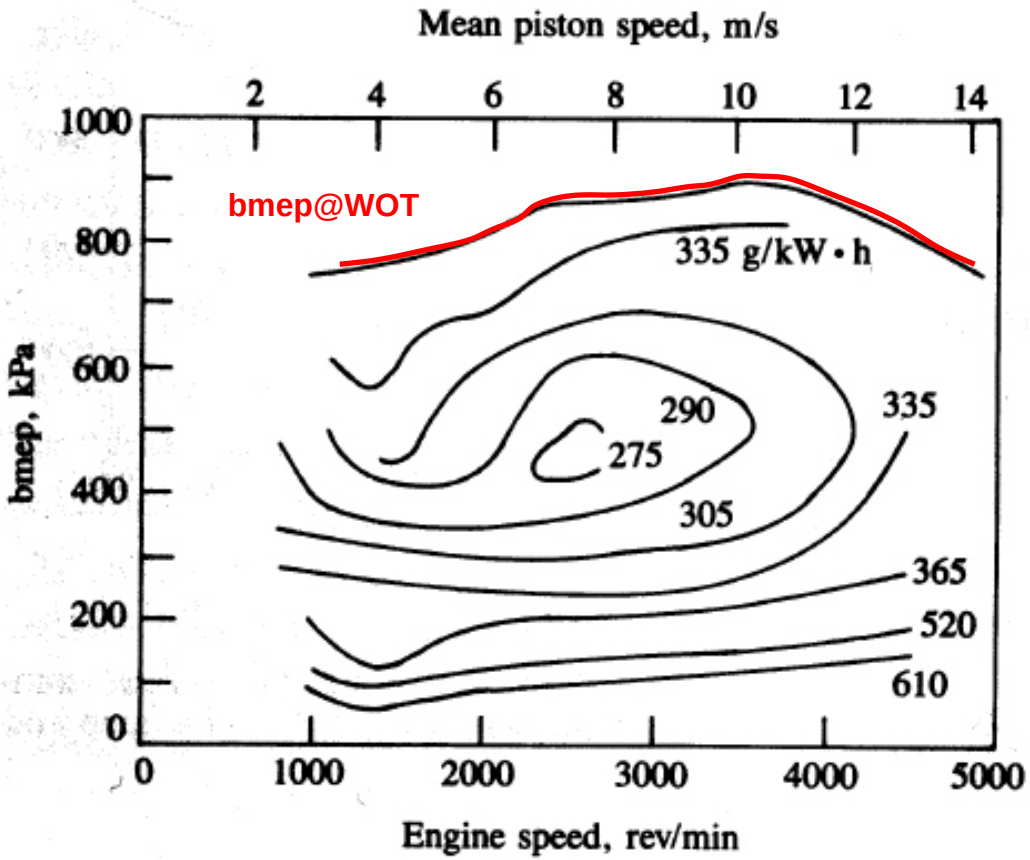
• La cse passe par un minimum



• A grande vitesse cse augmente à cause des frottements
• A faible vitesse cse augmente à cause du temps imparti aux échanges aux parois
• cse augmente avec le taux de compression à cause des pertes thermqiques plus importantes (niveaux de pression et tempéraure plus élevés)

Droites de Willans



Courbes iso-cse

$$bmep = \frac{2\pi \cdot T \cdot n_R}{V_d} \qquad bsfc = \frac{\dot{m}_f}{\dot{W}_b} \qquad \dot{W}_b = (2\pi \cdot N) \cdot T$$