Chapter 5:
Spark Ignition Engines (Otto engines)

Learning Objectives of Chapter 5

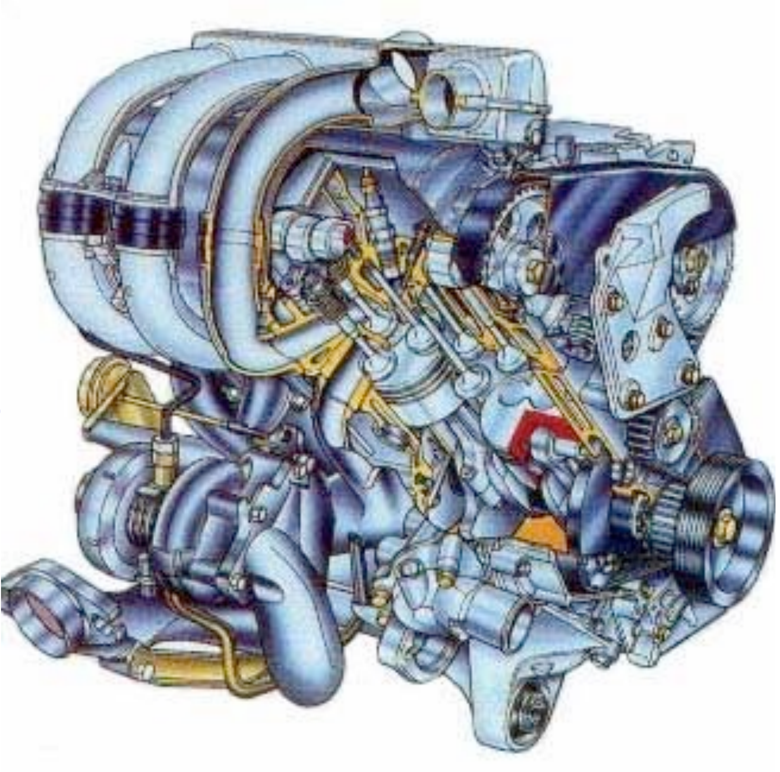
- ⇨ know the fuel properties required for an Otto cycle and recognize the different phases of the combustion process
- ⇨ know the operating principles of the most common fuel injection systems used in Spark Ignition Engines
- ⇨ understand the load regulation strategy of S.I engines and the influence of key control parameters on performances
- ⇨ identify the low & high efficiency regions in the operating map for S.I. engines and their associated limits

Content of Chapter 5

- Application range
- Operating principle
  - Fuel properties of “gasoline”
  - Injection system
  - Ignition system
  - Combustion process in S.I. engines
- Load regulation parameters
  - Partial load operation
  - Full load operation
- Energy distribution in S.I. engines
  - Origin of losses and representation in the operating map
  - Comparison between C.I. and S.I. Engines

Application range

- Common use and applications
  - 4-stroke cycle
    - Motorcycles ($V_{cyl} > 125\ cm^3$)
    - Passenger cars
    - High-speed marine engines
    - Agricultural machines (small V_{cyl})
    - Airborne vehicles (airplane, helicopters)
  - 2-stroke cycle (trend to ⇘)
    - Scooters
    - Motorcycles ($V_{cyl} \leq 125\ cm^3$)
    - Home-use (scale model)



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Operating principle

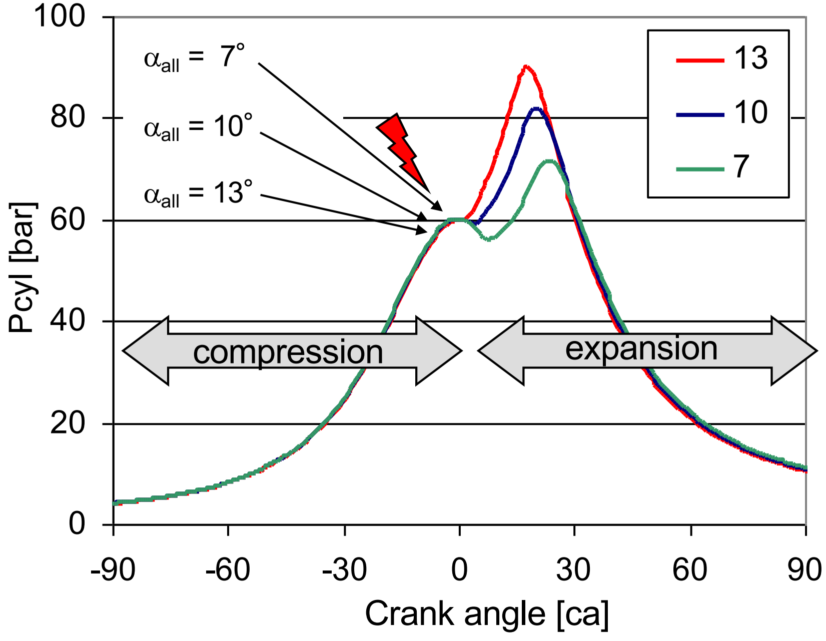
General

- The combustion process in Spark Ignition (S.I.) engines is ignited by an external device (generally by a spark plug which produces an electric arc) at a given time (=given crank angle) of the engine cycle

- The electric arc enables to :
  - ⇒ obtain the favorable conditions for auto-ignition of the mixture
  - ⇒ initiate the combustion process
  - ⇒ control the start of the combustion

- α_{all} : spark advance angle (7,10,13,..)
  (‘all=allumage (fr): spark ignition)
  - ⇒ (degrees **before** TDC) defines the timing of the combustion in the engine cycle

Cylinder pressure evolution = f(crank angle)



The optimum α_{all} obviously changes with **engine speed** and **quantity of fuel** injected.

Rule-of thumb : the most efficient point for combustion is when peak-pressure is reached at +10 to +15 crank angle degrees

Operating principle

Fuel properties of gasoline

⚠ λ : relative to a homogeneous mixture

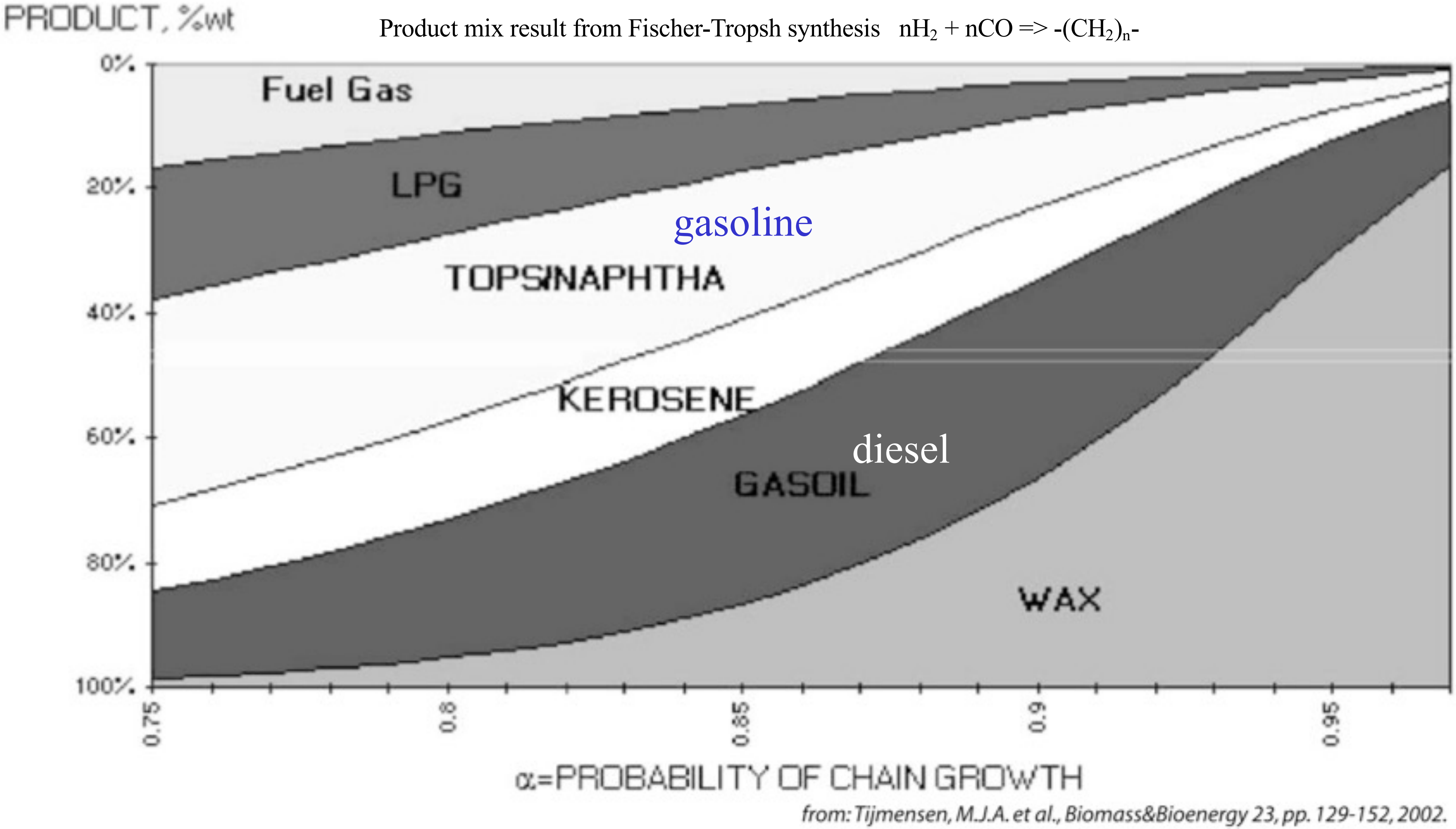
ρ [kg/L]	Distillation range [° C] Initial T°	Final T°	nmbr of carbon atoms	$R_{A/F}$ [kg_{air}/kg_{fuel}]	Upper flammability limit [ϕ] / [λ]	Lower flammability limit [ϕ] / [λ]
0.72 – 0.77	**30 - 35**	**180 - 200**	**4 - 11**	**≈ 14.4 – 14.7**	**3.8 / 0.27**	**0.6 / 1.66**

Octane Number : RON (Research) / MON (Motor)

- characterizes the resistance to the auto-ignition of a fuel
- RON xx $\Rightarrow$ corresponds to a binary mixture of 2 pure HC fuels with the same behavior than the one which is analyzed (i.e. knocking occurrence) on a reference engine (ε (CR) adjustable from 4:1 to 18:1)
  - RON 0 : corresponds to a fuel-mix identical to 100% n-heptane (very favorable for auto-ignition)
  - RON 100 : corresponds to a fuel-mix identical to 100% iso-octane (very resistant to auto-ignition)
  - RON 95 : corresponds to a fuel-mix identical to a mixture with 95% iso-octane and 5% n-heptane.
- Commercial fuels : RON = 95 to 98 (≈103 in F1)

Q : what happens if you fill diesel in a S.I.E.?
Q : what happens if you fill gasoline in a C.I.E?

Rem: fuel mixtures as f(carbon number)



from: Tijmensen, M.J.A. et al., Biomass&Bioenergy 23, pp. 129-152, 2002.

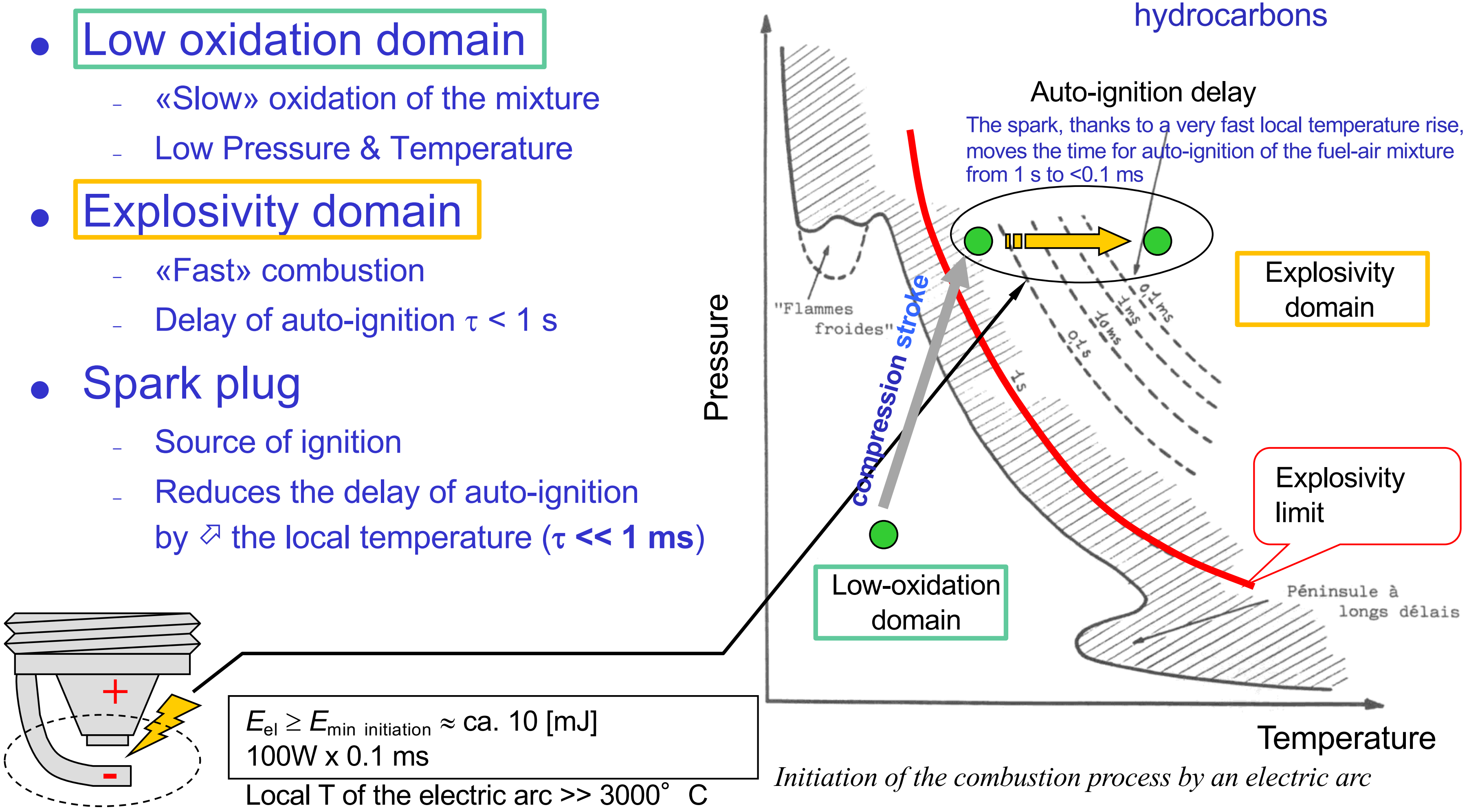
Corresponds to the different fractions from oil distillation

Operating principle

Representation of auto-ignition delays

- Low oxidation domain
  - «Slow» oxidation of the mixture
  - Low Pressure & Temperature
- Explosivity domain
  - «Fast» combustion
  - Delay of auto-ignition $\tau < 1$ s
- Spark plug
  - Source of ignition
  - Reduces the delay of auto-ignition by ⬀ the local temperature (τ **<< 1 ms**)

P-T-diagramme for hydrocarbons



Auto-ignition delay

The spark, thanks to a very fast local temperature rise, moves the time for auto-ignition of the fuel-air mixture from 1 s to <0.1 ms

$E_{el} \geq E_{min\ initiation} \approx$ ca. 10 [mJ]
100W x 0.1 ms

Local T of the electric arc >> 3000° C

Initiation of the combustion process by an electric arc

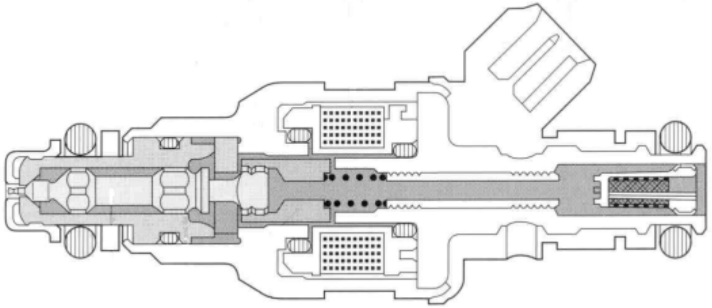
The spark creates radicals and ionizes air which starts the combustion chain reaction

Operating principle

- Injection systems (from old to new)
  - Carburetor — Continuous fuel injection
  - Indirect injection
  - Direct injection

  } electronic injection on timing with the engine cycle

- Indirect injection
  - Electronic actuators (magnet valves) ⇒

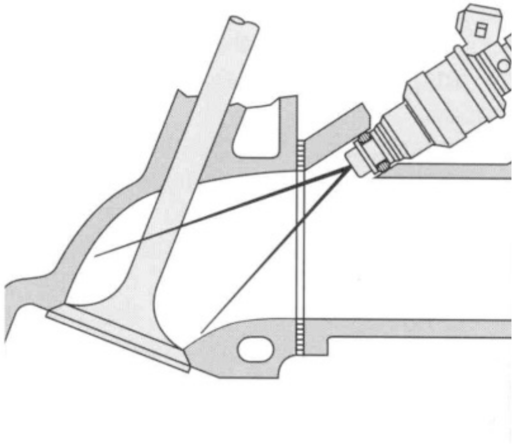


  - Sequential injection
  - Low pressure injection into the air circuit
    - in the range **between 3 and 6 bar**
    - **before the intake valves**
  - Air-fuel mixture is **homogenous** (const. λ)
  - Controlled by varying the current duration: $t_{injection}$

    Injection duration gives the fuel quantity : $t_{inj} = f\,(M_F)$

    ⇒ requires an ECU (Electronic Control Unit)

    ⇒ requires sensors to know the thermodynamic conditions of the engine



Operating principle

Direct injection

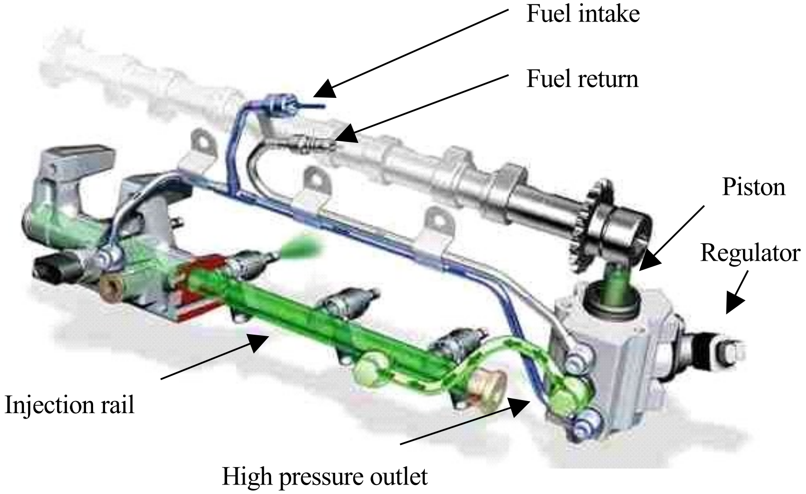
- Injection under high pressure directly **into the combustion chamber**
- P_{inj} set between 5 and **120 bar** (Diesel:2000 bar!)
- 2 strategies of injection are feasible:

  A) During *intake* of the air/mixture

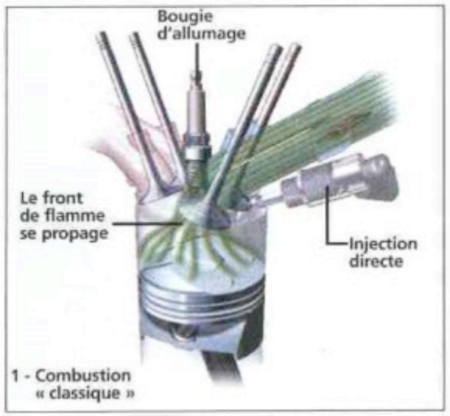
  ⇒ Air-Fuel mixture is **homogeneous**

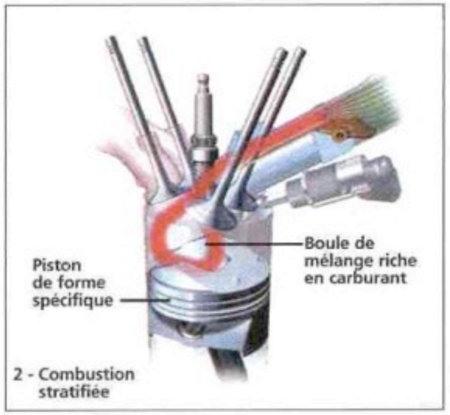
  B) At the *end of the compression* stroke

  ⇒ Air-Fuel mixture is **heterogeneous (or stratified)** – ‘diesel-like’



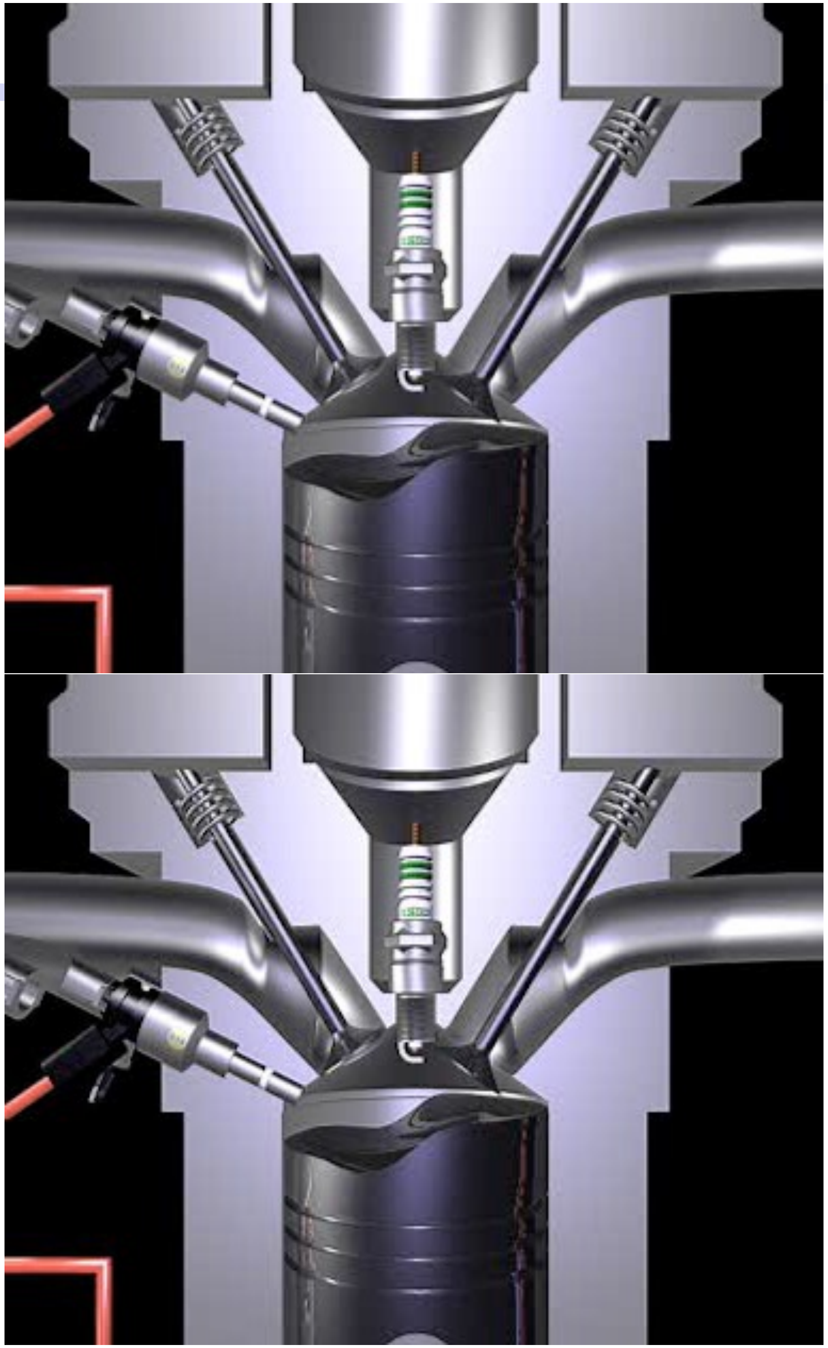
Injection in homogeneous mixture





Injection in heterogeneous (or stratified) mixture (FSI Fuel-stratified injection)

Operating principle



- Direct injection
  - **Homogeneous** mixture

for ***FULL*** *load*

or **Injection @1-2 bar @BDC**

homogeneous operating mode ⇒

$$\boxed{\lambda(x,y,z) = \lambda_{global} = cte}$$

$\lambda = 0.3 \ldots 1.7$

  - **Heterogeneous** mixture

for ***PART*** *load*

or **Injection @30-40 bar @TDC**

heterogeneous operating mode **(stratified mode)** ⇒

$$\boxed{\lambda(x,y,z) = \nabla_{x,y,z}}$$

λ = local

Only air is compressed, the throttle valve does not have to be closed too much => better part load efficiency

Operating principle

Ignition system

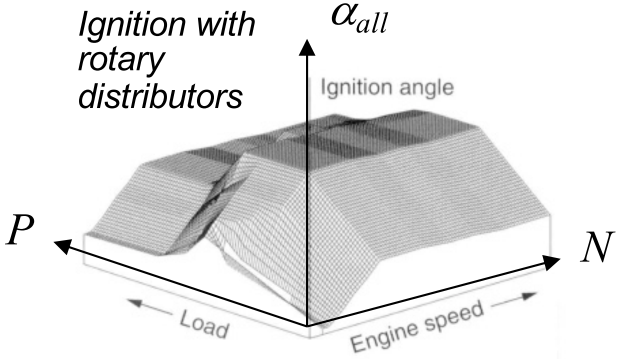
- Function : generate the required conditions to initiate the combustion process
- Energy input given by a spark ⇒ produced at high voltage between 2 electrodes ≈10 to 20 kV (10 kV * 10 mA = 100 W, for 0.1 ms => 10 mJ)
- The optimal spark timing angle (advance angle) depends on the engine speed (N) and load (P_{adm}) = operating map
- Control device for spark angle α_{all}

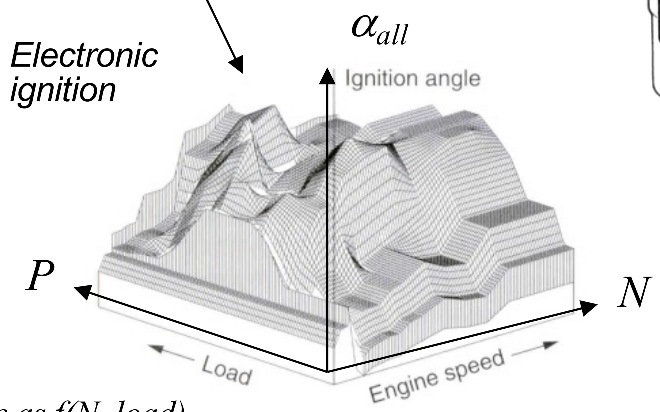
  1) Mechanical devices (=previously)

  ⇒ Conventional coil and rotary distributors

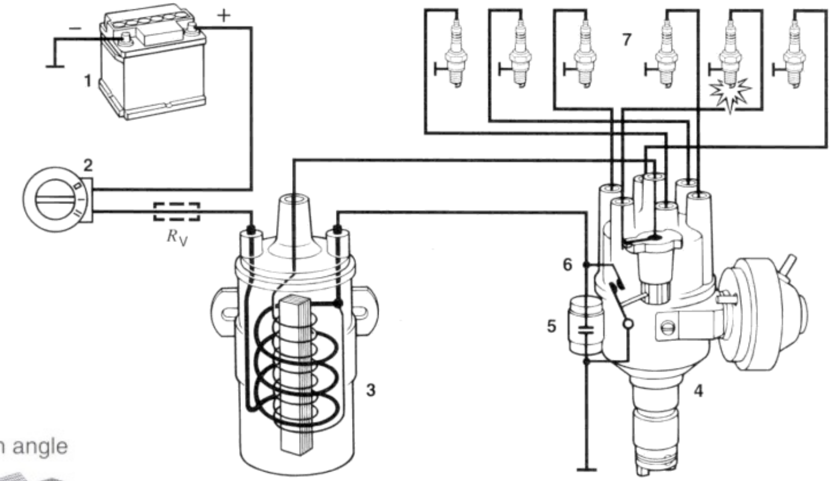
  2) Electronic units (fully programmable) = today

  ⇒ ECU (ignition angle map)


Ignition with rotary distributors


Electronic ignition

= *spark angle as f(N, load)*



Mechanical ignition system

(spark angle based on mech. load and N)

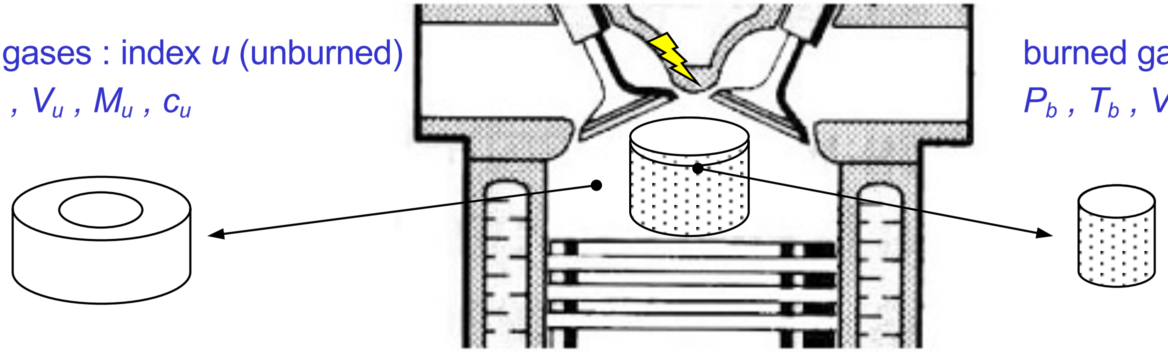
'all = allumage' (fr) = S.I.

Operating principle

Combustion process in S.I. engines

- According to the ignition system used (direct *or* indirect injection), there are 2 different combustion processes in S.I engines :
  - Combustion in homogeneous mixture
  - Combustion in stratified mixture

- For both cases, the mean to initiate the combustion is identical:
  - Ignition by an external source (spark generated by an electric discharge)
  - Propagation of a turbulent flame at high speed dividing the combustion chamber into 2 zones : fresh (unburned) gases (u) & burned gases (b) :



Fresh gases : index *u* (unburned)
P_u , T_u , V_u , M_u , c_u

burned gases: index *b* (burned)
P_b , T_b , V_b , M_b , c_b

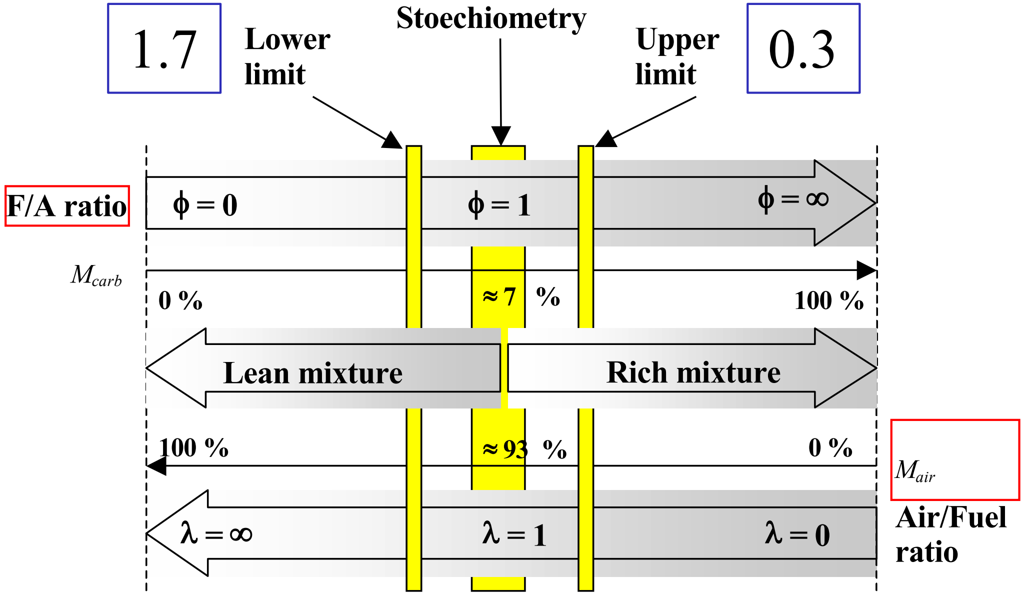
heat capacity

Operating principle

- Combustion process in S.I. engines
  - **Homogeneous** combustion process:
    - Air / Fuel ratio is constant everywhere in the comb. chamber: $\boxed{\lambda(x,y,z)=\lambda_{global}}$
    - Condition for flame propagation during the combustion : $\boxed{L_I<\lambda<L_S}$ lower and upper flammability limits (sl. 8)

      $\lambda_{mixture}$ should be contained in the flammability range: $0.3 < \lambda < 1.7$

      (going beyond these limits is only possible by stratified combustion)



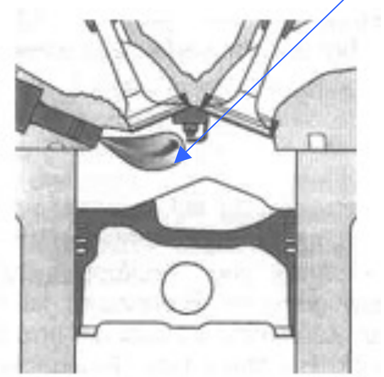
In practice: $\lambda = 1.0$ for exhaust gas after-treatment by 3-way catalyst (catalytic converter)

Operating principle

- Combustion process in S.I. engines
  - **Stratified** combustion process:
    - **Heterogeneity** of the Air / Fuel mixture in the C.C : $\boxed{\nabla\lambda(x,y,z) \rightarrow \lambda(x,y,z) \neq \lambda_{global}}$
    - Stratification of the mixture ⇒ consists of splitting the chamber in 2 zones:

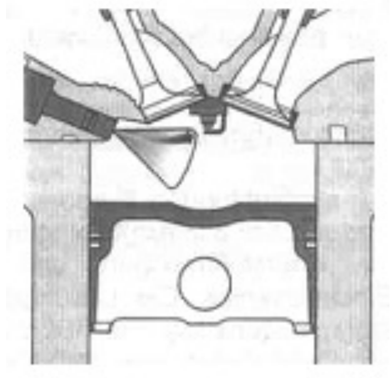
      1) A/F mixture at $\lambda_{local} \approx 1$

      2) Fresh Air domain (inert for the process)
    - 3 possibilities (ways) to control the stratification:



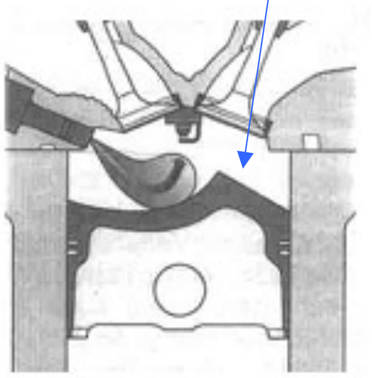
1) by the injection system

(orient fuel close to spark)



2) by the internal air motion

(vortex, turbulence)



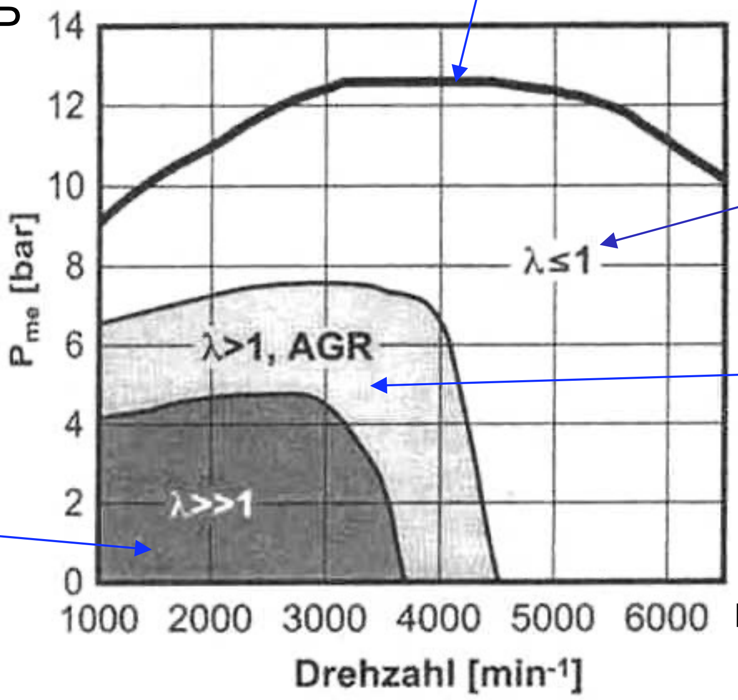
3) by the design (shape) of the chamber / piston

Operating principle

Combustion process in S.I. engines

<u>atmospheric</u> engine:

1. **full load** curve : stoichiometric combustion (homog.)



stoichiometric λ=1, or λ down to 0.9
for high specific power, at high speed

2. lean burn, homogeneous
(λ 1 to 1.6)
(AGR: exhaust gas recirculation
= lean burn combustion)

higher global λ,
2 to 5 (stratified)

3. stratified combustion domain (local combustion): used in **partial load** operation to improve the engine efficiency by reducing the pumping losses.
It represents only 1/5th of the operating **<u>map</u>** but most (80-90%!) of the operating <u>time</u>!

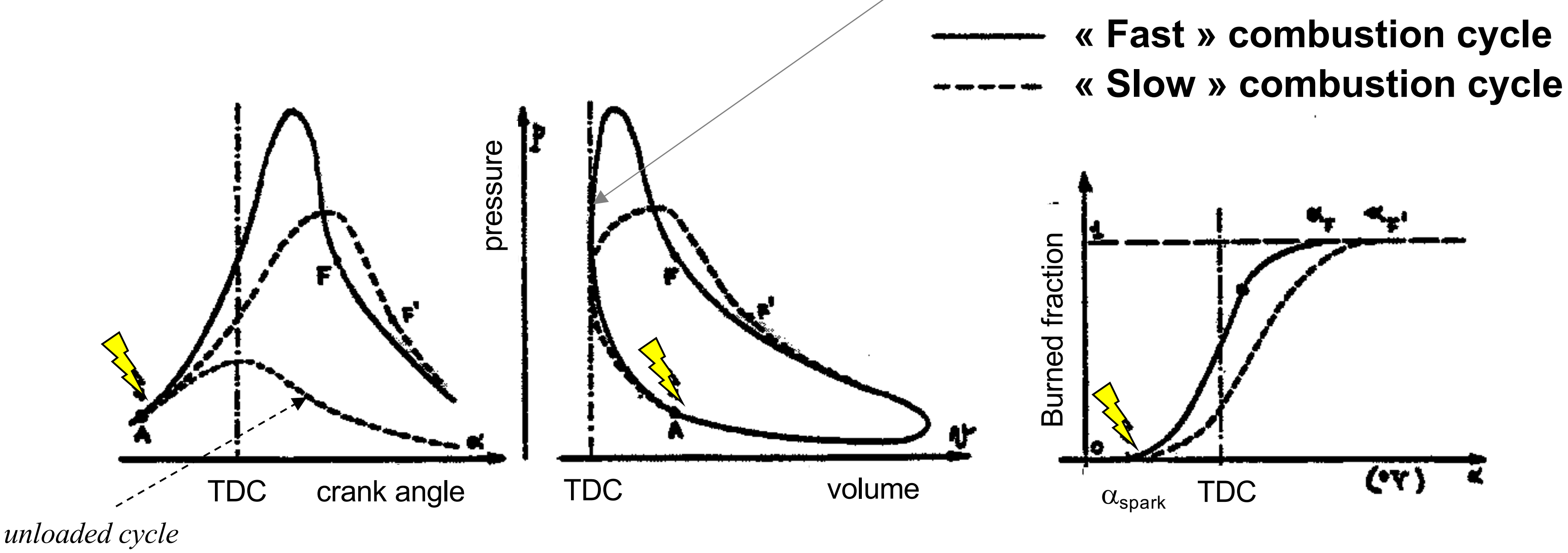
For turbocharged engines, the operating map is displaced a bit:
the engine is downsized => the full load curve goes down, the operating regime of the stratified range is widened

Operating principle

Combustion process in S.I. engines

Key parameters affecting the combustion

- Combustion **speed**:
  - Ideal spark ignition combustion cycle = constant volume cycle



=> we want to accelerate the combustion speed (to maximise efficiency) because the combustion process in Otto engines depends only on internal parameters (ε, γ)

≠ Diesel engine, where the rate of fuel injection influences the combustion duration

Operating principle

Combustion process in S.I. engines

Key parameters affecting the combustion (1):

v slow (laminar) speed for all fuels

- The combustion **speed** depends on the following 4 factors:

$$\begin{cases} \vec{v}_{CH4} \approx 45\ cm/s \\ \vec{v}_{Isooctane} \approx 41\ cm/s \\ \vec{v}_{H2} \approx 325\ cm/s \end{cases}$$

1) Type of fuel : example of laminar propagation speed at $\lambda \approx 1$: →
2) Pressure and temperature conditions of the mixture
3) Internal air motion ⇒ creation of vortex (**turbulence**)

factor 100

⇒ **Laminar** flame velocity ≈ 0.3-0.6 m/s

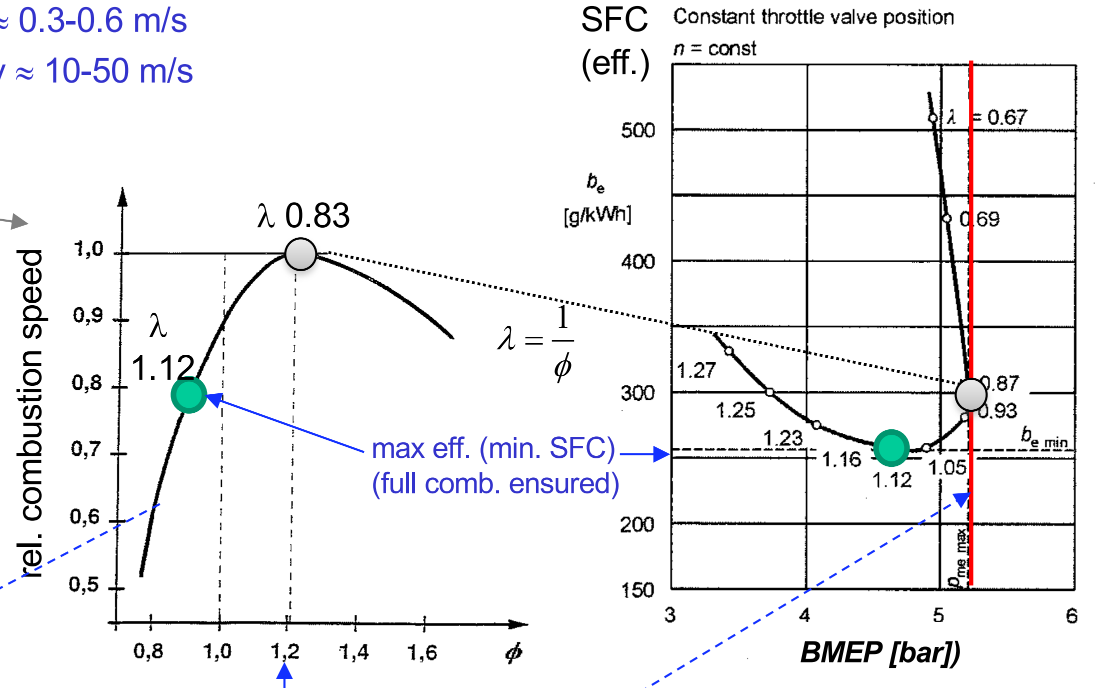
⇒ **Turbulent** flame velocity ≈ 10-50 m/s

4) A/F ratio :

Criteria of $\dot{E}_{e\,\max}$ $\neq$ Criteria of $\eta_{\max}$

specific fuel consumption

SFC (eff.)



max eff. (min. SFC) (full comb. ensured)

steep reduction of combustion speed at λ > 1

rich mixture! => max power!

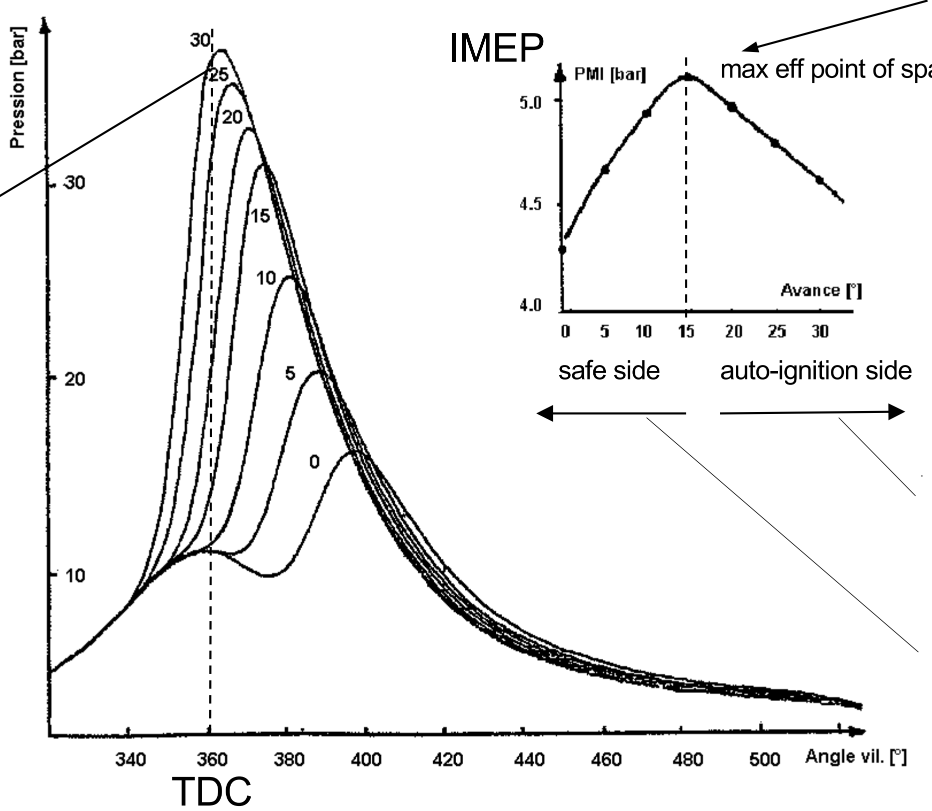
Operating principle

- Combustion process in S.I. engines

Key parameters affecting the combustion (2) : spark advance angle

⇒ enables to “set” / “time” correctly the combustion process in the engine cycle in order to minimize the loss of indicated efficiency:

$$\boxed{\eta_{i,\max} = \eta_i(\alpha_{optimal})}$$



Auto-ignition danger (knocking) is at the larger advance angles since higher pressure is reached

max eff point of spark adv angle

safe side ← → auto-ignition side

Δ-IMEP: 0.8 bar (15-20%):
The spark advance angle changes the combustion P-v diagramme by 15-20%, thus also the IMEP and hence the power by 15-20%

If angle is too early, then the starting combustion will push back the piston still moving up.

If angle is too late (piston already going back down when combustion starts), too much combustion enthalpy will leave the exhaust

⇒ The « optimal » spark advance angle (called MBT: maximum break torque) maximizing the engine torque is directly linked to the combustion speed

Operating principle

Combustion process in S.I. engines

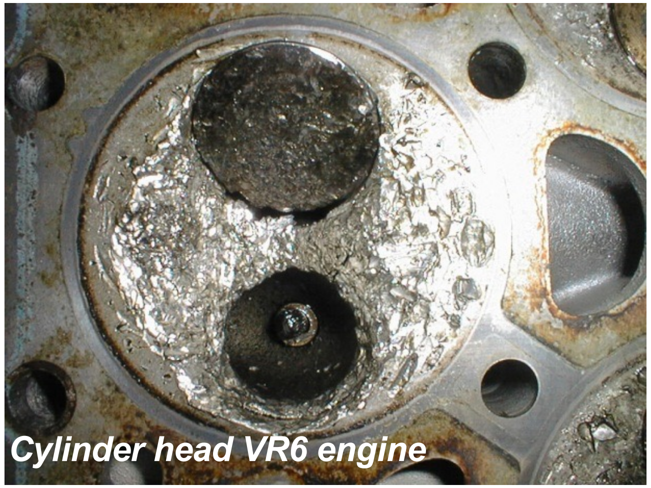
Auto-ignition phenomenon: knocking (*in french: cliquetis*)

- The optimal timing of the combustion is limited by the **knock** phenomenon:

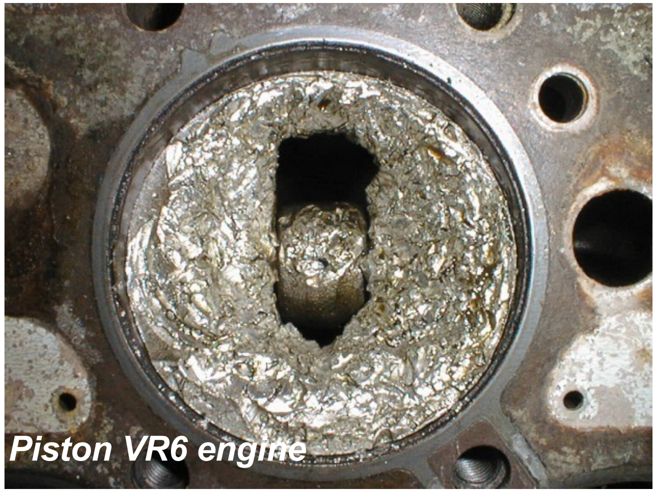
  ⇒ corresponds to the auto-ignition of a part of the unburned fuel-air mixture (end-gas) still not reached by the flame propagation.

  ⇒ This auto-ignition produces a spontaneous and rapid combustion (v_{comb} ⇗⇗) in a 2nd zone => 2 flame fronts collide, which causes high local pressure variations (shock waves) followed by high vibrations of the gases (propagation of pressure waves at a velocity of 500 to 900 m/s). (1 Mach = 340 m/s)

  ⇒ engine components can be extremely damaged (in a matter of seconds):



Cylinder head VR6 engine



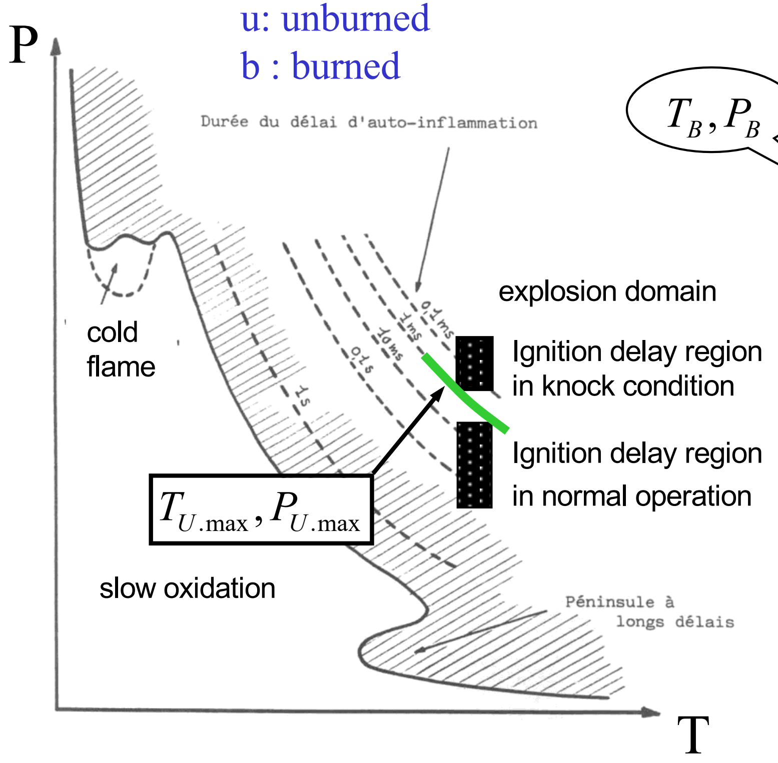
Piston VR6 engine

Operating principle

- Combustion process in S.I. engines

Auto-ignition phenomenon: knocking

- Engine cycle with knocking appearance:



P

u: unburned

b : burned

cold flame

explosion domain

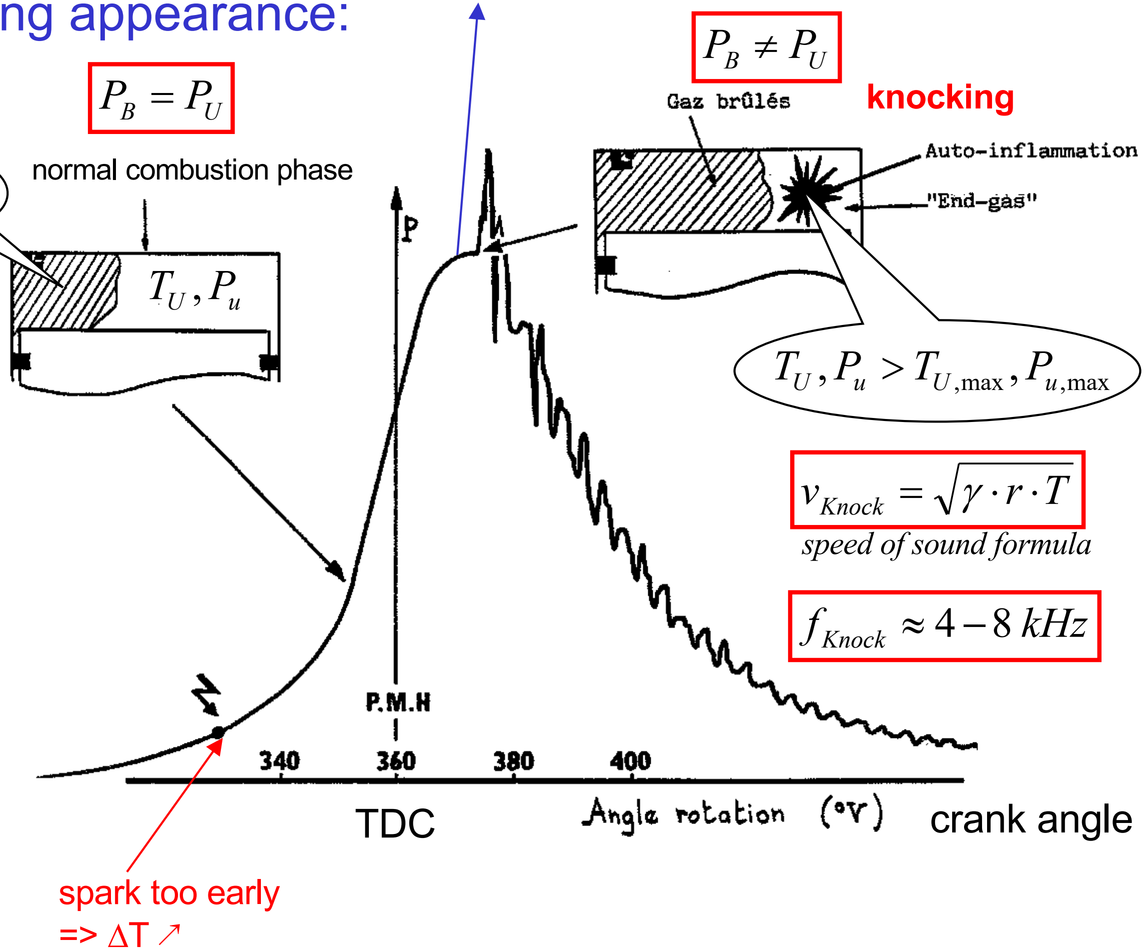
Ignition delay region in knock condition

Ignition delay region in normal operation

$T_{U.\max}, P_{U.\max}$

slow oxidation

T



high P reached in unburned zone
=> autoignition => knocking

$P_B \neq P_U$

knocking

$P_B = P_U$

T_B, P_B

normal combustion phase

T_U, P_u

$T_U, P_u > T_{U,\max}, P_{u,\max}$

$v_{Knock} = \sqrt{\gamma \cdot r \cdot T}$

speed of sound formula

$f_{Knock} \approx 4 - 8\ kHz$

TDC

crank angle

spark too early
=> ΔT ↗

When the accelerometer registers 4-8 kHz vibrations, the ECU has to reduce the spark advance angle.

Operating principle

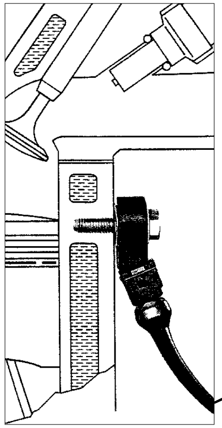
- Combustion process in S.I. engines

Auto-ignition phenomenon: knocking

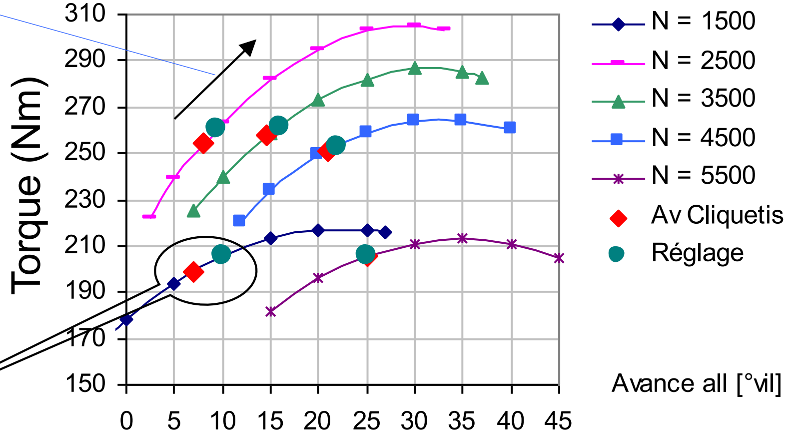
- Influence of operating parameters on knocking tendency:
  1. Air/Fuel mixture composition
     $\Rightarrow$ Tendency to increase the ***RON*** of the fuel
  2. Temperature and pressure of the fresh gas mixture
     $\Rightarrow$ Tendency to reduce (!) the compression ratio ($\varepsilon \nearrow$ for $\nearrow \eta_i$) !
     $\Rightarrow$ Tendency to reduce α_{all} (spark advance angle) until knock occurrence

corresponds to RON increase (higher resistance to auto-ignition)

Courbe de chapeau d'avance pleine charge du moteur F4RT



knock sensor (accelerometer)



@2500 rpm: Torque 250 Nm → 300 Nm: we could have 20% more power by moving the advance angle by -20; however, the knocking limit prevents us from doing it.

Green : limit of knocking occurrence
Red : safety margin fixed by the ECU

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Load regulation parameters

- Relations (cf. Diesel engine slides)
  - **Multicylinder** :
    - $\dot{E}_e$ as a function of $\dot{M}_A$:

$$\boxed{\dot{E}_e = \underbrace{\eta_{mec}\cdot\eta_i}_{\eta_e}\cdot\underbrace{\dot{M}_A\cdot q}_{\dot{M}_F\cdot LHV}}$$

with

$$q = \begin{cases} \dfrac{LHV}{R_{A/F}}\cdot\dfrac{1}{\lambda} & if \quad \lambda \geq 1 \\ \dfrac{LHV}{R_{A/F}} & if \quad \lambda \leq 1 \end{cases}$$

    - $\dot{M}_a$ as a function of P_{coll}, T_{coll} :

$$\boxed{\dot{M}_A = n_c\cdot\underbrace{\eta_{vol}\cdot\frac{P_{coll}}{r\cdot T_{coll}}\cdot V_u\cdot n}_{M_A}}$$

with

$$V_{cyl} = n\cdot V_u$$

$\dot{M}_A$: Total mass air flow of the engine

n_c : Number of engine cycles per second

M_A : Mass of air introduced into a cylinder and per cycle

q : Energy content of the mixture : [kJ/kg$_{air}$]

    - $\dot{E}_e$ as a function of P_{coll}, T_{coll} :

$$\boxed{\dot{E}_e = \underbrace{\eta_{mec}\cdot\eta_i}_{\eta_e}\cdot\underbrace{\underbrace{\frac{N}{60\cdot n_{TM}}}_{n_c}\cdot\underbrace{\eta_{vol}\cdot\frac{P_{coll}}{r\cdot T_{coll}}\cdot V_u\cdot n}_{M_A}}_{\dot{M}_A}\cdot q}$$

<u>Rem</u>: 'coll(ector) = intake, <u>admission</u>'

Load regulation parameters

- Load regulation for S.I. engines: summary

A) **Stoichiometric** engines : $\boxed{\lambda = 1}$ → λ ≠ no means of action !

- Effective power depends on ⇒ $\dot{E}_e = f\left(\cancel{\eta_{mec}}, \cancel{\eta_i}, \cancel{N}, \overset{\checkmark}{M_A}, \cancel{q(\lambda = 1)}\right)$

Means of action on $\dot{E}_e$:

Mass of air : M_A

$$M_{air} = f(\overset{\searrow}{\eta_{vol}}, \overset{\searrow}{T_{adm}}, \overset{\nearrow}{P_{adm}})$$

Pressure variation into the intake manifold

⇒ P_{coll} is the only means of action to control the power

⇒ Problem: for atm. Otto engines: $P_{coll} \approx P_0$

⇒ creation of a pressure drop on the intake manifold system (throttle valve) in order to have $P_{coll} << P_0$

Energy content of the mixture : q

$$q = f(\cancel{LHV}, \cancel{R_{A/F}}, \cancel{\lambda})$$

Fuel/Air ratio variation is limited by the stoichiometric operating mode of the engine

q = cte

P_{adm} ⇒ means of action to reduce the power of stoichiometric engines

⇒ potential to increase the maximal power of the engine

Load regulation parameters

- Load regulation for S.I. engines: summary

B) **Lean burn** engines : $\boxed{\lambda > 1}$

- Effective power depends on ⇒ $\dot{E}_e = f\left(\cancel{\eta_{org}}, \cancel{\eta_i}, \cancel{N}, \overset{\checkmark}{M_A}, \overset{\checkmark}{q(\lambda)}\right)$

secondary action ← Means of action on $\dot{E}_e$: → primary action

Mass of air : M_A

$$M_{air} = f(\overset{\searrow}{\eta_{vol}}, \overset{\searrow}{T_{adm}}, \overset{\nearrow}{P_{adm}})$$

Pressure variation into the intake manifold

⇒ P_{coll} is a means of action to control the power

⇒ Creation of a pressure drop on the intake manifold system (throttle valve) in order to have $P_{coll} < P_0$

P_{coll} ⇒ complementary means of action to change / control the engine load

Energy content of the mixture : q

$$q = f(\cancel{LHV}, \cancel{R_{A/F}}, \overset{\nearrow}{\lambda})$$

Fuel/Air ratio variation

homogeneous

⇒ Problem : flammability range (λ >1.6)

⇒ Solution : F/A ratio gradient ($\nabla\lambda$) heterogeneous, global λ 2-5

Stratified engines

λ ⇒ main means of action to change / control the engine load

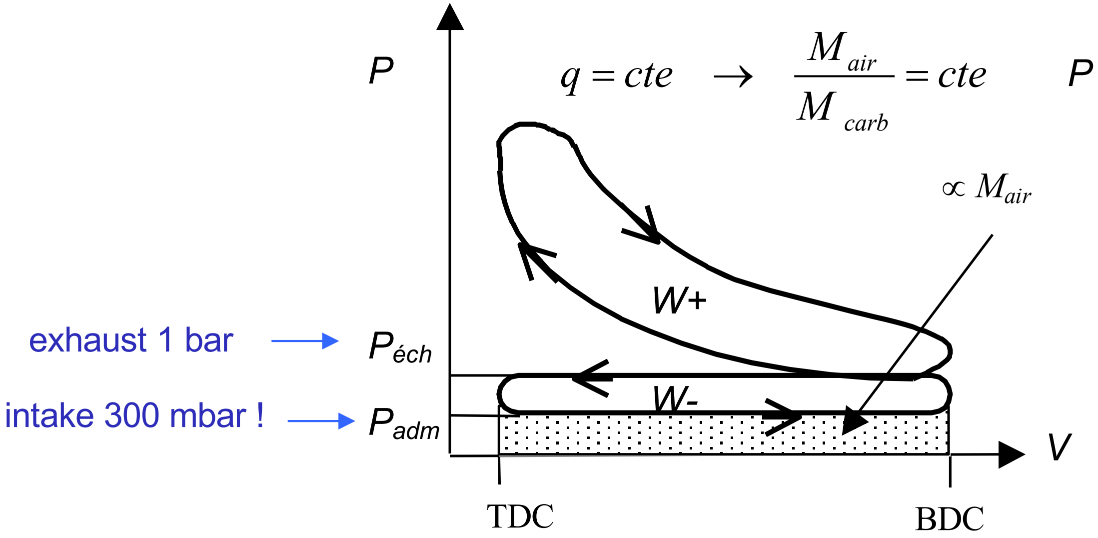
A stratified engine still has a throttle valve, but it is more often wide open, and reduced only slightly.

Load regulation parameters

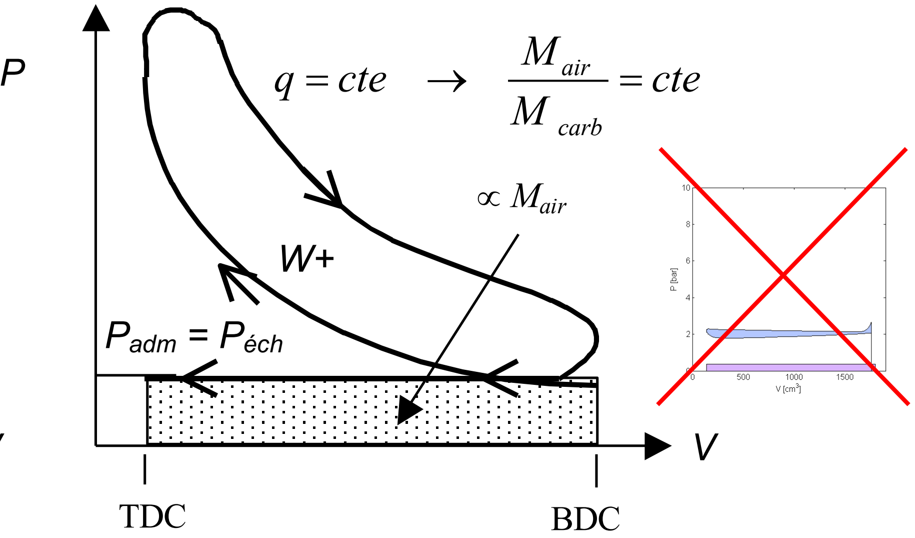
- **Partial** load operation

1. Action on P_{coll} ($=P_{adm}$):

Partial *load*



Full *load / Full throttle*



⇒ Operation at a constant A/F ratio : $\lambda = 1$

⇒ During partial load operation, creation of a negative low-pressure loop in the engine cycle generates "pumping losses":

$$\boxed{IMEP_{LP} \approx \Delta P_{exh-adm} = P_{exh} - P_{adm}}$$

Load regulation parameters

- **Partial** load operation
  - Control of $\dot{E}_e$ by action on the throttle valve in order to reduce the pressure into the intake manifold (to maintain λ=1)

$M_A \rightarrow \mathrm{var}$

$P_{adm} \rightarrow \mathrm{var}$

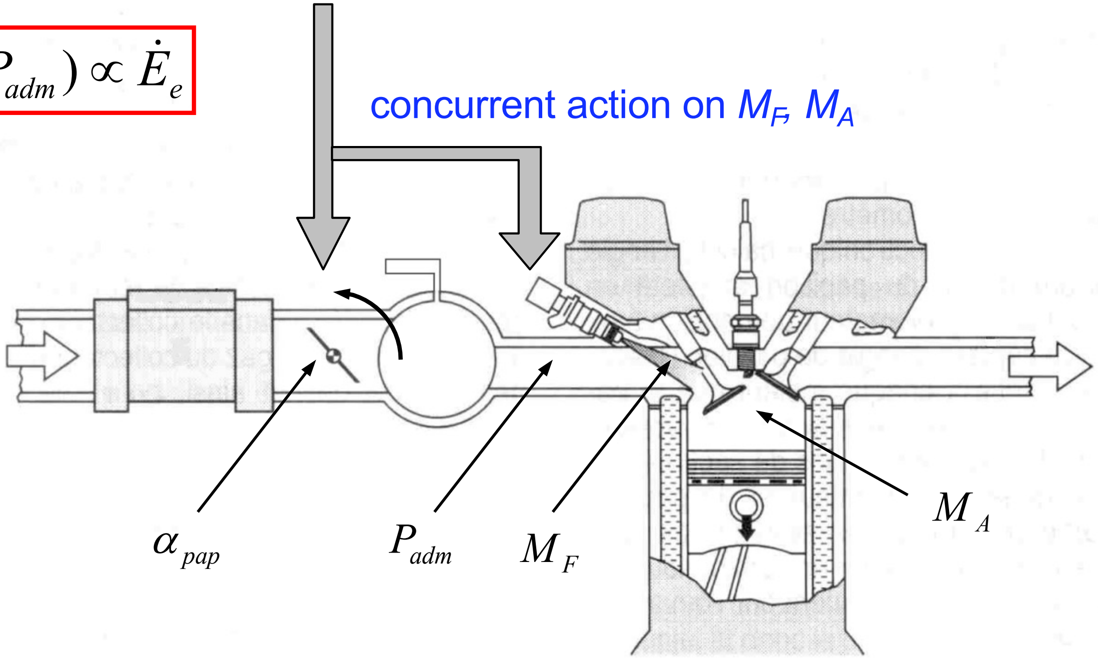
$M_F \rightarrow \mathrm{var}$

$\lambda \rightarrow cte$

$\nearrow \alpha_{pap} \rightarrow \nearrow P_{adm} \rightarrow \nearrow M_F \; (\propto \nearrow M_A) \rightarrow \nearrow \dot{E}_e$

(vanne papillon)

$$\boxed{M_A(P_{adm}) \propto \dot{E}_e}$$

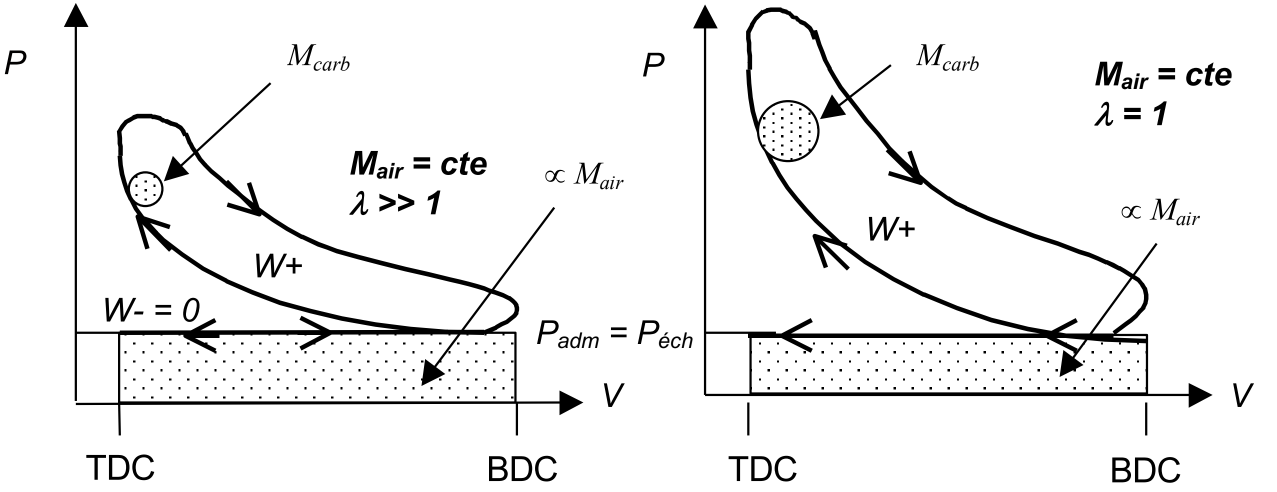


See animation (throttle valve)

Load regulation parameters

Partial load operation

2. Action on λ :



***Partial** load*

***Full** load / Full throttle*

with FSI, no need to reduce M_A as much (by the throttle valve)

⇒ λ_{global} is above the flammability limit, but $\lambda_{local} \approx 1$ so the flammability conditions of the mixture are locally satisfied

⇒ In both cases, absence of a negative low pressure loop in the engine cycle, leading to improvement of the global efficiency

Avoid the low pressure loop by having a ≈same amount of air in the cylinder, by the fuel stratified condition: controls the partial load without a throttle valve at the air inlet.

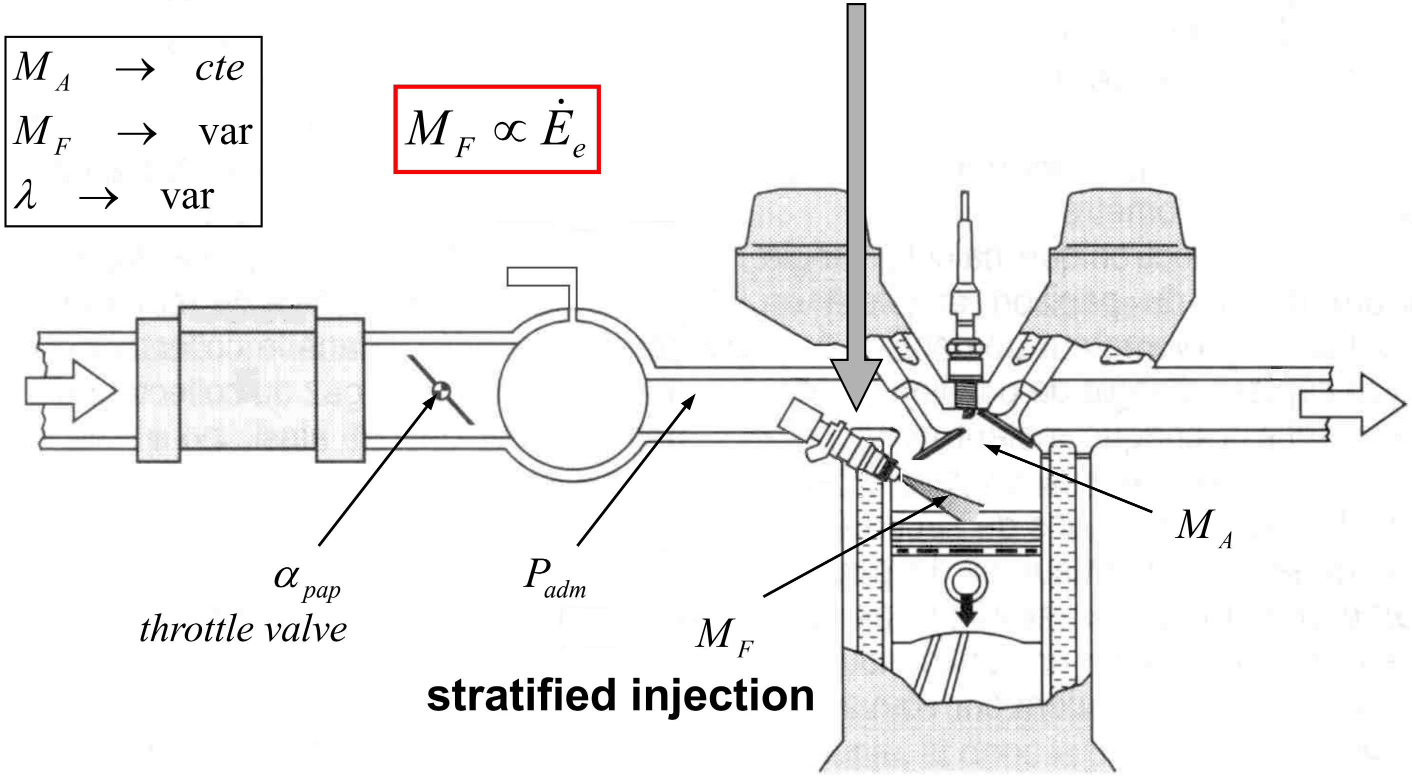
Load regulation parameters

- Partial load operation
  - Control of $\dot{E}_e$ by **action on the injected fuel quantity** :

$$\nearrow M_F\ (M_A = cte) \rightarrow \searrow\lambda \rightarrow \nearrow q \rightarrow \dot{E}_e \nearrow$$

$$\begin{array}{lll} M_A & \rightarrow & cte \\ M_F & \rightarrow & \text{var} \\ \lambda & \rightarrow & \text{var} \end{array}$$

$$\boxed{M_F \propto \dot{E}_e}$$



stratified injection

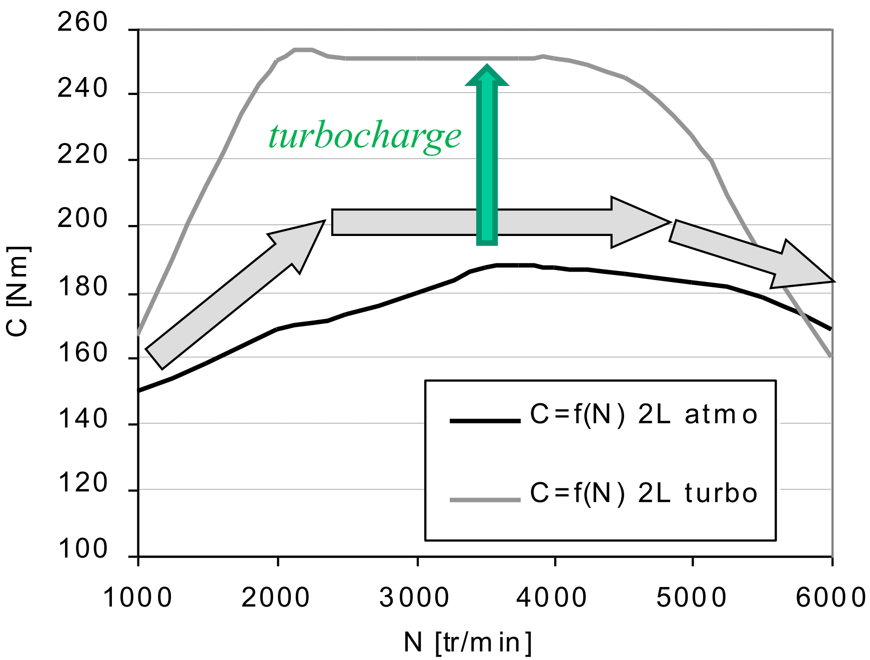
Load regulation parameters

- **Full** load operation

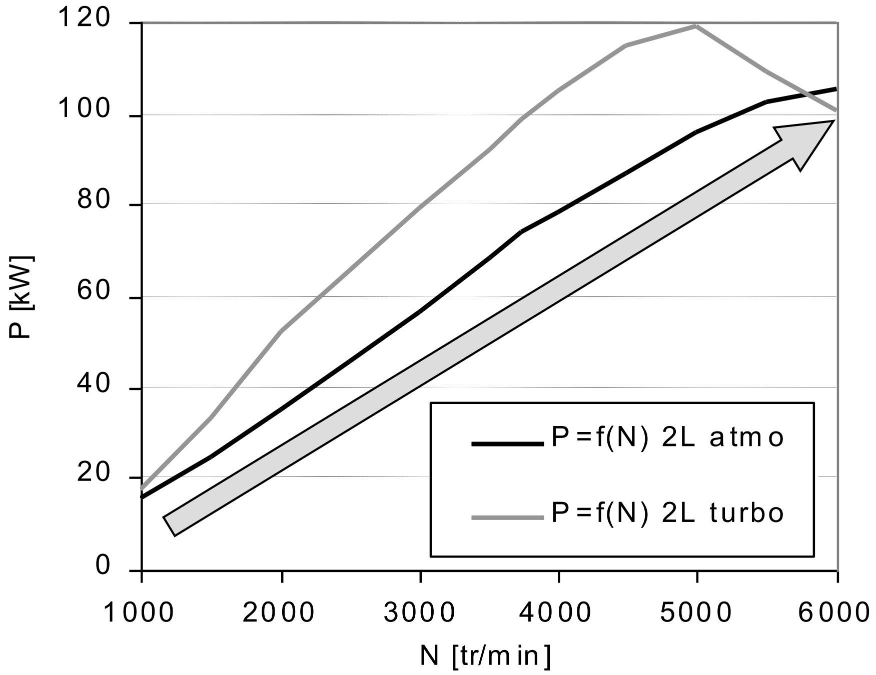
  means of action

  - Reminder : Effective power depends on ⇒ $\dot{E}_e = f(\overset{\nearrow}{N}, \overset{\nearrow}{\eta_{vol}}, \overset{\nearrow}{P_{adm}}, \overset{\nearrow}{\eta_i}, \overset{\searrow}{q})$

1. Engine speed : *N*



torque at full load



power at full load

Load regulation parameters

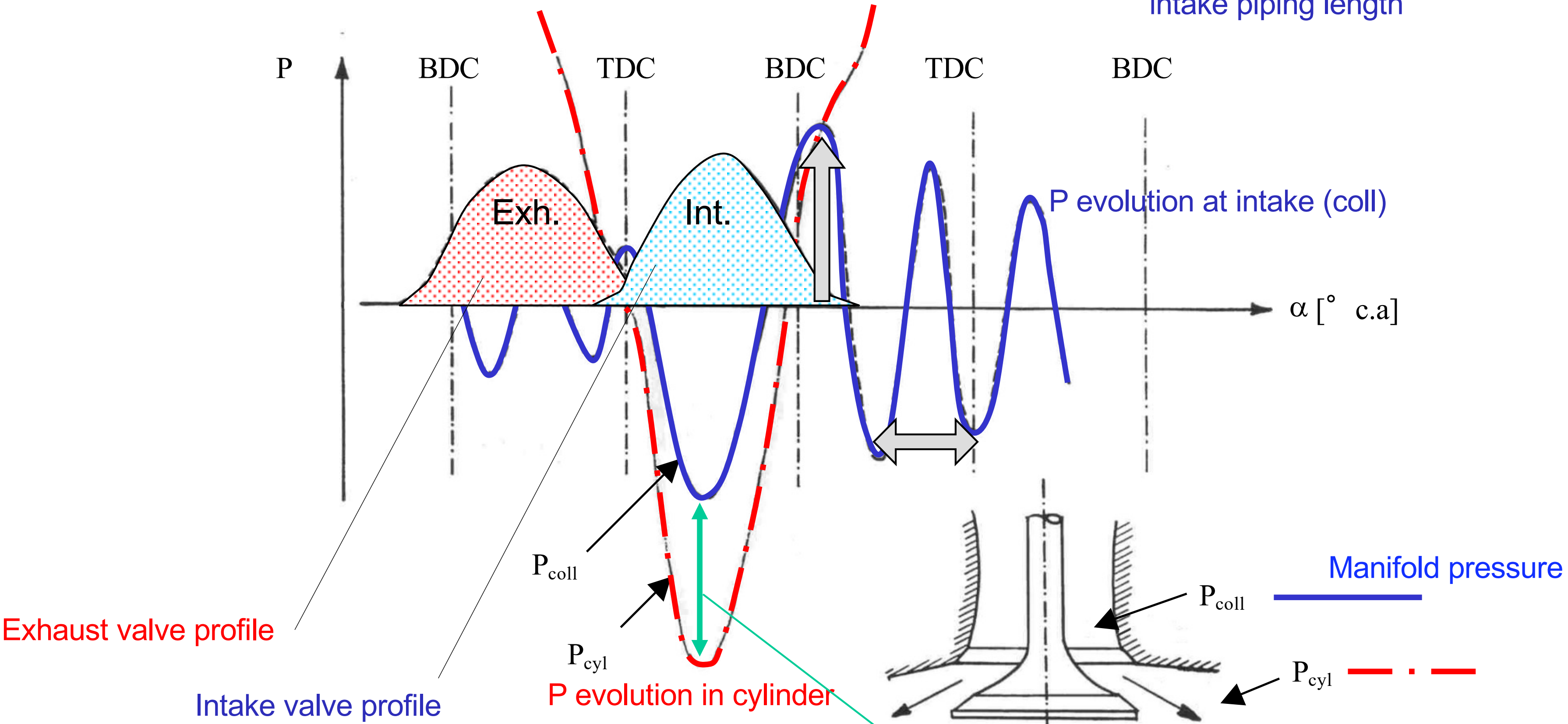
- **Full** load operation

2. Volumetric efficiency : η_{vol}

crank angle at inlet valve opening (IO) and closing (IC)

$$\boxed{\eta_{vol} = f\left(L_{pipes}, \alpha_{IO}, \alpha_{IC}\right)}$$

intake piping length



The target is to achieve positive ΔP when inlet valve is open

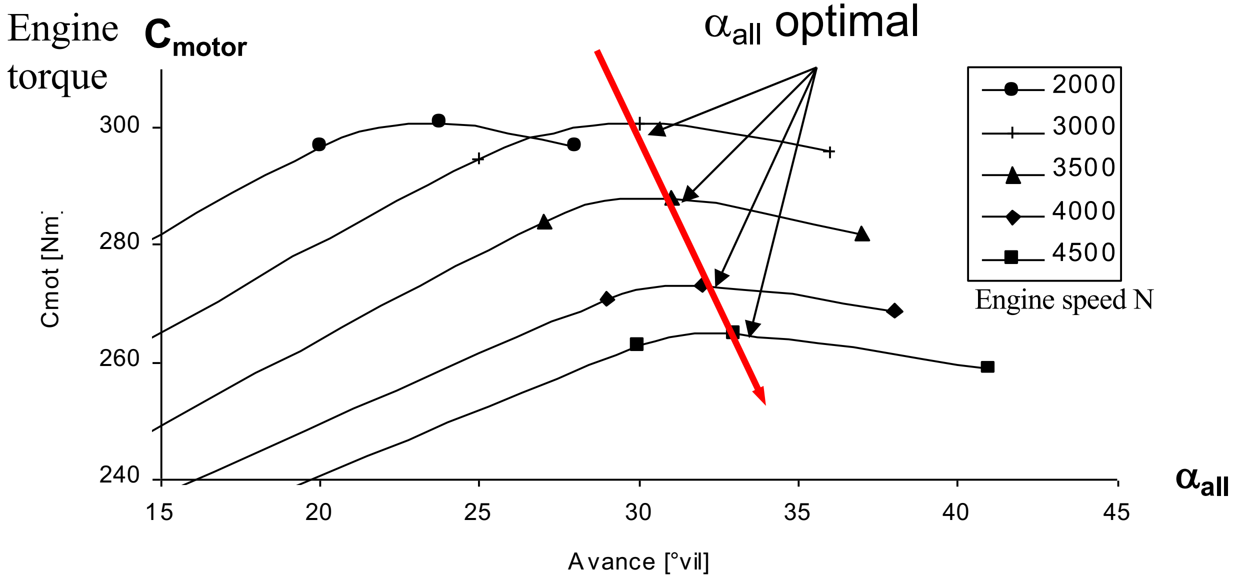
Load regulation parameters

- **Full** load operation

3. Intake pressure : P_{coll} (Turbocharging, see Chapter 4)

- ~~Compressor~~ ⇒ mechanical driveshaft on the crankcase
- Turbocharger ⇒ $h_{exhaust}$ recovery by a turbine (= equipped on all S.I.E. now)

4. Indicated efficiency : η_i ⇒ optimal spark advance angle α_{all} (limited action)



For each full load point (as fct of engine speed N) there is an optimal spark advance angle α_{all} , in order to maximize the torque C

Content of Chapter 5

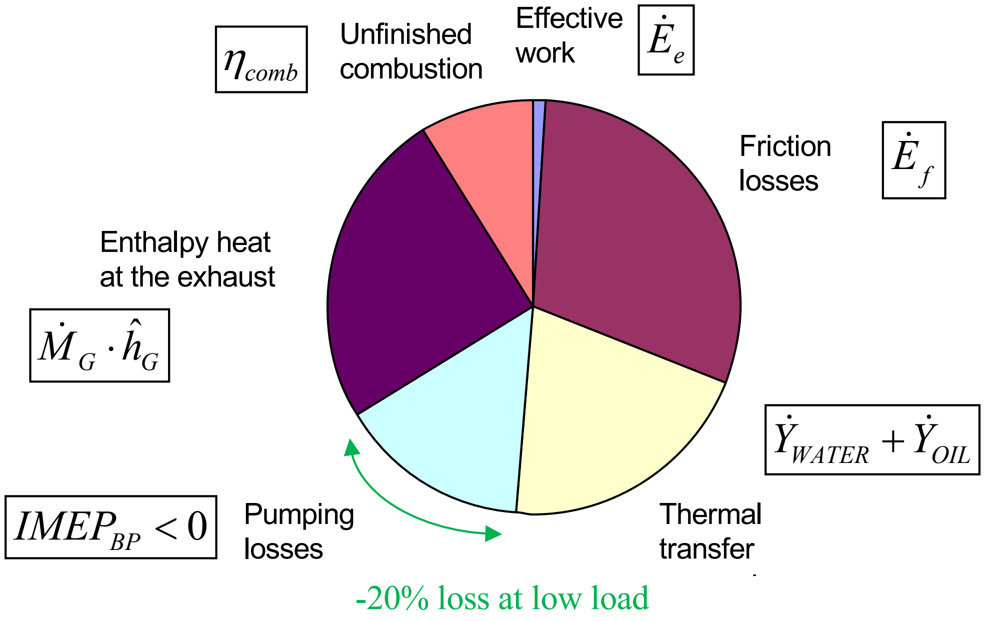
- Application range
- Operating principle
  - Fuel properties of gasoline
  - Injection system
  - Ignition system
  - Combustion process in S.I engines
- Load regulation parameters
  - Partial load operation
  - Full load operation
- Energy distribution in S.I. engines
  - Origin of losses and representation in the operating map
  - Comparison between C.I. and S.I. Engines

Energy distribution in S.I. engines

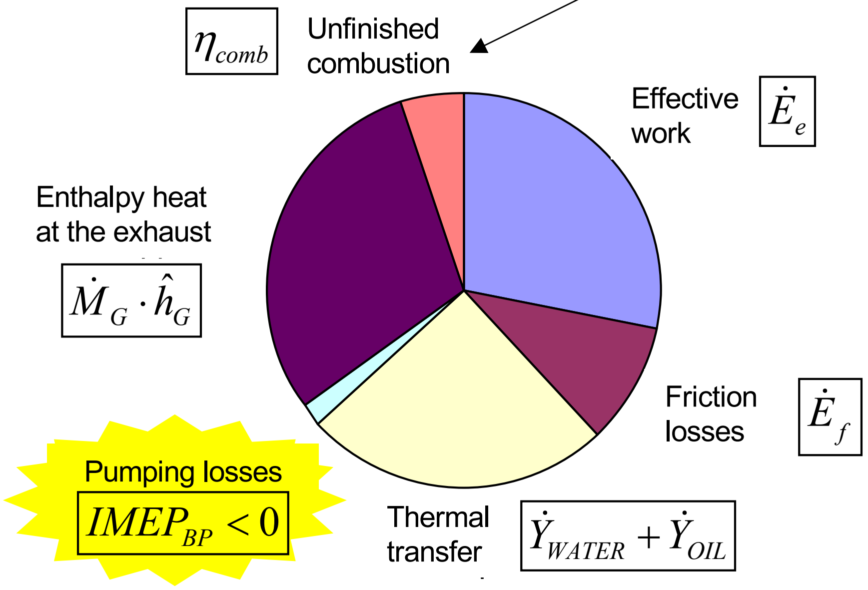
Energy balance for S.I. Engines

- Origin of losses :
  - Losses by unfinished combustion (specially in full load operation if $\lambda < 1$, rich burn conditions)
  - Enthalpy losses at the exhaust (T_{exh} is higher than C.I. engines because lower ε)
  - Heat transmitted to cooling / oil circuits
  - Friction losses and driving the auxiliary components
  - Pumping losses in partial load operation ($IMEP_{BP} < 0$) (not the case with C.I.)

Idle operation



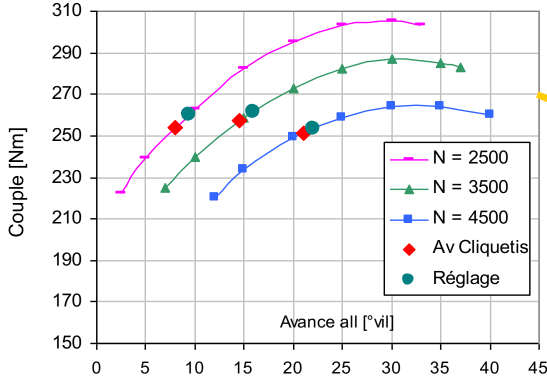
Full load operation

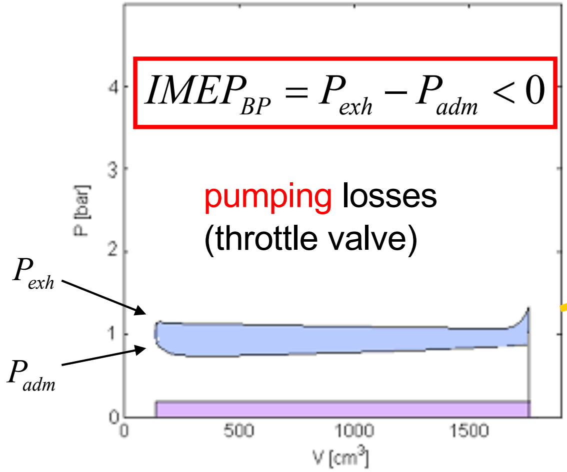


Energy distribution in S.I. engines

- Energy balance for S.I. Engines
  - Representation in operating map

knocking limit: spark advance angle has to be reduced=>lower efficiency





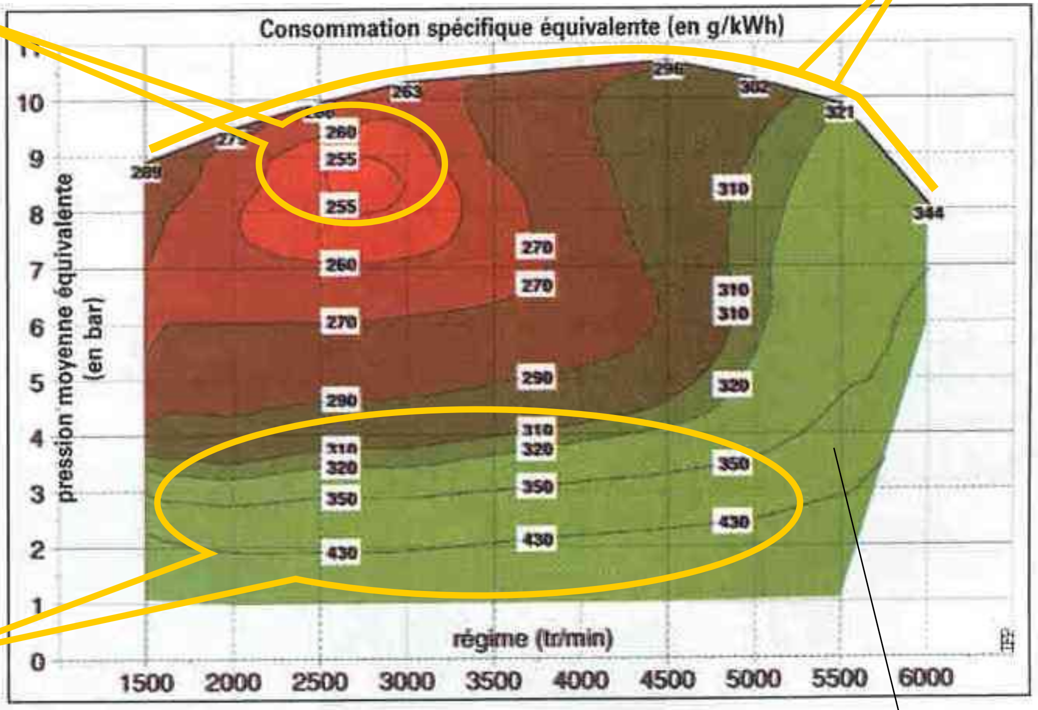
$$IMEP_{BP} = P_{exh} - P_{adm} < 0$$

pumping losses
(throttle valve)

red: high efficiency
green: low efficiency

BMEP

SFC



Fuel excess for high power: poor efficiency

$$\lambda(\dot{E}_{e,\max}) < 1$$

SFC [g/kWh]	η_g [%]
220	38.0
230	36.4
250	33.5
260	32.2
280	29.9
300	27.9
350	23.9
400	20.9
500	16.7
900	9.3
1500	5.6
3000	2.8

engine speed↗ : higher friction loss

Energy distribution in S.I. engines

- Energy balance for S.I. Engines
  - Origin of losses and operating map
    SUMMARY :

⇒ Low efficiency by **low load** operation due to pumping losses for stoichiometric engines ($\lambda=1$)

⇒ Optimal efficiency at **high load** is limited by knocking phenomena (reduction of spark advance angle, towards TDC)

⇒ The use of a low compression ratio (limited by knocking) puts at a disadvantage the global efficiency in the whole operating map

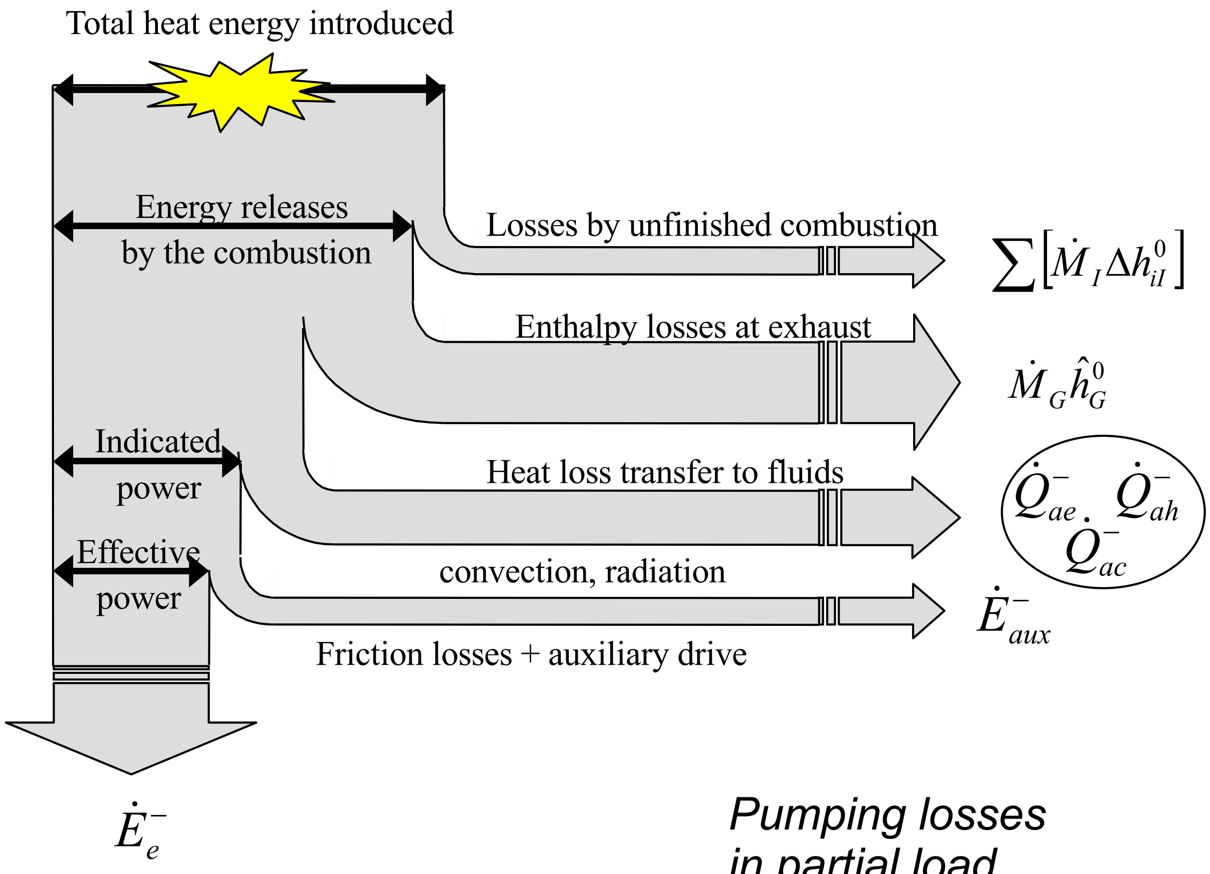
⇒ The maximal power (in full load) is obtained for rich burn conditions ($\lambda<1$), hence efficiency degrades

=> Development axes of S.I. engines are focused on the improvement of global efficiency

Energy distribution in S.I. engines

Comparison between C.I. and S.I. Engines

- Energy balance :



$\eta_{Otto} \approx 30-35\%$

$\eta_{Diesel} \approx 40-45\%$

λ @ max power

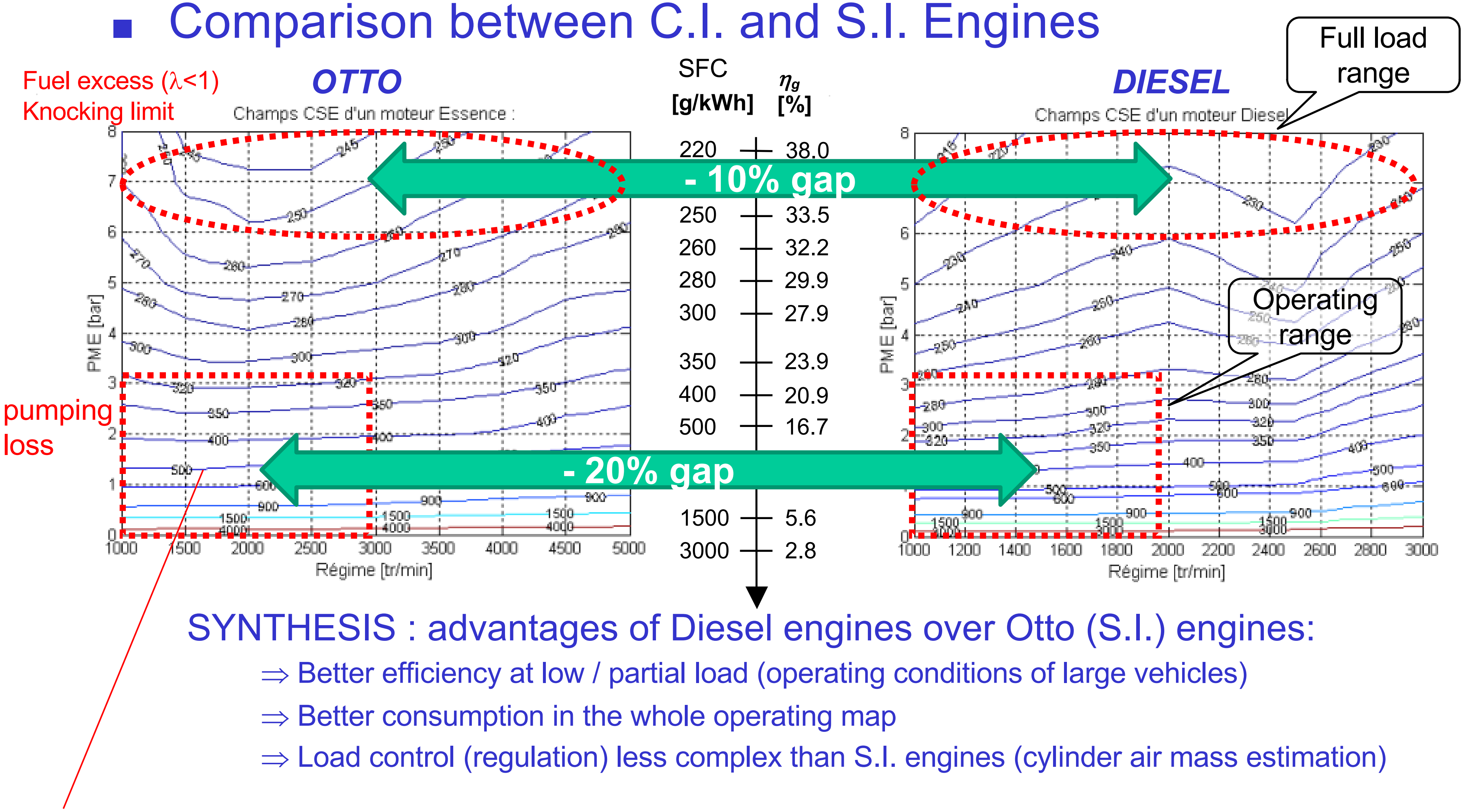
Otto (S.I.)	**Diesel (C.I.)**
- (λ_{max} < 1)	+ (λ_{mean} > 1)
- - $T_{exh} \approx$ 800-900° C	+ $T_{exh} \approx$ 500-600° C
=	=
+ (low auxiliaries)	- (injection syst.)

(fuel injection pump)

Pumping losses in partial load	- -	+

Energy distribution in S.I. engines

Comparison between C.I. and S.I. Engines



Fuel excess (λ<1)
Knocking limit

OTTO

DIESEL

Full load range

Operating range

- 10% gap

- 20% gap

pumping loss

80% of operating time

SFC **[g/kWh]**	η_g **[%]**
220	38.0
250	33.5
260	32.2
280	29.9
300	27.9
350	23.9
400	20.9
500	16.7
1500	5.6
3000	2.8

SYNTHESIS : advantages of Diesel engines over Otto (S.I.) engines:

⇒ Better efficiency at low / partial load (operating conditions of large vehicles)

⇒ Better consumption in the whole operating map

⇒ Load control (regulation) less complex than S.I. engines (cylinder air mass estimation)