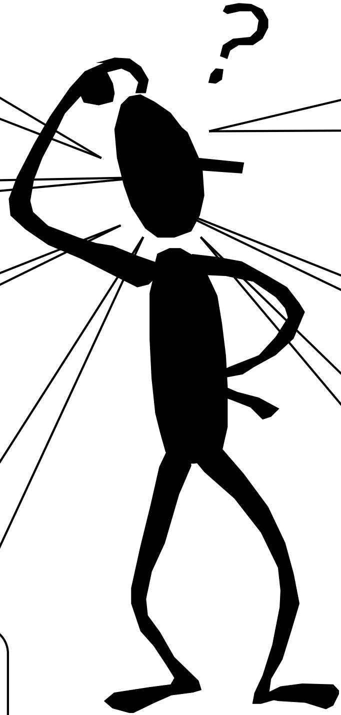
Chapter 3: Terminology and key values

$$\dot{E}_e = C_e \cdot \frac{2\pi}{60} \cdot N$$

$$E_i = \oint_{cycle} P \cdot dV = IMEP \cdot V_u$$

$$\eta_{mec} = \frac{BMEP}{IMEP} = \frac{ISFC}{BSFC}$$

$$\eta_i = \frac{\dot{E}_i}{\dot{Y}_{comb}}$$



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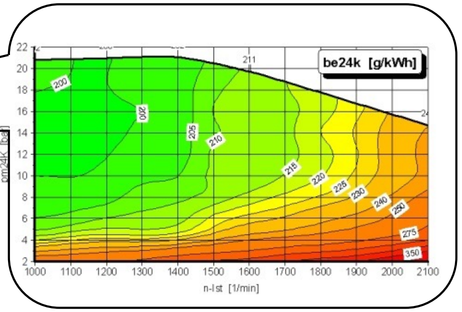


$$BMEP = \frac{4\pi}{100} \cdot \frac{C_e}{V_u}$$

$$\eta_e = \frac{\dot{E}_{effective}}{\dot{Y}_{comb}}$$

Efficiencies, energies, powers, pressures, consumption, ... Operating map.

Learning objectives Chapter 3

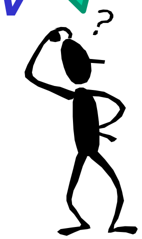
- ⇨ know the main performance parameters used for reciprocating engines and the relations between them
- ⇨ understand the representation of engine parameters / key values into the whole wide operating range (**Operating Map**).

Content

- Engine cycle representation
- Key values of reciprocating engines
  - Power
  - Torque
  - Mean pressure
  - Efficiency
  - Specific consumption
- Important Engine characteristic curves
  - Full load curve
  - Operating map

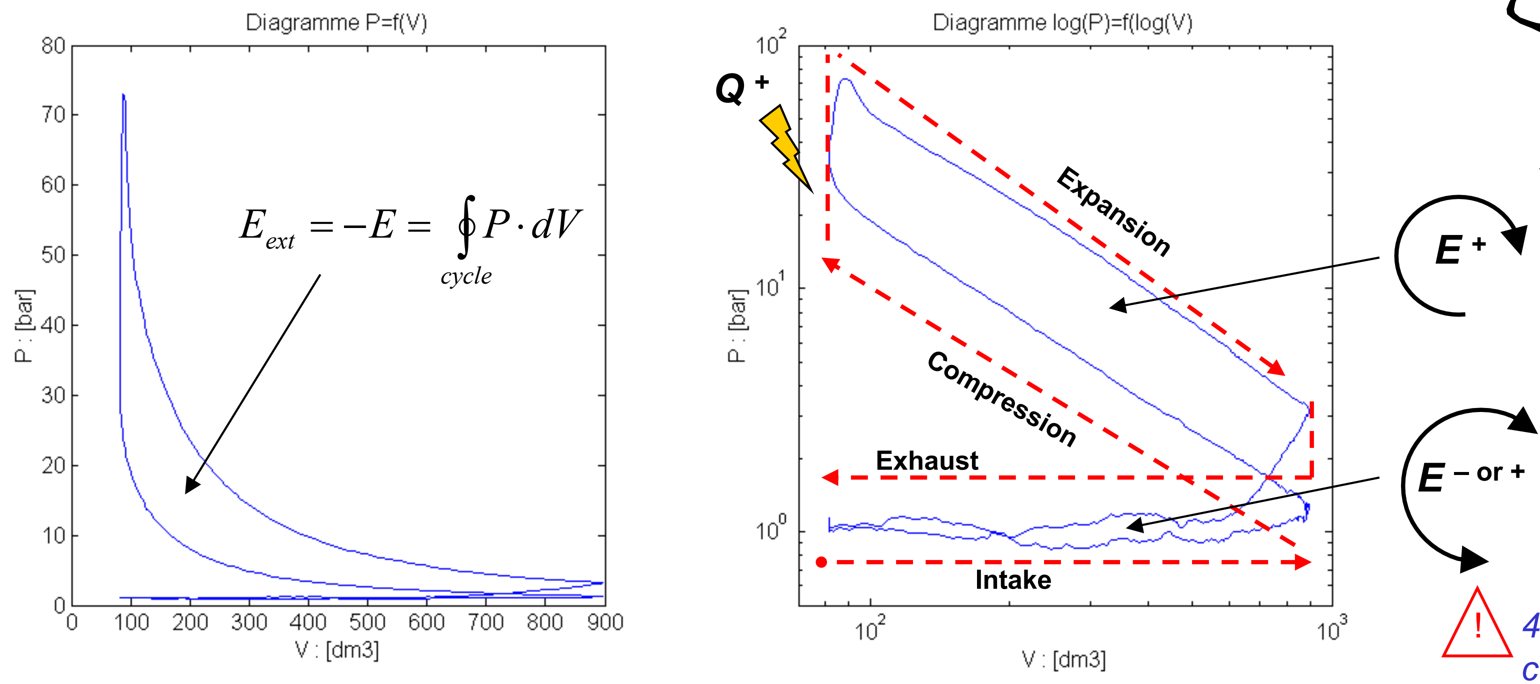
Engine cycle representation

1) V_0 = ?
2) V_U = ?
3) ε = ?
4) Engine type
(# Stroke, TC)



Engine cycle representation:

1. Representation with P as a function of the displacement volume: ***V***



⚠ *4stroke cycle*

E_{ext} : Mechanical work given by the fluid to the surrounding during the cycle

$\Rightarrow E_{ext} < 0$ for a compression ($dV < 0$)

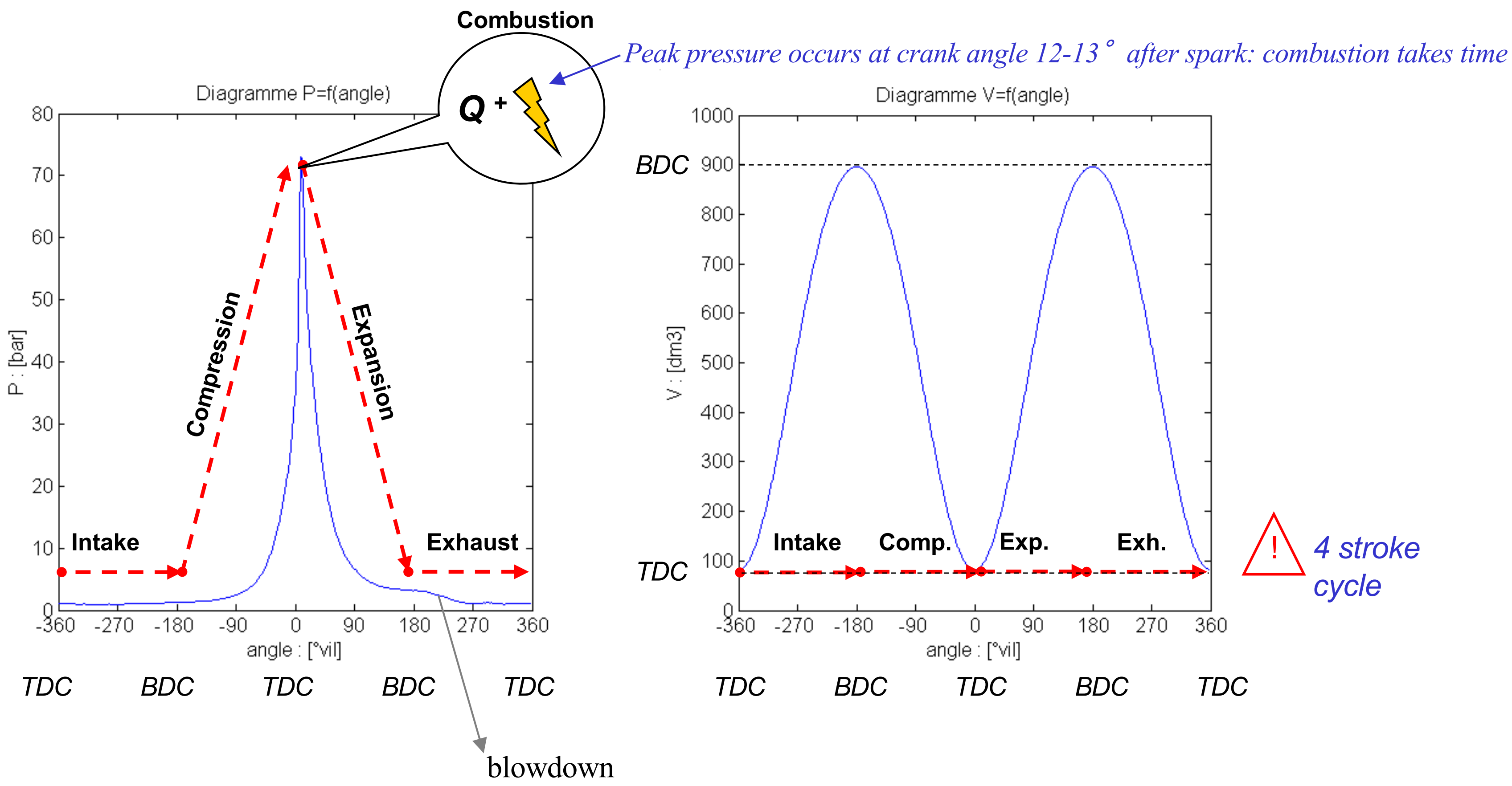
$\Rightarrow E_{ext} > 0$ for an expansion ($dV > 0$)

Engine cycle representation

- ## Engine cycle representation:

   2. Representation with P as a function of the crank angle: $\varphi_{C.A}$

   Definition: $\varphi_{C.A} = 0°\ \Rightarrow$ ***TDC combustion***



Content

- Engine cycle representation
- Key values of reciprocating engines
  1. Power
  2. Torque
  3. Mean “pressure”
  4. Efficiency
  5. Specific fuel consumption
- Important engine characteristic curves
  - Full load curve
  - Operating map

Key values of reciprocating engines

1. Power $\dot{E}[W] = T[Nm \text{ or } J].\omega\,[s^{-1}]$

- Function of the output **torque** delivered at shaft and of the revolution **speed**
- Unit: **[kW]** or **[hp]** : Reminder ⇒ 1 [kW] = 1.34 [hp], 1 hp = 746 W
- Specific power*: reported to the engine displacement [kW/dm^3] or [kW/*L*]

A) **Effective**/Brake power = *delivered power by the engine (at **shaft**)*

i.e. with friction losses

- Notation: $\dot{E}_e$
- Measured with a dynamometer at the engine's outlet shaft (before the gearbox)
- Needs a dynamometer rotor (and a test bed)

$\dot{E}_{e,Gross}$ = Power with auxiliaries absolutely required to run the engine

⇒ valve train system, pumps (oil, water, fuel), alternator,…

$\dot{E}_{e,Net}$ = Power with auxiliaries + accessories (compressor, steering assistance,..)

$\dot{E}_{e,Nom}$ = Power at nominal speed ⇒ only for low-speed or stationary engines

$\dot{E}_{e,Max}$ = Maximal power of the engine

*specific power : nowadays 100 kW/L

Key values of reciprocating engines

B) **Indicated** power = *generated power by the gas pressure acting on the piston during the cycle (=P-v cycle surface)*

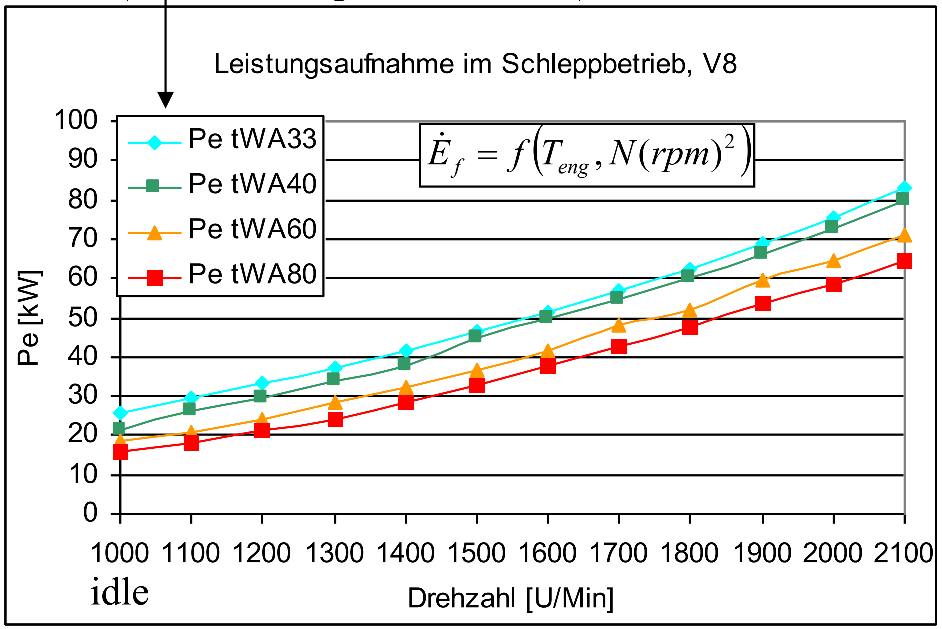
- Notation: $\dot{E}_i$
- measured with a pressure sensor / **indicator**
- needs a dynamic pressure sensor placed into the combustion chamber
- characterizes the engine power <u>without</u> any mechanical <u>friction</u>
- $\dot{E}_i > \dot{E}_e$

$$\dot{E}_i = \dot{E}_e + \dot{E}_f$$

C) **Friction** power

- Notation: $\dot{E}_f$
- characterizes the engine frictional losses
- depends on mechanical losses and the absorbed power by driving the auxiliaries

engine oil temperature (the colder, the more friction)
(WA = cooling water outlet T)

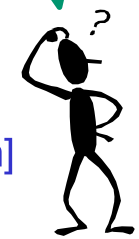


V8 500kW engine

Friction power increases ~quadratically with speed

Key values of reciprocating engines

Slide 4:
Indicated power = ?



- Relations

(T torque (engl.) = C couple (fr.) in Nm or J)

  - Effective / brake power:

$$\dot{E}_e = C_e \cdot \omega$$

ω in [rad/s]

$$\dot{E}_e = C_e \cdot \frac{2\pi}{60} \cdot N$$

N in [1/min] or [rpm]

$$\dot{E}_{e,tot} = \dot{E}_{i,cyl} \cdot n_{cyl,E^+} - \dot{E}_{f,eng}$$

n_{cyl} : nb of cylinder

  - Indicated power:

$$\dot{E}_i = \dot{E}_e + \dot{E}_f$$

$$\dot{E}_i = n_c \cdot E_i \quad with \quad n_c = \frac{N(rpm)}{60 \cdot n_{TM}} \quad and \quad E_i = \oint_{cycle} P \cdot dV$$

$$\Rightarrow \dot{E}_i = \frac{1}{120} \cdot N(rpm) \cdot E_i$$

n_c = number of cycles per second

n_{TM} = number of revolutions per cycle

for 2-Stroke $n_{TM} = 1$,

for 4-Stroke $n_{TM} = 2$

E_i = indicated work per cycle

(TM : tacte moteur = strokes (4 or 2))

  - Friction power:

$$\dot{E}_f = \dot{E}_i - \dot{E}_e$$

  - Rated brake power: $\dot{E}_{e,0}$

$$\dot{E}_{e,0} = C_F \cdot \dot{E}_e \quad with \quad \begin{cases} C_F = \left[\frac{99}{P_a}\right]^{1.2} \cdot \left[\frac{T}{298}\right]^{0.6} & or \\ C_F = \frac{P_{s,dry}}{P_m - P_{v,m}} \cdot \left[\frac{T_m}{T_s}\right]^{0.5} \end{cases}$$

(correction factor for T, P other than 298 K, 1013 mbar)

Key values of reciprocating engines

2) Torque

- Unit: **[Nm]** (X00 Nm in cars, X000 Nm in trucks)
- Specific torque*: reported to engine displ. [Nm/dm^3] ⇒

  ⇒ this value characterizes the engine load and is expressed in [bar]

⚠ *Unit of pressure (see § mean pressure)*

Decomposition of the different torques during a cycle (highly dynamic):

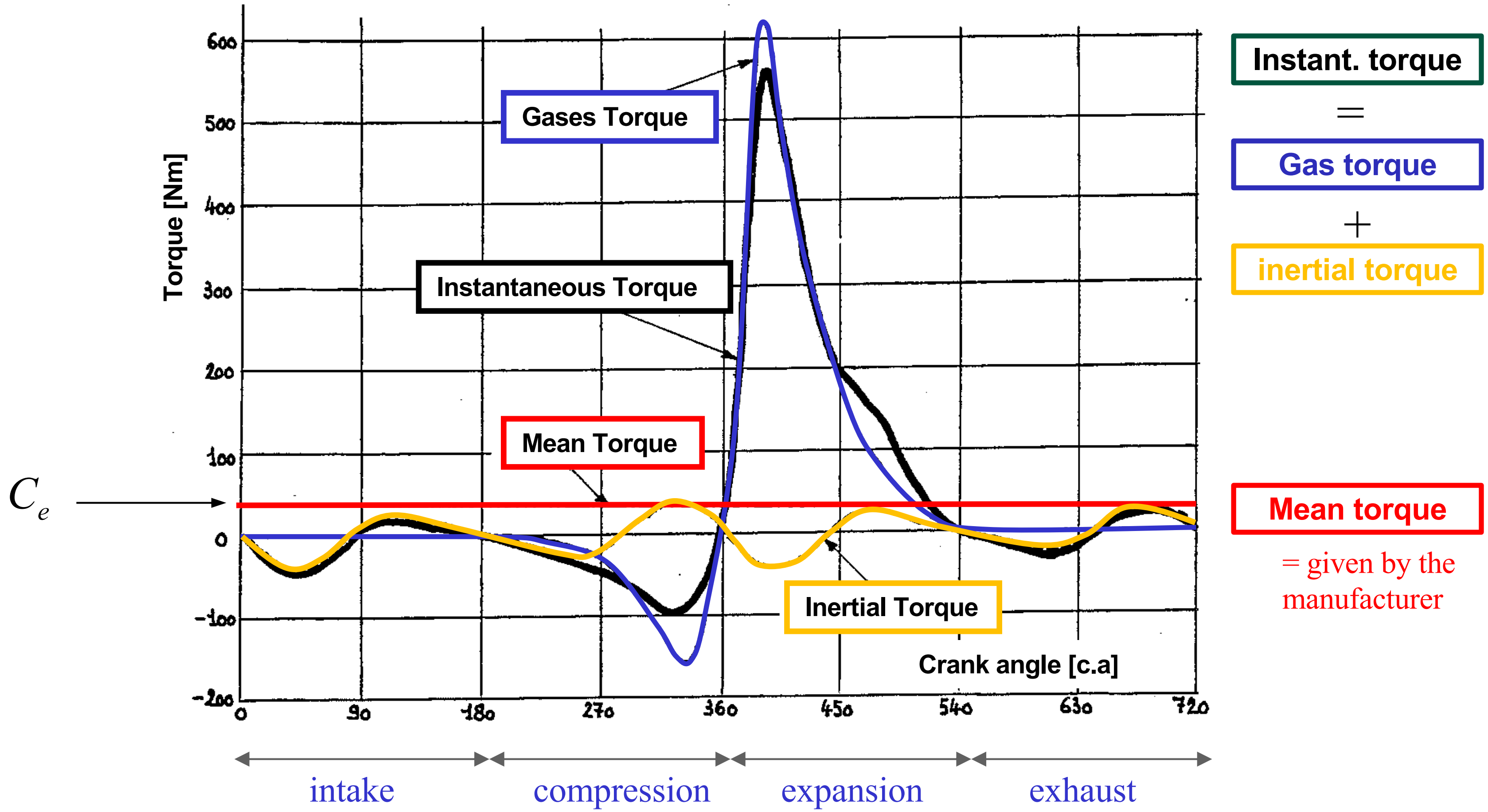
1) **Gas torque** ⇒ *torque produced by the gas pressure (following combustion) acting on the piston and by means of the lever arm on the crankpin*
2) **Inertial torque** ⇒ *produced by the inertial forces due to the reciprocating (=accelerating/decelerating) moving masses (piston, connecting rod, crankpin)*
3) **Instantaneous torque** ⇒ *result of "gas torque" + "inertial torque"*
4) **Mean torque** ⇒ *average of the instant. torque produced on the crankshaft*
   - measured at the engine's outlet shaft (effective torque): C_e
   - *or* determined with the *P-v* diagram (indicated torque) : C_i

*example specific torque : 800 Nm/L = 800 J / 0.001 m^3 = 800'000 Pa = 800 kPa = 8 bar

Key values of reciprocating engines

Torque

- Representation of the different torques acting on the crankpin in a single cylinder during a 4-stroke cycle :



inertial torque every 90° acceleration then deceleration

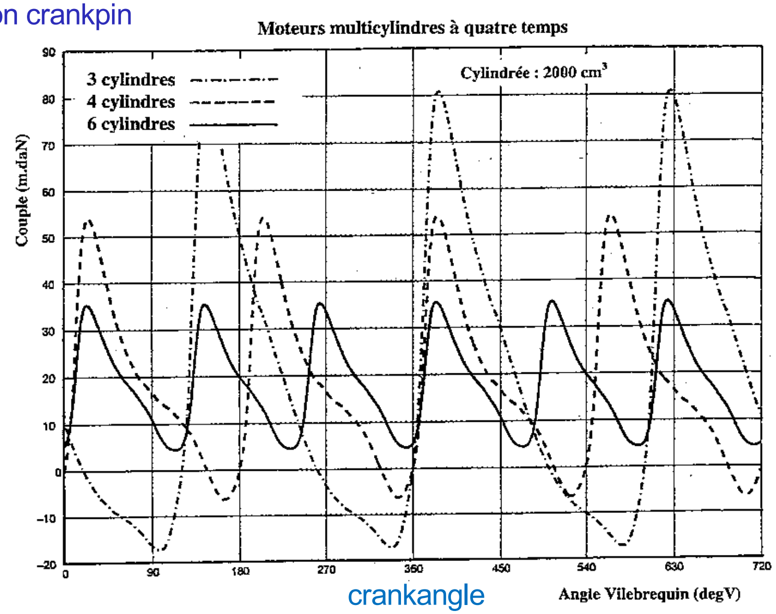
Key values of reciprocating engines

■ Torque

- Instantaneous torque and speed variations on a multicylinder engine:

Variation of instantaneous torque:

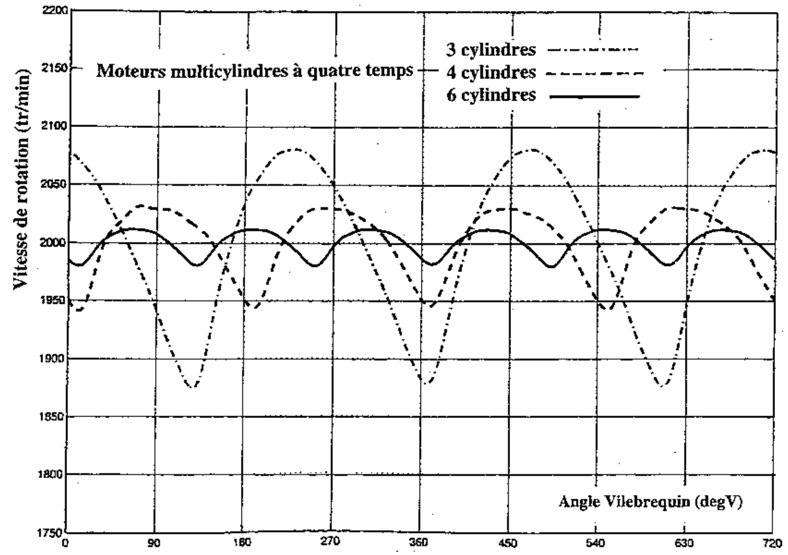
Torque on crankpin



crankangle

Variation of instantaneous speed:

rpm (crankshaft)



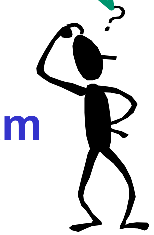
crankangle

- The fluctuations of instantaneous torque influence the acyclism of engines

⇒ Coefficient of regularity: $\dfrac{\omega_{moy}}{\omega_{\max} - \omega_{\min}}$

Key values of reciprocating engines

1) V_0 = ?
2) V_C = ? (n = 6)
3) ε = ?
4) Engine Type
(# Stroke, TC)

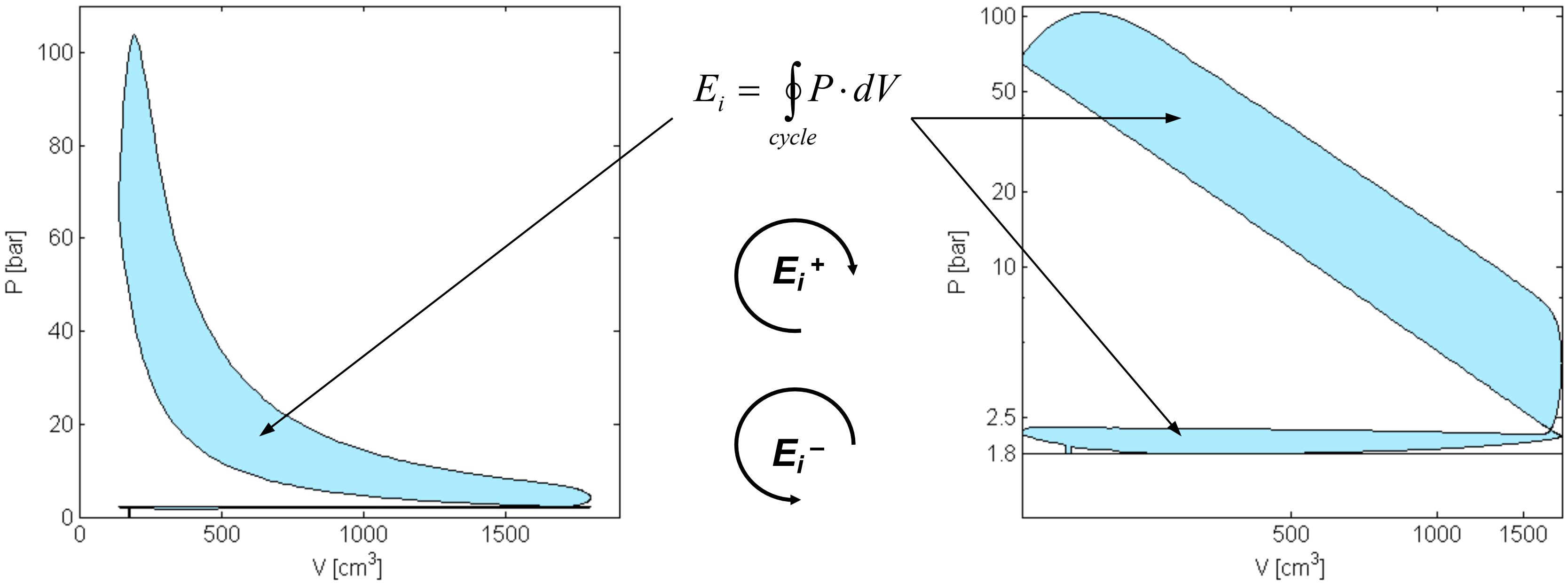


3) Mean "pressure"

- Reminder: if a pressure sensor inside the combustion chamber gives *P* for each instant during the cycle, so:

  The indicated work E_i = the surface delimited by the curve in the diagram

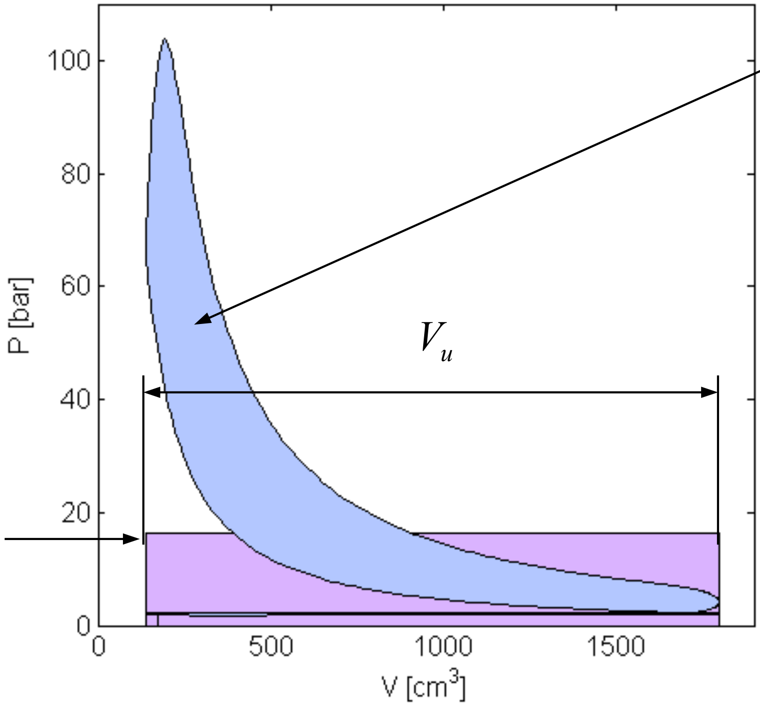
  P = f(V) $\Rightarrow \quad E_i = \oint_{cycle} P \cdot dV$ ($E_i > 0$ if clockwise, $E_i < 0$ if counterclockwise)



Key values of reciprocating engines

- **Mean “pressure”**
  - The ***indicated mean effective pressure*** **(IMEP)** corresponds to the theor. const. equivalent pressure which would be applied over the piston during the whole cycle ⇒ $E_i = \oint_{cycle} P \cdot dV = IMEP \cdot V_u$
  - Unit: **[bar]**

$$E_i = \oint_{cycle} P \cdot dV$$



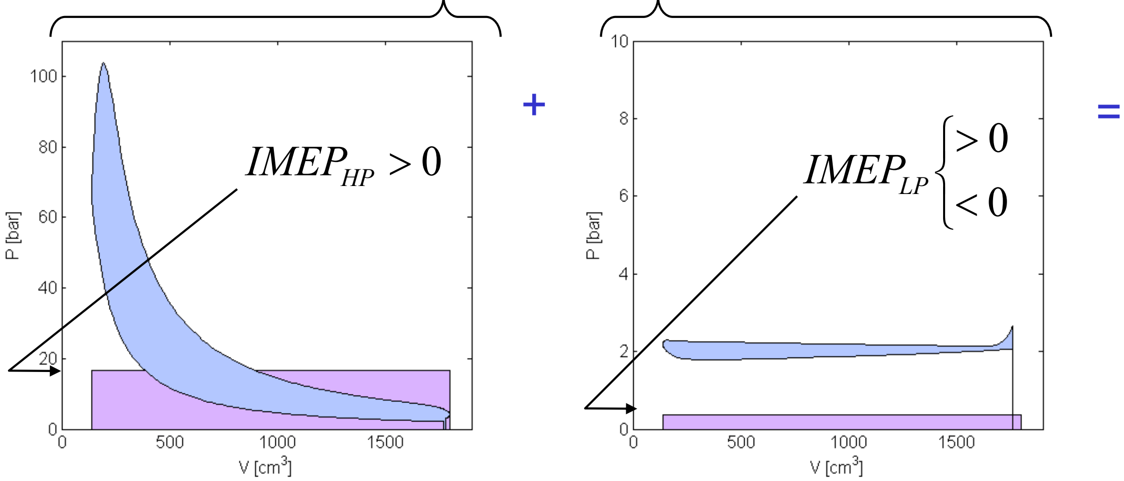
$$IMEP = \frac{E_i}{V_u}$$

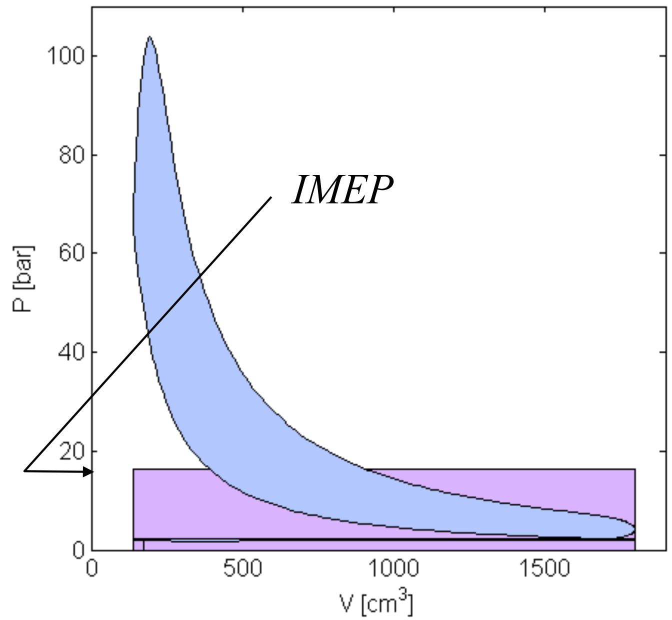
Mean Pressure

- For a 4-stroke engine, the IMEP (*fr: PMI*) contains 2 parts:
  - IMEP high pressure ($IMEP_{HP}$): Compression stroke ⇒ Expansion stroke, $IMEP_{HP} > 0$
  - IMEP low pressure ($IMEP_{LP}$): Intake stroke ⇒ Exhaust stroke, $IMEP_{LP} < 0$ (or > 0)
  - Sum of the 2 terms gives the total IMEP (PMI in French): $IMEP = IMEP_{HP} + IMEP_{LP}$

$$\left(PMI = PMI_{HP} + PMI_{LP}\right)$$

$$E_i = \oint_{cycle\,HP} P \cdot dV + \oint_{cycle\,LP} P \cdot dV = \left(IMEP_{HP} + IMEP_{LP}\right)$$





Key values of reciprocating engines

- Relations :
  - Work and IMEP: $E_i = \oint_{cycle} P \cdot dV = IMEP \cdot V_u = 4\pi \cdot C_i$
  - IMEP and indicated torque C_i : $IMEP = \frac{4\pi}{100} \cdot \frac{C_i}{V_u}$
    - The IMEP is measured thanks to a in-cylinder pressure sensor
    - C_i corresponds to engine torque without mechanical friction
    - IMEP corresponds to a « specific torque » in [Nm/m^3]
  - IMEP and indicated power E_i : $\dot{E}_i = \frac{1}{1200} \cdot IMEP \cdot V_u \cdot N$
  - BMEP and effective torque C_e : $\dot{E}_e = \frac{1}{1200} \cdot BMEP \cdot V_u \cdot N$
    - C_e corresponds to the measured torque:
    - BMEP is the "brake mean effective pressure": $BMEP = \frac{4\pi}{100} \cdot \frac{C_e}{V_u}$
  - BMEP, IMEP and FMEP: $BMEP = IMEP - FMEP$
    - FMEP is the "Friction mean effective pressure"

'C' for 'couple' (Fr) = torque (engl.)

with:
$\dot{E}$ in [kW]
IMEP in [bar]
C in [Nm]
V_u in [dm^3]

with :
IMEP in [bar]
BMEP in [bar]
V_u in [dm^3]
N in [rpm]

Key values of reciprocating engines

4a) Efficiency

1) Global *or* effective efficiency of an engine: $\eta_e = \dfrac{\dot{E}_{effective}}{\dot{Y}_{comb}}$

with : $\dot{E}_{effective}$: Effective power

$\dot{Y}^{+}_{comb}$: Fuel transformation power (during combustion)

$$\dot{Y}^{+}_{comb} = \dot{M}_F \cdot \left(LHV + \hat{h}_F\right) + \dot{M}_A \cdot \hat{h}_A - \dot{M}_G \cdot \hat{h}_G + \dot{M}_{cond} \cdot q_{vap}$$

with:
- Δh° = *LHV* in [KJ/kg]
- $\dot{M}_F$ in [kg/s]
- $\dot{Y}^{+}_{comb}$ in [kW]

After simplification $\Rightarrow$ $\dot{Y}^{+}_{comb} = \dot{M}_F \cdot LHV$ *Hypothesis*: gases sur-enthalpy and condensation are omitted (intake engine conditions: P_0 = 1 bar, T_0 = 25° C)

2) Indicated efficiency: $\eta_i = \dfrac{\dot{E}_i}{\dot{Y}_{comb}}$

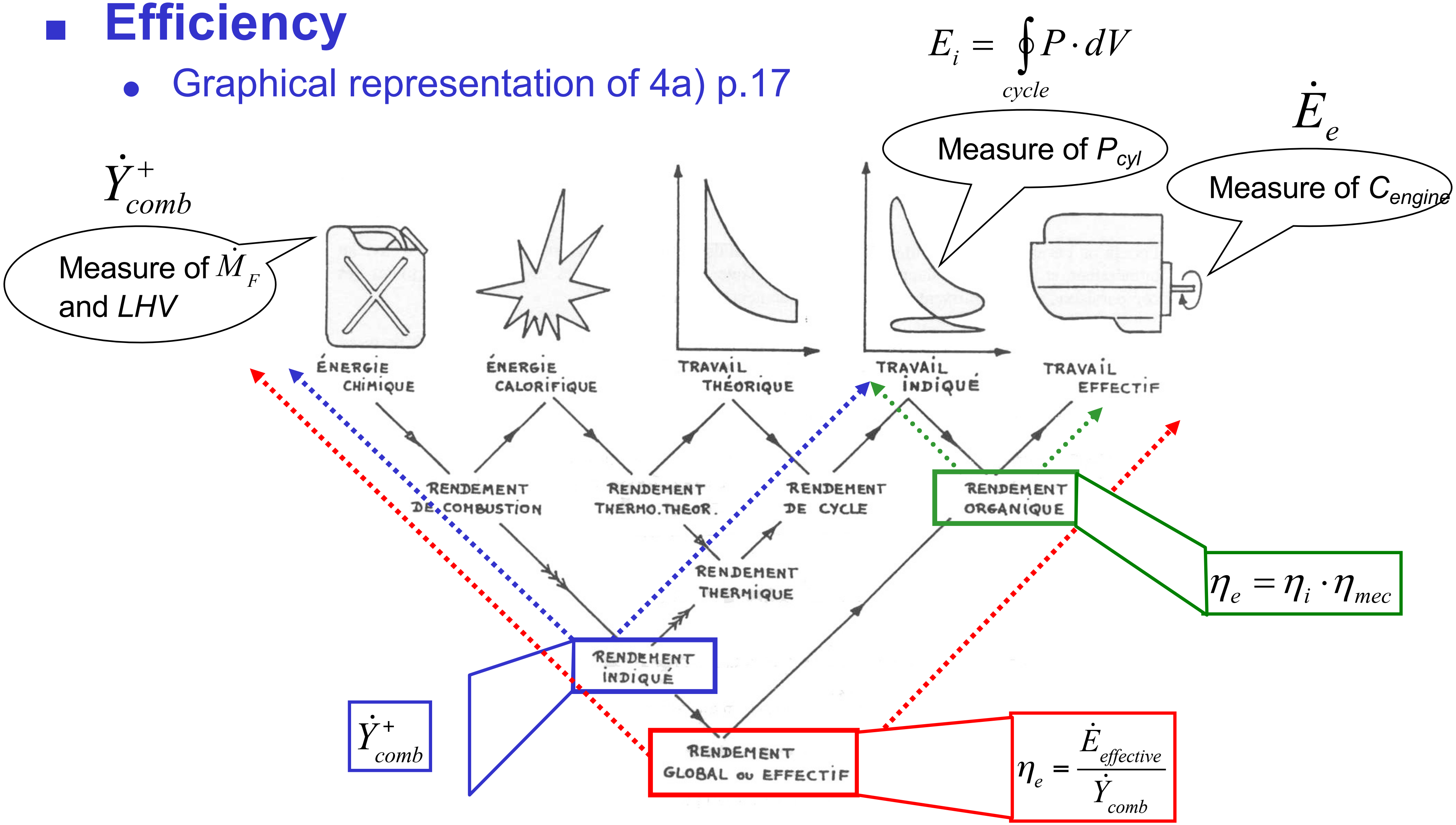
characterizes the global efficiency of an engine without mechanical friction

3) Mechanical efficiency: $\eta_{mec} = \dfrac{\dot{E}_e}{\dot{E}_i} = \dfrac{\eta_e}{\eta_i}$

characterizes the friction losses

Key values of reciprocating engines

- **Efficiency**
  - Graphical representation of 4a) p.17



4b) Efficiency

4) Theoretical thermodynamic efficiency: $\eta_{th.th}$

- Ratio between the **ideal** cycle work AND the thermal energy given by the combustion process

$$\eta_{th.th} = \frac{E^{-}_{ideal\ cycle}}{Q^{+}_{comb}}$$

Example:
(Otto cycle)

$$\eta_{th.th} = 1 - \frac{1}{\varepsilon^{\gamma-1}}$$

5) Thermal efficiency: η_t

- Ratio between the indicated work (=**real** cycle) AND the thermal energy given by the combustion process

$$\eta_t = \frac{E^{-}_{i}}{Q^{+}_{comb}}$$

6) Cycle efficiency (shape efficiency) : η_{cycle}

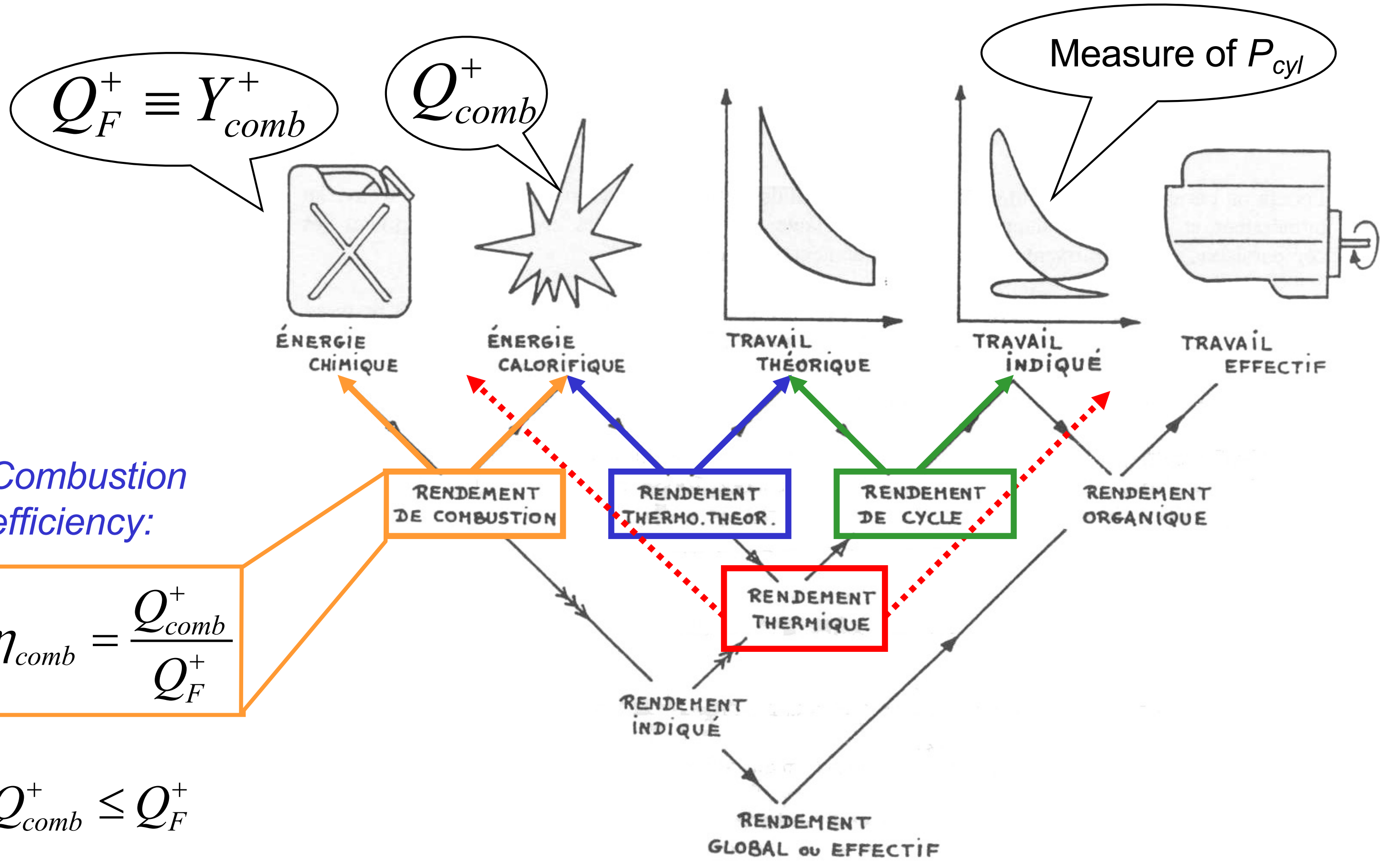
- Ratio between the (real) indicated work AND the ideal cycle work

$$\eta_{cycle} = \frac{E^{-}_{i}}{E^{-}_{ideal\ cycle}} \quad \Rightarrow \quad \eta_t = \eta_{th.th} \cdot \eta_{cycle}$$

Key values of reciprocating engines

- **Efficiency**
  - Graphical representation of 4b) p.19

$$E_i = \oint_{cycle} P \cdot dV$$



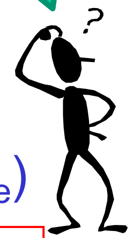
Combustion efficiency:

$$\eta_{comb} = \frac{Q_{comb}^+}{Q_F^+}$$

$$Q_{comb}^+ \leq Q_F^+$$

Key values of reciprocating engines

> **Exercise:**
> Pe = 500 kW
> BSFC = 200 g/kWh
> Operating hours = 7000 h/yr
> Fuel costs = 2 € / L
> Fuel density = 0.83 kg / L
> Operating costs = ?



5) Specific fuel consumption (SFC; *fr: CSE*)

- corresponds to the mass of fuel consumed by work unit
- Unit: **[g/kWh]**
- Could be expressed as a function of the engine efficiency: $SFC = f(\eta_e)$

- **Brake specific fuel consumption:** $BSFC = \frac{\left(g/h \right)}{(kW)} \rightarrow BSFC = \frac{\dot{M}_F \cdot 3600 \cdot 10^3}{\dot{E}_e}$

  - with $\dot{E}_e = \eta_e \cdot \underbrace{LHV \cdot \dot{M}_F}_{\approx \dot{Y}^+_{comb}}$ $\Rightarrow$ $\eta_e = \frac{3'600'000}{LHV \cdot BSFC}$
  - for engines with «standard» fuel
    i.e. Gasoline or Diesel with a *LHV* ≈ 42'000 kJ/kg ⇒ $\eta_e \approx \frac{83.7}{BSFC}$

  with:
  SFC in [g/kWh]
  $\dot{M}_F$ in [kg/s]
  $\dot{E}_e$ in [kW]
  LHV in [kJ/kg]

- (Indicated specific fuel consumption(ISFC)): $ISFC = \frac{\dot{M}_F}{\dot{E}_i}$

Key values of reciprocating engines

- Relations
  - Relation between BSFC, ISFC and power: $\dot{M}_F = BSFC \cdot \dot{E}_e = ISFC \cdot \dot{E}_i$

  - Relation between BSFC, ISFC and mean pressure:

$$BSFC \cdot BMEP = ISFC \cdot IMEP$$

  - Mechanical efficiency:

$$\eta_{mec} = \frac{\dot{E}_e}{\dot{E}_i} = \frac{BMEP}{IMEP}$$

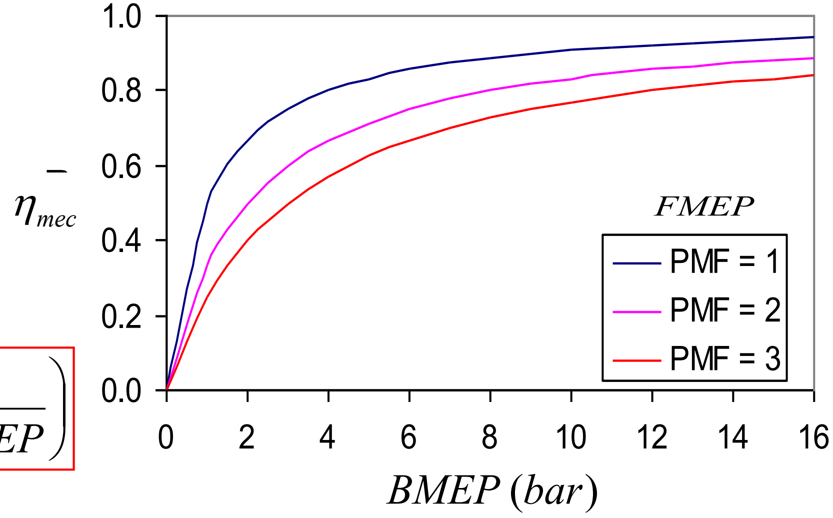
$$\eta_{mec} = \frac{BMEP}{IMEP} = \frac{ISFC}{BSFC}$$

  - Mean pressure relations:

$$BMEP = IMEP - FMEP$$

$$\eta_{mec} = \frac{ISFC}{BSFC} = \frac{BMEP}{IMEP} = \left(\frac{BMEP}{BMEP + FMEP} \right)$$

Mechanical efficiency in function of the BMEP



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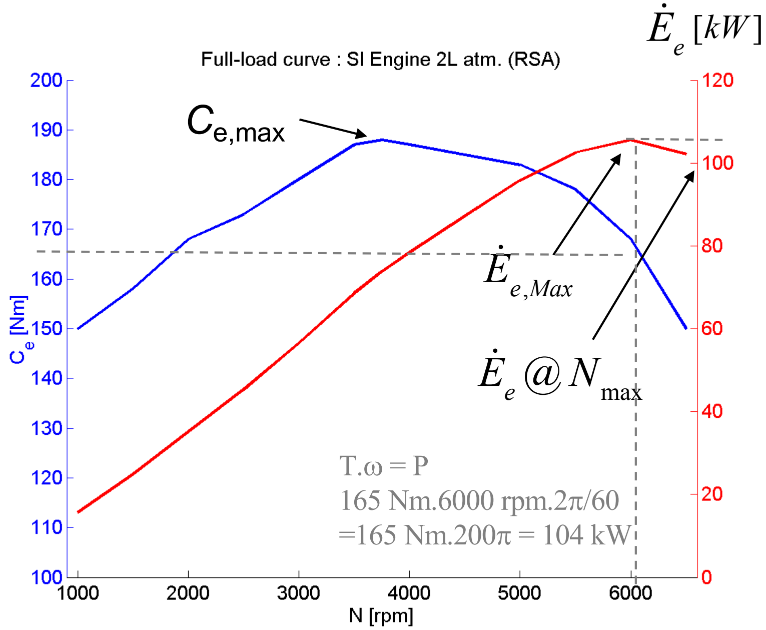
  - Mean pressure
  - Efficiency
  - Specific consumption
- Important engine characteristic curves
  1) Full load curve
  2) Operating map

Important engine characteristic curves

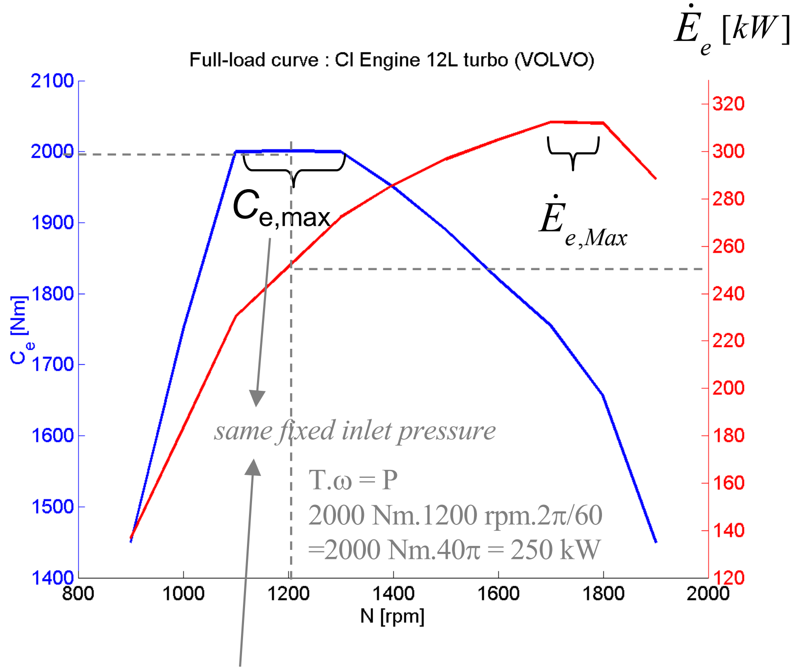
1) **Full load** curve:

1. Performance: representation of torque (or specific torque), mean pressure or maximal power of the engine (=load) as a function of the revolution speed:

$$\boxed{C_{e,\max} = f(N)} \quad or \quad BMEP_{\max} = f(N) \quad or \quad \boxed{\dot{E}_{e,\max} = f(N)}$$



atmospheric car engine



turbocharged truck engine

*torque $C_{e,max}$ designed to be maximal at ~1/2 max. engine speed

Important engine characteristic curves

Fuel delivery rate (g/h) = specific fuel consumption (g/kWh) * effective power (kW)

1) **Full load** curve:

$$\dot{M}_F = BSFC \cdot \dot{E}_e = ISFC \cdot \dot{E}_i$$

2. Performance: representation of several engine parameters in <u>full load</u> ($_{FL}$) operation as a function of the revolution speed: $X_{FL} = f(N)$

Engine characteristics & Thermodynamic conditions

$$\left.\begin{aligned} BSFC_{FL} &= f(N) \\ \dot{M}_{F,FL} &= f(N) \\ P_{adm} &= f(N) \end{aligned}\right\}$$

Thermal & mechanical limits

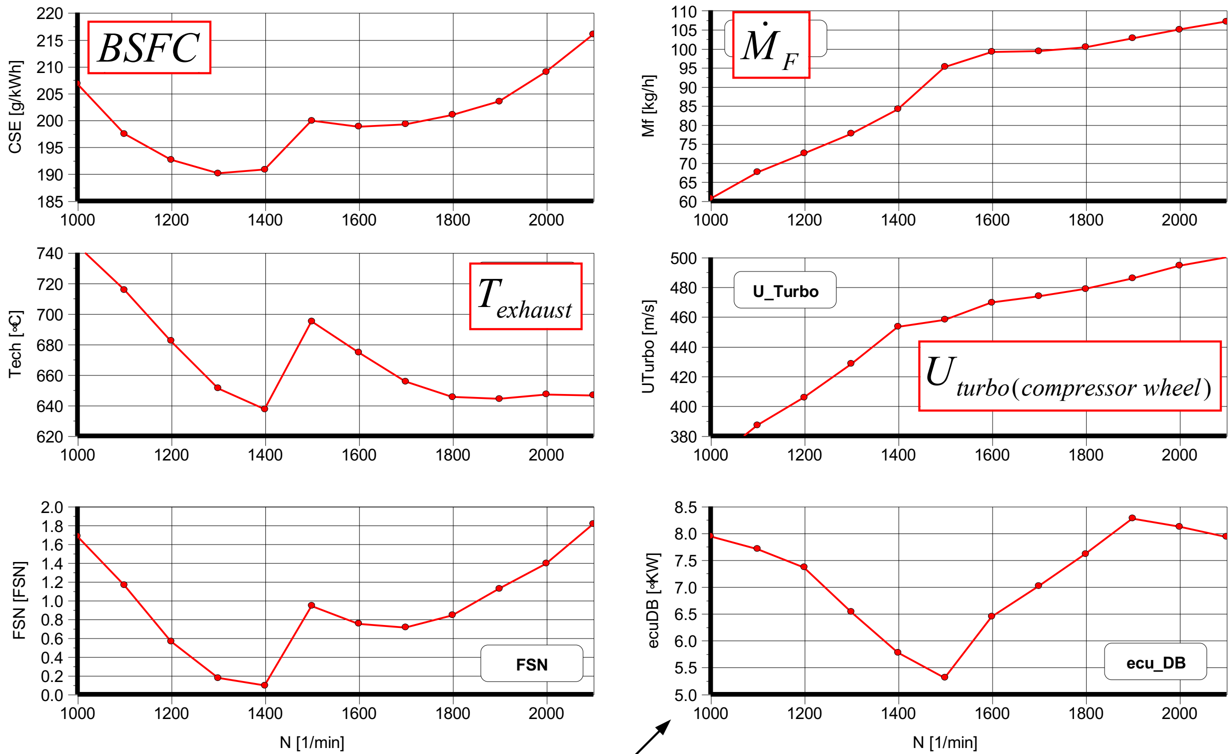
$$\left.\begin{aligned} T_{ech,FL} &= f(N) \\ U_{turbo,FL} &= f(N) \end{aligned}\right\}$$

Pollutant emissions

$$\left.\begin{aligned} NOx_{FL} &= f(N) \\ CO_{FL} &= f(N) \\ FSN_{FL} &= f(N) \end{aligned}\right\}$$

Engine regulation parameters

$$DB - ECU_{FL} = f(N)$$



'FSN' = smoke limit
Index 0 : no sooth particles. Index 2 : many sooth particles

ECU: electronic control unit
'DB' : delivery begin (of fuel injection)

1400 rpm: turbocompressor speed stops increasing => less air => more fuel => consumption goes up (BSFC), T goes up, emissions go up
1500 rpm: fuel flow adapted => consumption goes down, T goes down, emissions go down

Important engine characteristic curves

2) Operating map:

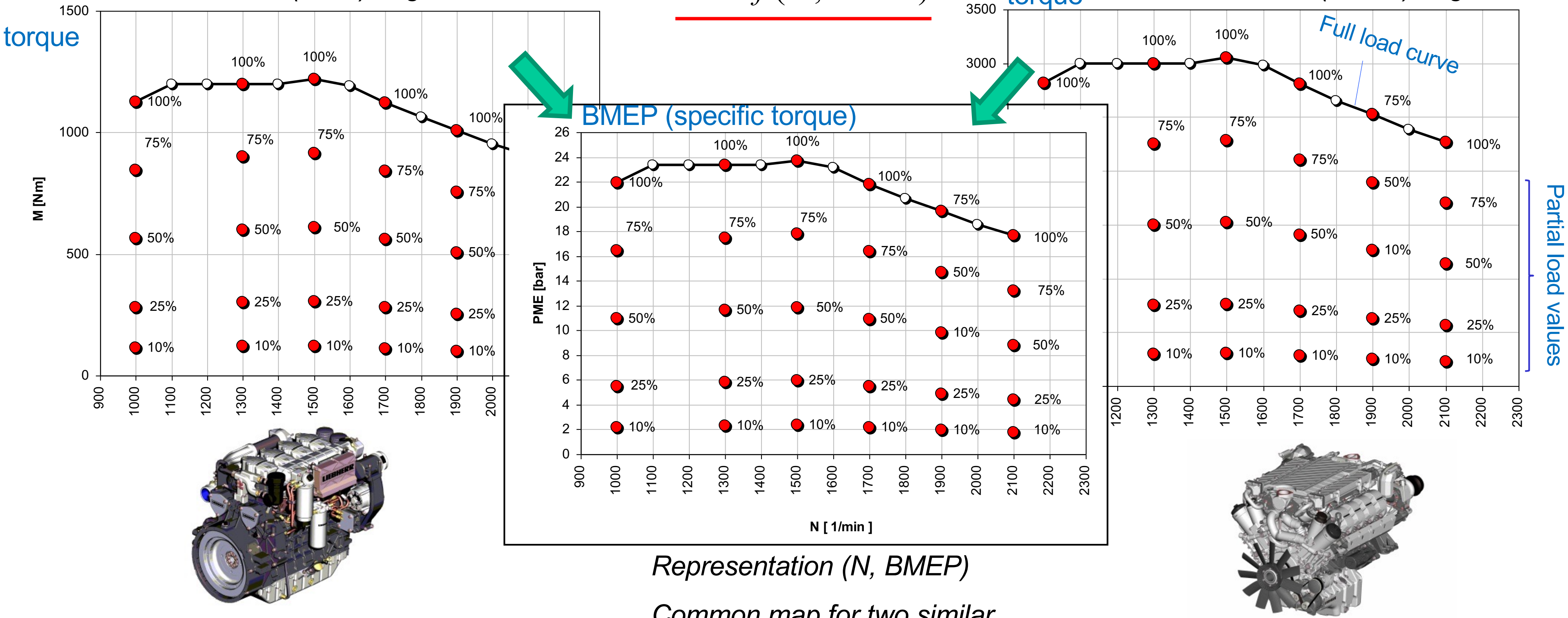
Representation of engine's parameters in the whole operating range:

Representation (N,C_e) on a 4-inline 200 kW (6.5 L) engine

$$X = f(N, C_e) \quad ; \quad X = f(N, \dot{E}_e)$$

$$X = f(N, BMEP)$$

Representation (N,C_e) on a V8, 500 kW (16.2 L) engine



Representation (N, BMEP)

Common map for two similar engines of different size

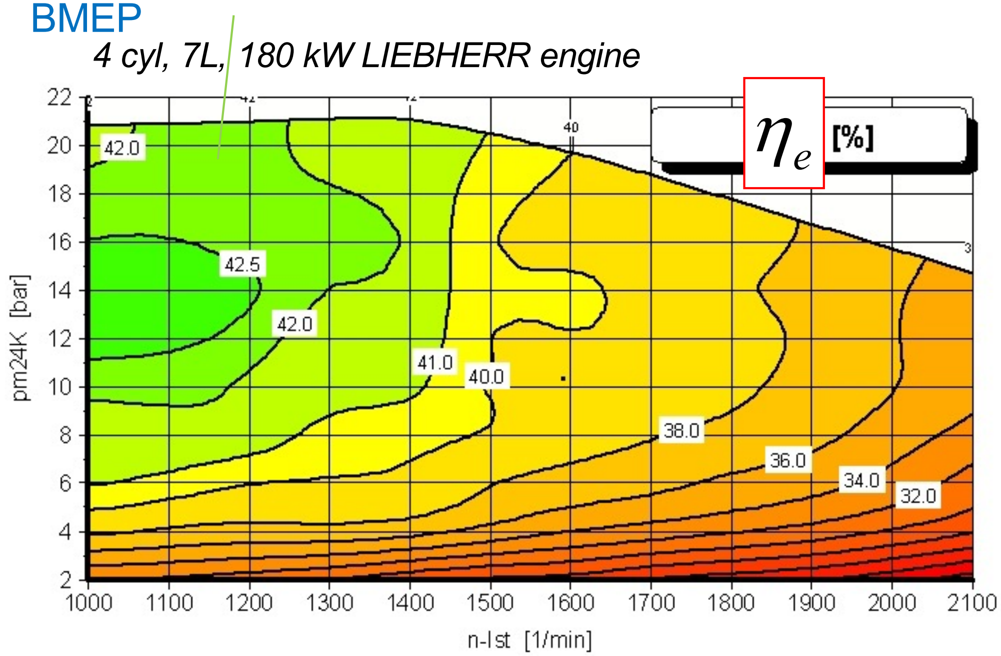
(torque divided by volume = specific torque)

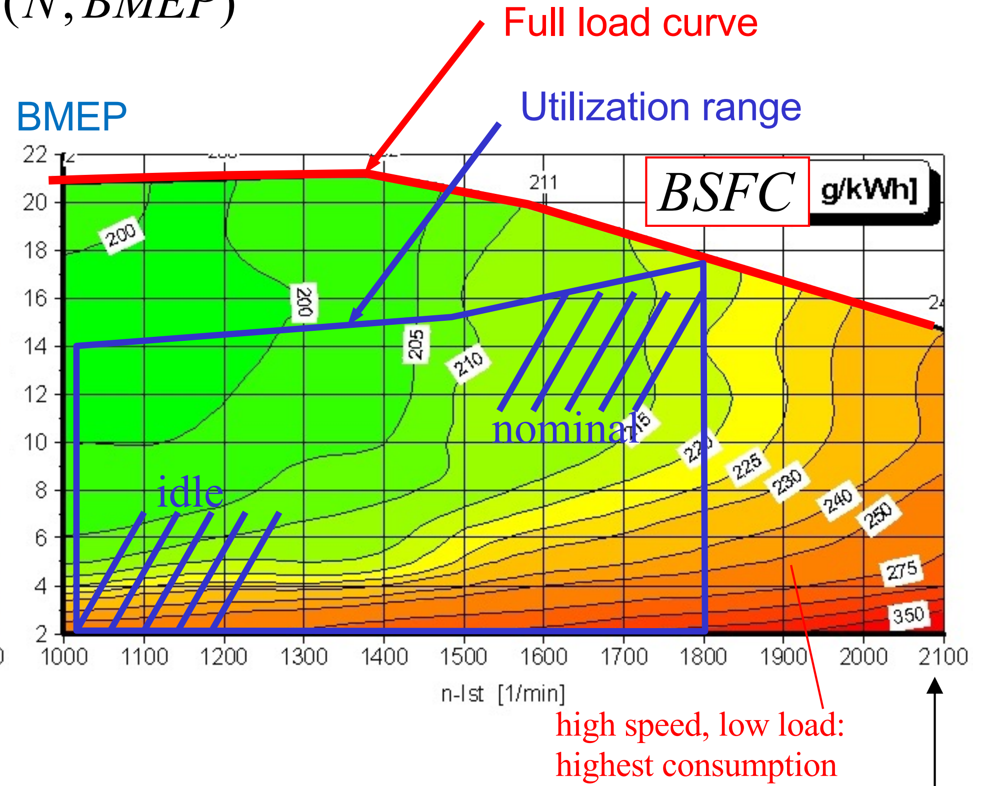
Important engine characteristic curves

2) **Operating map**:

1. Representation of specific effective fuel consumption map (=efficiency%):

$$BSFC = f(N, BMEP)$$





- The engine’s full load curve limits the BSFC map
- Immediate reading of low-consumption zones and utilization ranges

Important engine characteristic curves

2) Operating map:

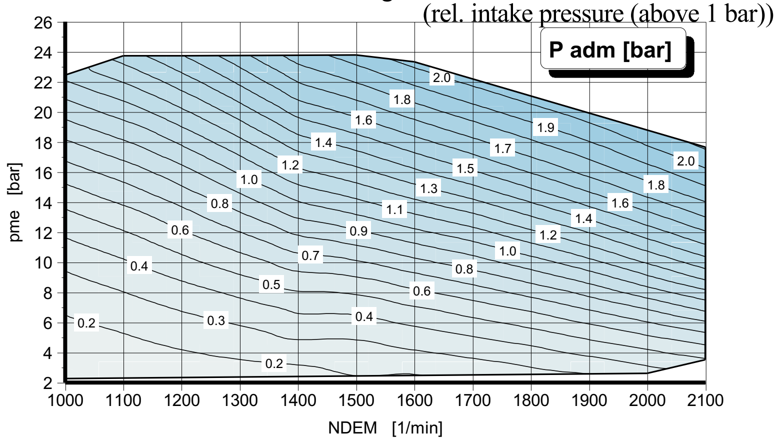
2. Representation of the thermodynamic conditions/states of the engine:

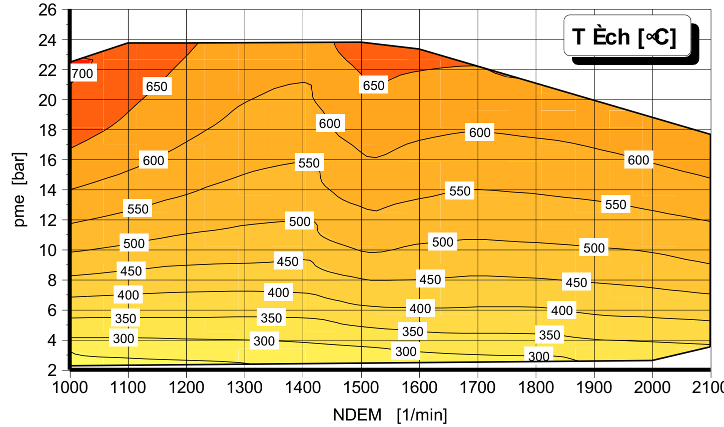
V8, 500 kW LIEBHERR engine

(rel. intake pressure (above 1 bar))

Exhaust manifold temperature

BMEP

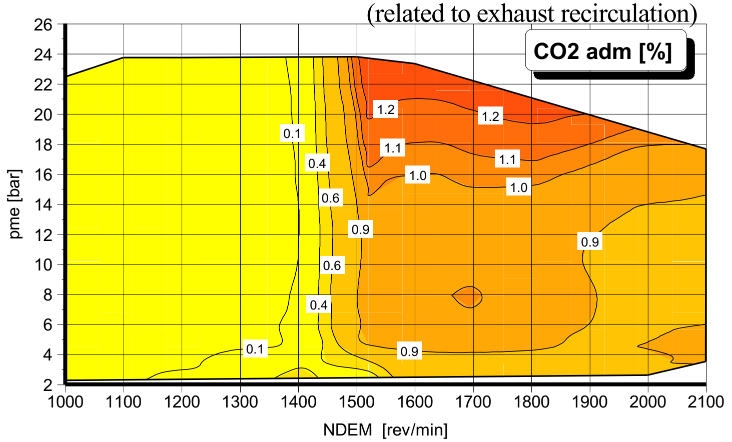


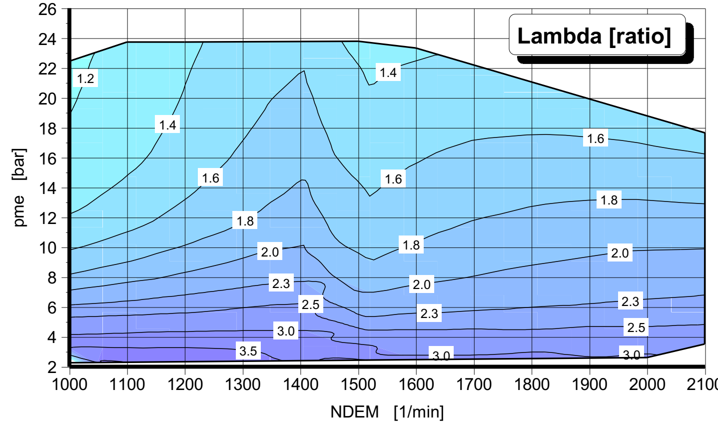


rpm

(related to exhaust recirculation)

BMEP





rpm

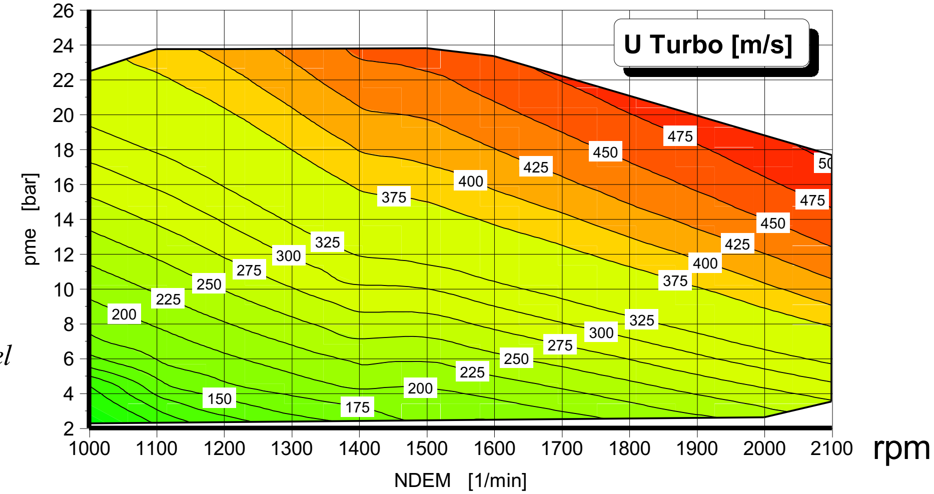
Important engine characteristic curves

2) **Operating map**:

3. Representation of thermal and mechanical limits in the whole operating range:

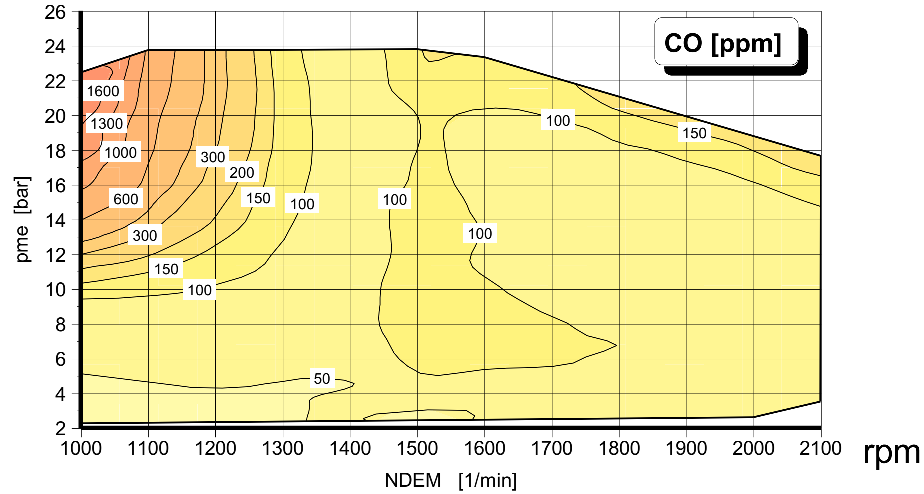
U_turbo = peripheral speed (tip) of compressor wheel
(500 m/s max for aluminium, 650 m/s for titanium)

V8, 500 kW LIEBHERR Engine



4. Representation of pollutant emissions:

Units ⇒ [ppm]
⇒ [%]
⇒ [g/kWh]

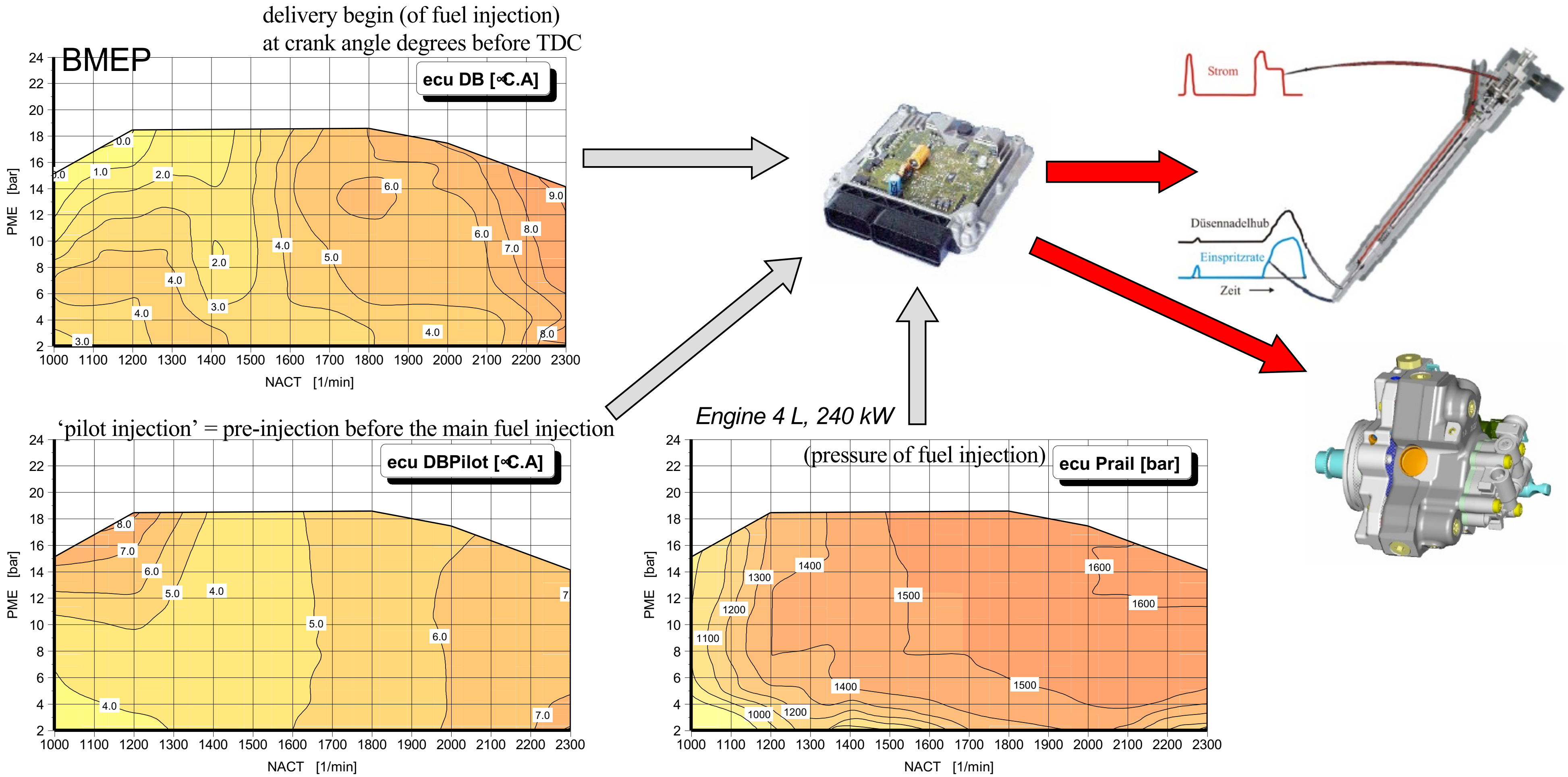


Some region shows 20-30 x higher CO emission than other region !

Important Engine characteristic curves

2) Operating map:

5. Representation of engine regulation (ECU) parameters (f.ex: fuel injection) :



Reminder - combustion

Combustion process (cf. § 11.3 - Borel / Favrat)

Reminder of a combustion process

Reactant + Oxidant —Combustion Process→ Products + Heat

$$\underbrace{C_vH_wS_xO_yN_z}_{Hydrocarbons} + \underbrace{\left(O_2 + 3.76 \cdot N_2\right)}_{Air\ (21\%\ O_2, vol)} \quad \rightarrow \quad \begin{matrix} CO_2 + H_2O \\ (NO_x + CO + HC) \end{matrix} \quad + \quad \Delta H$$

- Reactant
  - Fuel (hydrocarbon) : $C_vH_wS_xO_yN_z \rightarrow C_vH_w \rightarrow H_2$
- Oxidant (Air) : $O_2 + 3.762 \cdot N_2$
- Products :
  - Combustion products: $CO_2\ ;\ H_2O$
  - Pollutants: $NO_x\ ;\ CO\ ;\ HC\ ;\ SO_2 ...$
  - Others (no reaction): $N_2\ ;\ O_2$

Combustion process

Combustion process: possible cases

- **Rich combustion or incomplete combustion** ⇒ Fuel excess versus O_2
- **Lean combustion or complete combustion** ⇒ O_2 excess versus Fuel
- **Stoichiometric combustion** ⇒ exact minimal O_2 for a complete combustion

Air/Fuel ratio *or* stoichiometric ratio: $R_{A/F}$

- Corresponds to the *mass* ratio (*or molar* ratio) of the air quantity versus the required Fuel quantity to obtain a stoichiometric combustion
  - $R_{A/F}$ *mass* [kg_F / kg_{Air}]: $$R_{A/F} = \frac{M_{A,sto}}{M_F} = \frac{N_{A,sto}}{N_F} \cdot \frac{\tilde{m}_A}{\tilde{m}_F}$$
  - $R_{A/F}$ *molar* [$kmol_F$ / $kmol_{Air}$]: $$\tilde{R}_{A/F} = \frac{N_{A,sto}}{N_F}$$

With:

M_A in [kg of A]

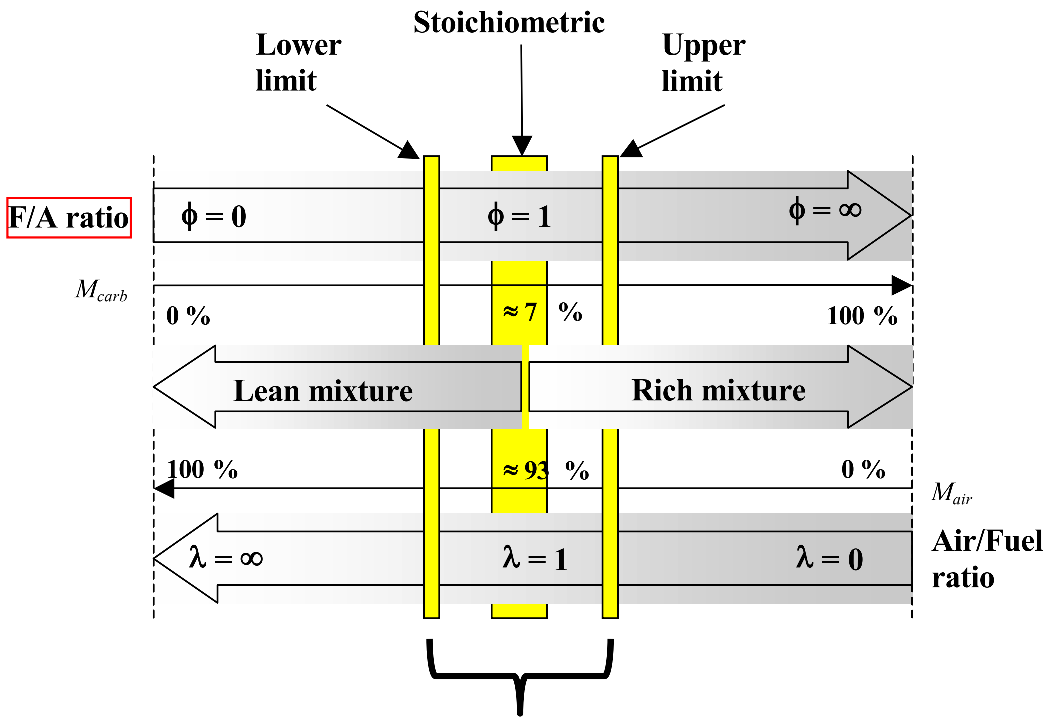
N_A in [kmol of A]

$\tilde{m}_A$ in [kg/kmol of A]

SI engines : A/F ≈ constant with load, typically 15. Regulation at λ=1.
CI engines: air flow ≈ constant with partial load, it is the fuel flow that varies. A/F ≈ 18 at full load, and A/F ≈ 80 for 'no' load.

Combustion process

- Relative Air/Fuel ratio: λ ratio
  - Characterizes the deviation between M_A and $M_{A\text{-stoich}}$: $\lambda = \frac{M_A}{M_{A,sto}} = \frac{N_A}{N_{A,sto}}$
    - $\lambda > 1$: lean mixture
    - $\lambda < 1$: rich mixture



- Fuel/Air ratio: ϕ
  - Inverse of λ : $\phi = \frac{1}{\lambda}$
    - $\phi > 1$: rich mixture
    - $\phi < 1$: lean mixture

Gasoline : $R_{A/F} \approx 14.5$

Natural gas : $R_{A/F} \approx 16.6$

Combustion process

- General equation of combustion

$$N_F \cdot C_v H_w S_x O_y N_z + N_{O_2,sto} \cdot \left(O_2 + 3.762 \cdot N_2\right) \rightarrow N_{CO_2} \cdot CO_2 + N_{H_2O} \cdot H_2O + N_{SO_2} \cdot SO_2 + N_{N_{2,sto}} \cdot N_2$$

$$R_{A/F} = \frac{M_{A,sto}}{M_F} = \frac{N_{A,sto}}{N_F} \cdot \frac{\tilde{m}_A}{\tilde{m}_F} = \frac{4.762 \cdot N_{O_2,sto}}{N_F} \cdot \frac{\tilde{m}_A}{\tilde{m}_F} = 4.762 \cdot \left(v + \frac{w}{4} + x - \frac{y}{2}\right) \cdot \frac{28.85}{\tilde{m}_F}$$

- Conventional fuels: **x = 0, z = 0, y = 0** $\Rightarrow C_v H_w$

$$N_F \cdot C_v H_w + N_{O_2,sto} \cdot \left(O_2 + 3.762 \cdot N_2\right) \rightarrow N_{CO_2} \cdot CO_2 + N_{H_2O} \cdot H_2O + N_{N_{2,sto}} \cdot N_2$$

$$R_{A/F} = \frac{M_{A,sto}}{M_F} = \frac{N_{A,sto}}{N_F} \cdot \frac{\tilde{m}_A}{\tilde{m}_F} = \frac{4.762 \cdot N_{O_2,sto}}{N_F} \cdot \frac{\tilde{m}_A}{\tilde{m}_F} = 4.762 \cdot \left(v + \frac{w}{4}\right) \cdot \frac{28.85}{12 \cdot v + w}$$

- Oxygenated fuels: **x = 0, z = 0** $\Rightarrow C_v H_w O_y$

$$N_F \cdot C_v H_w O_y + N_{O_2,sto} \cdot \left(O_2 + 3.762 \cdot N_2\right) \rightarrow N_{CO_2} \cdot CO_2 + N_{H_2O} \cdot H_2O + N_{N_{2,sto}} \cdot N_2$$

$$R_{A/F} = \left(v + \frac{w}{4} - \frac{y}{2}\right) \cdot \frac{4.762 \cdot 28.85}{12 \cdot v + w + 16 \cdot y}$$

Combustion process

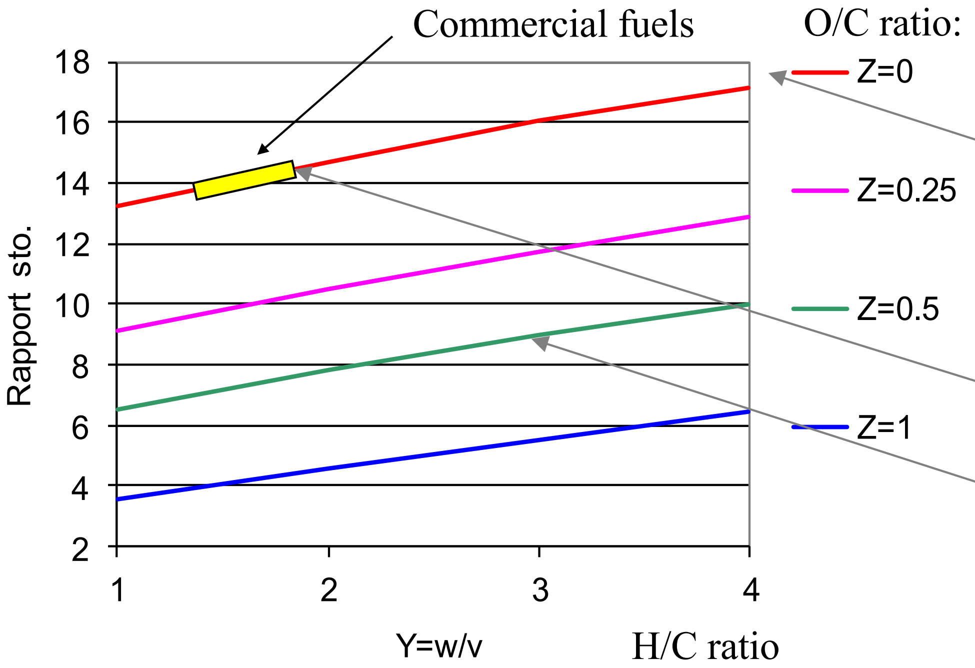
- C_vH_w :

$$With \quad Y = \frac{w}{v} \quad \rightarrow \quad R_{A/F} = \left(1 + \frac{Y}{4}\right) \cdot \frac{4.762 \cdot 28.85}{12 + Y}$$

- $C_vH_wO_y$:

$$With \quad Y = \frac{w}{v}, Z = \frac{y}{v} \quad \rightarrow \quad R_{A/F} = \left(1 + \frac{Y}{4} - \frac{Z}{2}\right) \cdot \frac{4.762 \cdot 28.85}{12 + Y + 16 \cdot Z}$$

- Stoichiometric ratio as a function of Y (=H/C) and Z (=O/C):



mass ratio

Product	Molecules	Y	Z	$R_{A/F}$
Methane	CH_4	4	0	17.17
Propane	C_3H_8	2.66	0	15.6
Butane	C_4H_{10}	2.5	0	15.4
Conv. Gasoline	$CH_{1.8}$	1.8	0	14.45
Ethanol	C_2H_5OH	3	0.5	8.96
Methanol	CH_3OH	4	1	6.44