Ciências ULisboa

Faculdade
de Ciências
da Universidade
de Lisboa

# DISCIPLINA MIEA 2018

# Technologies of combustion

# Corpo docente

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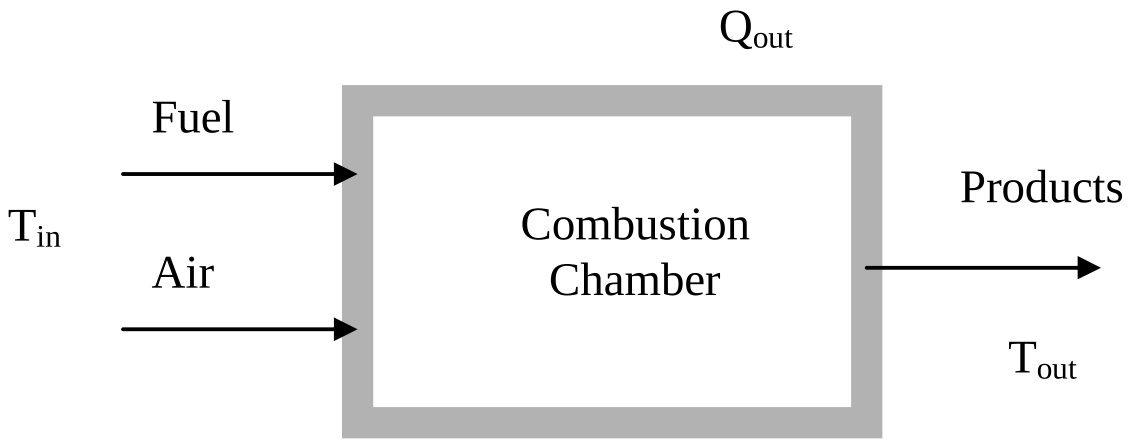
# Thermochemistry

**P#10 Following table list the results of an experiment of boiler that is used to produce superheated vapour. The boiler is feed by natural gas trough a conventional burner.**

**a) The air/fuel ratio**
**b) The higher heating value of the fuel**
**c) Heat transfer to water, assuming that heat loss trough boiler walls are 3% of the lower heating value.**

| | |
|---|---|
| **Fuel rate** | **150 $m^3/h$** |
| Reactants temperature@ entrance | 25ºC |
| Products temperature @exit | 227ºC |
| Fuel composition by volume(%) | $CH_4$: 88<br>$H_2$: 2<br>$CO_2$: 3<br>$N_2$: 7 |
| Dry analysis combustion products (%) | $O_2$: 1.1<br>$CO_2$: 10.8<br>$N_2$: 88.1 |

# Thermochemistry

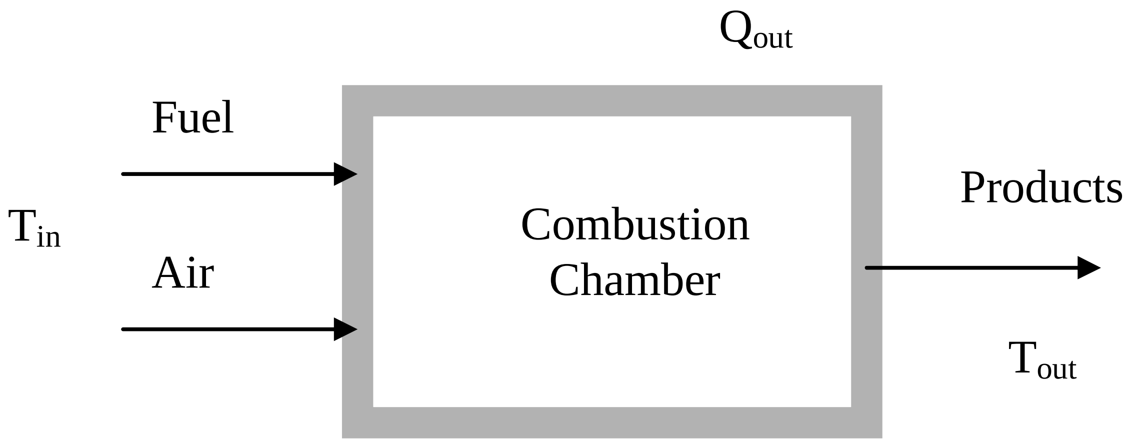



- Maximum heat release, max $Q_{out}$: $T_{out}=T_{in}$
- Maximum flame temperature, $T_{ad}$:

  Hreag($T_{in}$)=Hprod ($T_{ad}$)(constant pressure, e.g. Diesel engine, gas turbine, furnace)

  Hreag($T_{in}$)=Hprod ($T_{ad}$)-R($n_{prod}T_{ad}$-$n_{reag}T_{in}$) (constant volume, e.g. gasoline engine)

# Thermochemistry




- Ideal stoichiometric combustion

$$C_xH_yO_z + n(O_2 + 3.76N_2) \rightarrow xCO_2 + yH_2O + 3.76nN_2$$

- Real stoichiometric combustion

$$C_xH_yO_z + n(O_2 + 3.76N_2) \rightarrow aCO_2 + bCO + cH_2O + dH_2 + eH + fO_2 + gO + hN_2 + iN$$

# Chemical Equilibrium

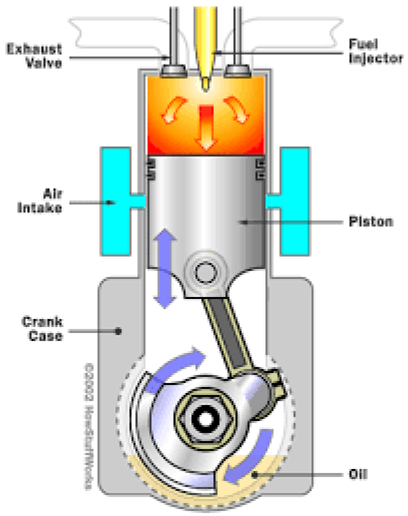
$K$ is tabulated as a function of temperature for different equilibrium reactions

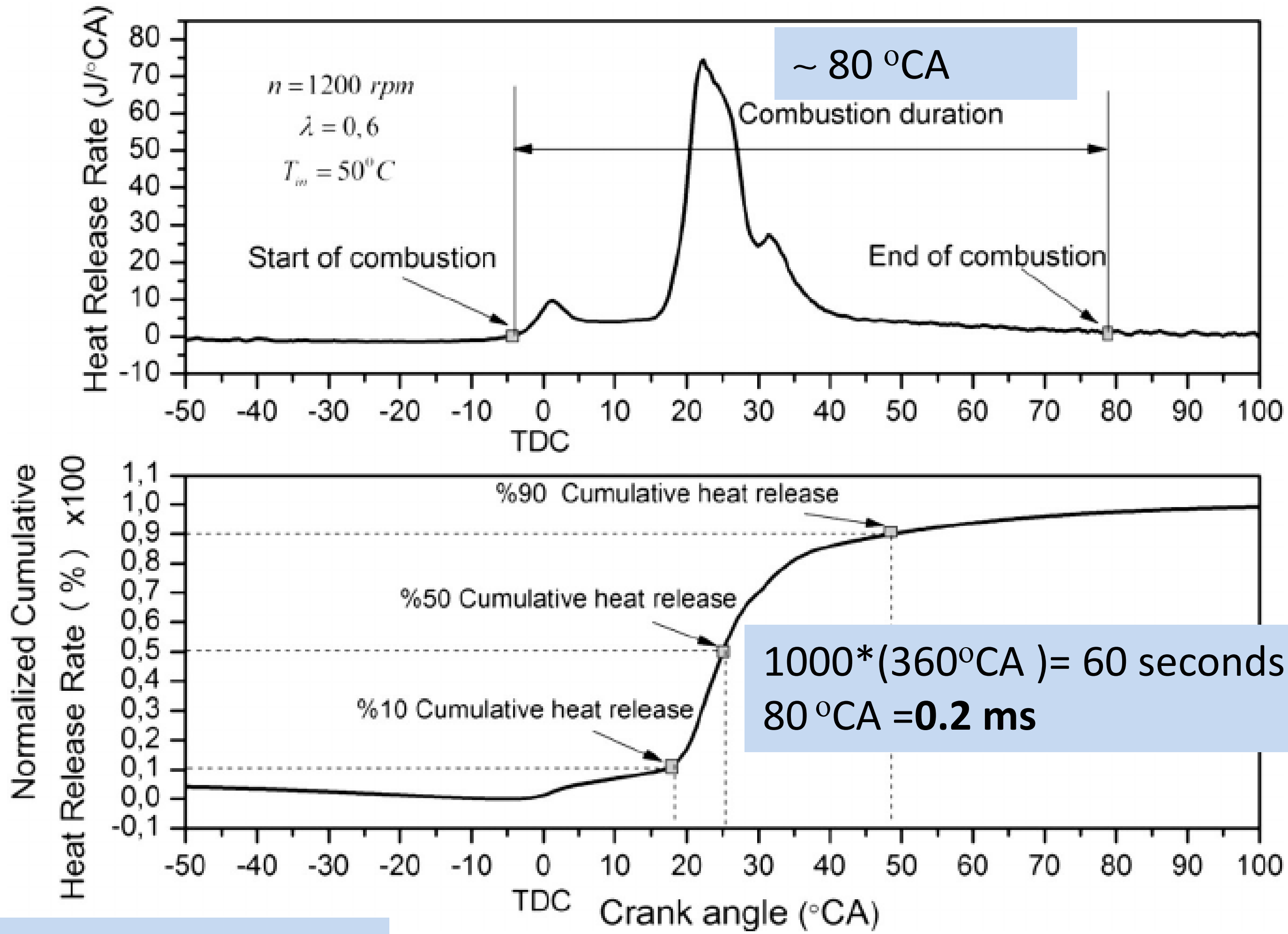
**APÊNDICE 4**
**CONSTANTES DE EQUILÍBRIO**

| | $H_2+1/2O_2 \Leftrightarrow H_2O$ | $CO+1/2O_2 \Leftrightarrow CO_2$ | $CO+H_2O \Leftrightarrow CO_2+H_2$ | $OH+1/2H_2 \Leftrightarrow H_2O$ | $1/2O_2+1/2N_2 \Leftrightarrow NO$ | $2H \Leftrightarrow H_2$ | $2O \Leftrightarrow O_2$ | $2N \Leftrightarrow N_2$ |
|---|---|---|---|---|---|---|---|---|
| | $\log_{10} K_p$ com as pressões parciais em atmosferas | | | | | | | |
| $T$ (K) | $\frac{p_{H_2O}}{p_{H_2}\sqrt{p_{O_2}}}$ | $\frac{p_{CO_2}}{p_{CO}\sqrt{p_{O_2}}}$ | $\frac{(p_{H_2O})(p_{CO})}{(p_{H_2})(p_{CO_2})}$ | $\frac{p_{H_2O}}{p_{OH}\sqrt{p_{H_2}}}$ | $\frac{p_{NO}}{\sqrt{p_{O_2}}\sqrt{p_{N_2}}}$ | $\frac{p_{H_2}}{(p_H)^2}$ | $\frac{p_{O_2}}{(p_O)^2}$ | $\frac{p_{N_2}}{(p_N)^2}$ |
| 298 | 40,048 | 45,066 | –5,018 | 46,181 | –15,171 | 71,232 | 81,202 | 159,600 |
| 300 | 39,786 | 44,760 | –4,974 | 45,876 | –15,073 | 70,762 | 80,664 | 158,578 |
| 400 | 29,240 | 32,431 | –3,191 | 33,600 | –11,142 | 51,758 | 58,944 | 117,408 |
| 600 | 18,633 | 20,087 | –1,454 | 21,264 | –7,210 | 32,676 | 37,146 | 76,162 |
| 800 | 13,289 | 13,916 | –0,627 | 15,060 | –5,243 | 23,082 | 26,202 | 55,488 |
| 1000 | 10,062 | 10,221 | –0,159 | 11,322 | –4,062 | 17,294 | 19,612 | 43,056 |
| 1200 | 7,899 | 7,764 | 0,135 | 8,822 | –3,275 | 13,416 | 15,208 | 34,754 |
| 1400 | 6,347 | 6,014 | 0,333 | 7,030 | –2,712 | 10,632 | 12,054 | 28,812 |
| 1600 | 5,180 | 4,706 | 0,474 | 5,686 | –2,290 | 8,534 | 9,684 | 24,350 |
| 1800 | 4,270 | 3,693 | 0,577 | 4,638 | –1,962 | 6,896 | 7,836 | 20,874 |
| 2000 | 3,540 | 2,884 | 0,656 | 3,799 | –1,699 | 5,582 | 6,356 | 18,092 |
| 2200 | 2,942 | 2,226 | 0,716 | 3,113 | –1,484 | 4,504 | 5,142 | 15,810 |
| 2400 | 2,443 | 1,679 | 0,764 | 2,541 | –1,305 | 3,602 | 4,130 | 13,908 |

**Tabela A4.1**
*Constantes de equilíbrio. (Dados extraídos de Rogers e Mayhew, 1994.) (continua)*

# Emissions




~ 80 $^{o}$CA

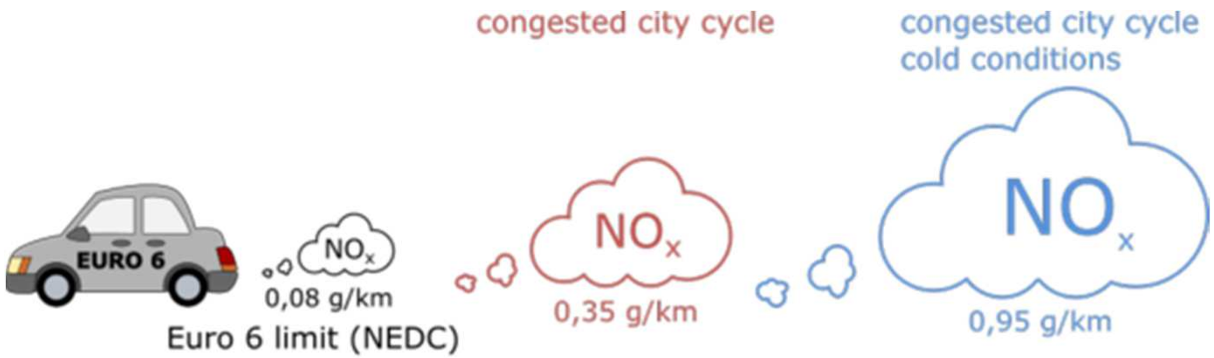
1000*(360$^{o}$CA )= 60 seconds
80 $^{o}$CA =**0.2 ms**

**More rpm, less combustion time!!!**

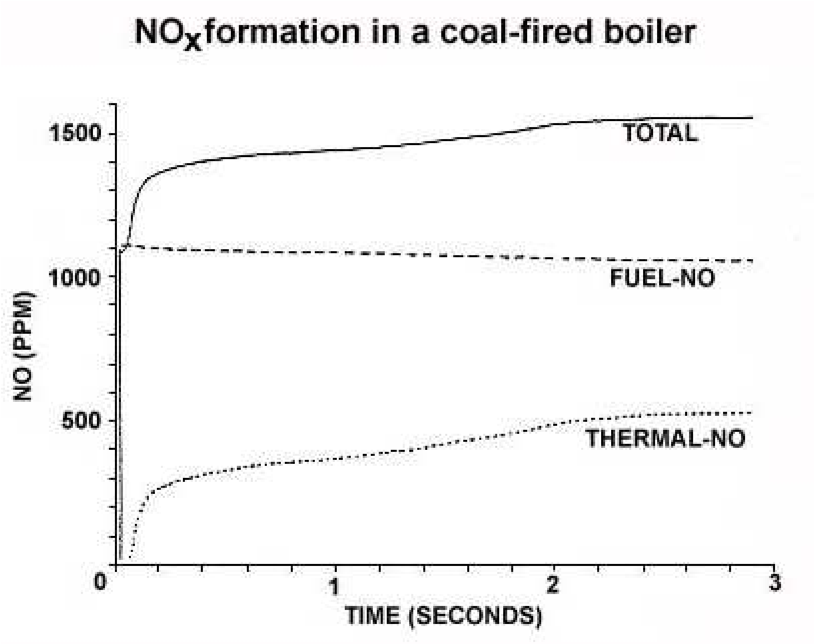
# Emissions

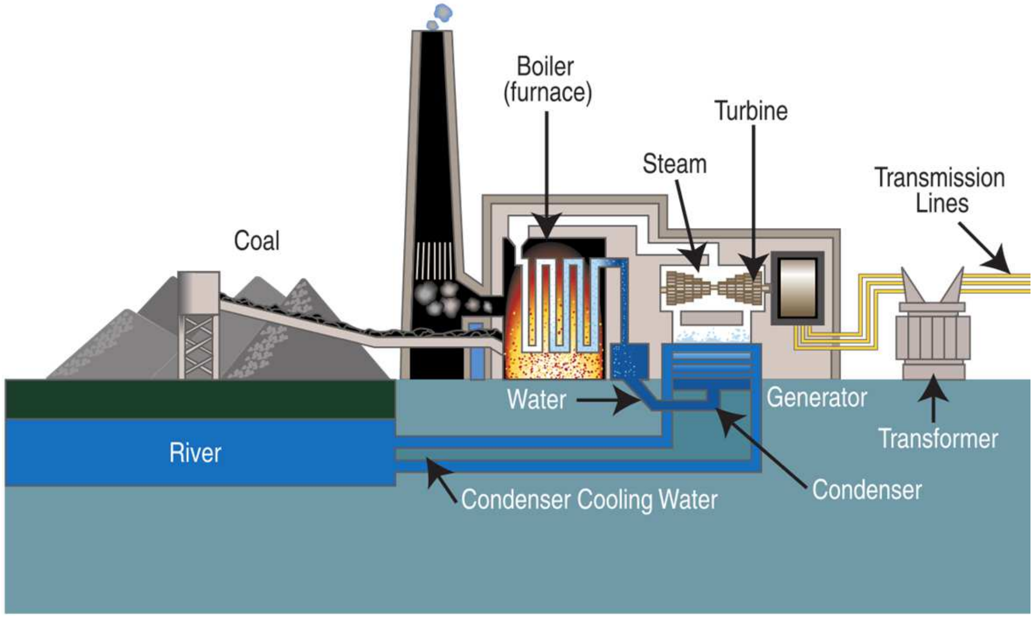
Adiabatic flame temperature ↑

NOx emissions ↑



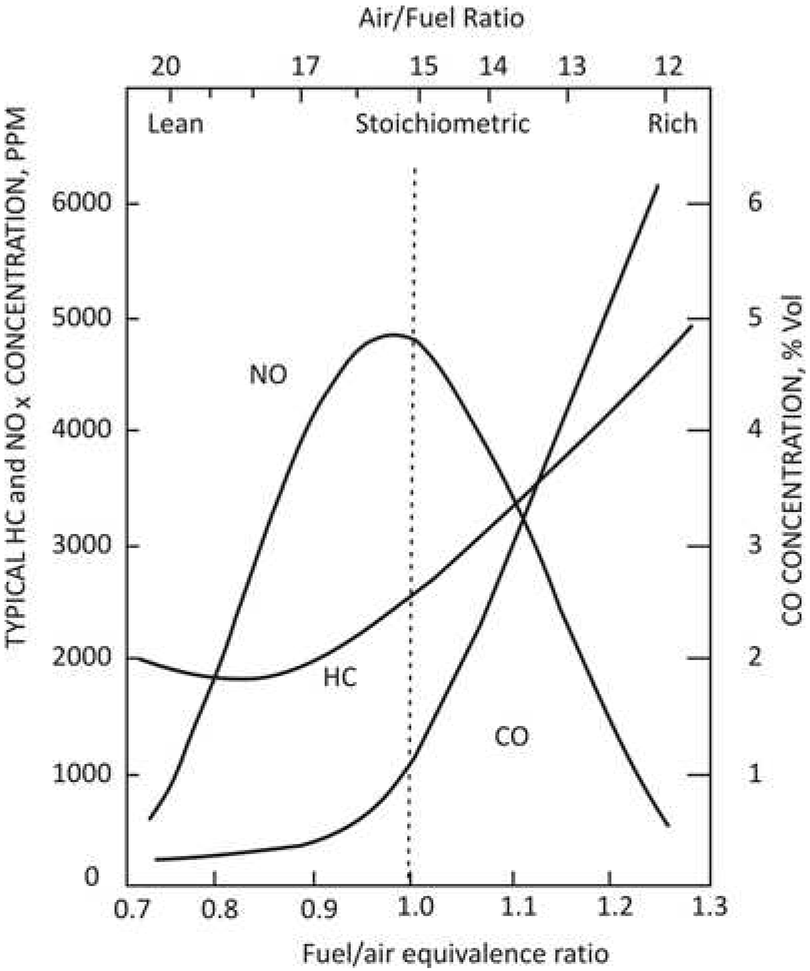
# Emissions



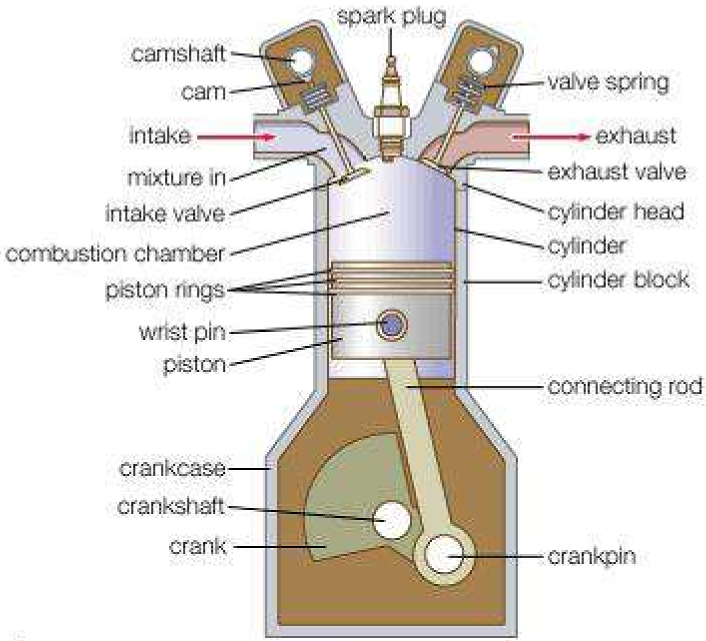




ppm ☺ !!!!

# Emissions

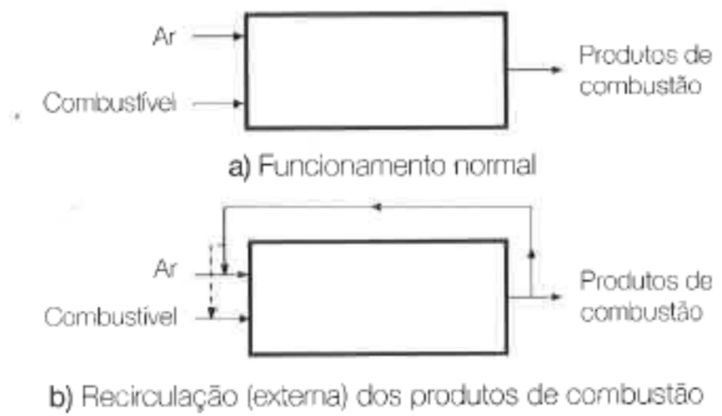



$$\phi = \frac{1}{\lambda}$$



# Emissions

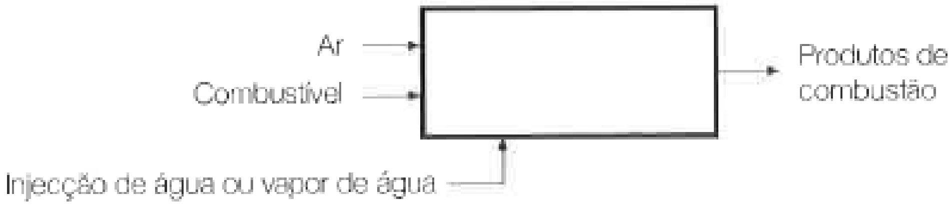
**How to control combustion to lower at least NOx emissions?**



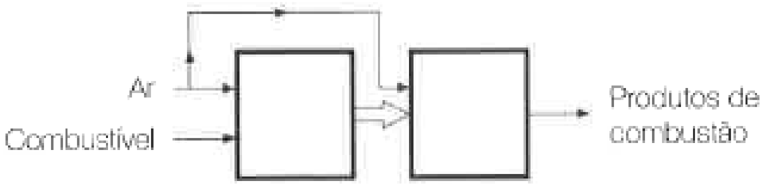

EGR-Exhaust gas recirculation

# Emissions

Water injection



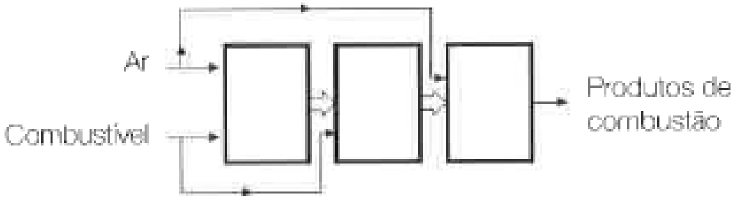

**c)** Injecção de água ou vapor de água




**d)** Estagiamento do ar de combustão

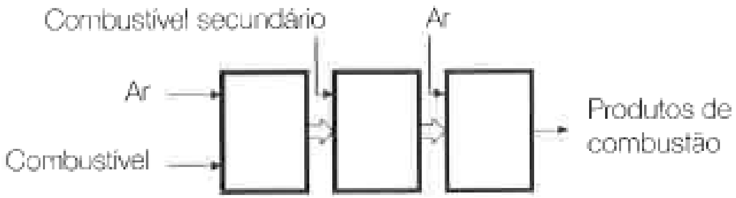
Air introduction in 2 stages

# Emissions




e) Estagiamento do combustível

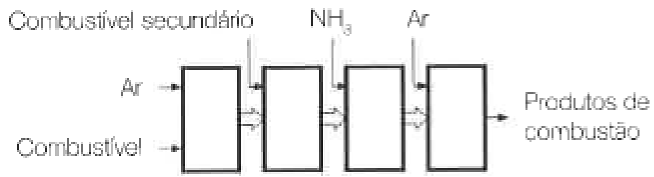
Air introduction in 2 stages
+fuel introduction in 2 stages




f) "Reburning"

Poor pre-mixtures


g) Pré-misturas pobres

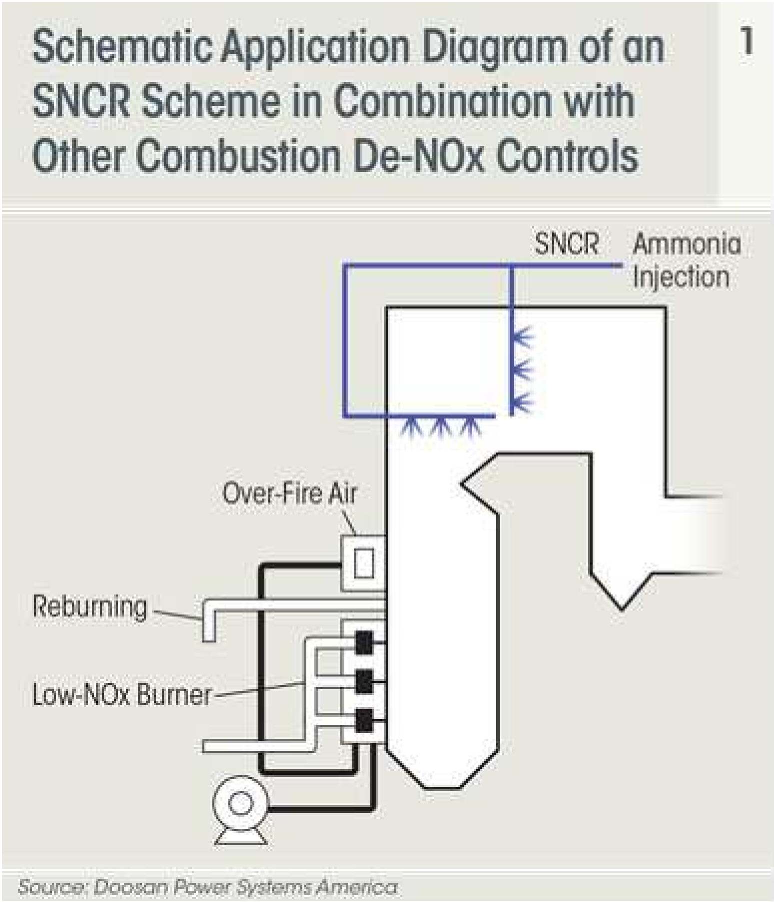



h) "Reburning" + Redução não catalítica selectiva

“Reburning”
+Non-catalytic Selective NOx reduction

# Emissions

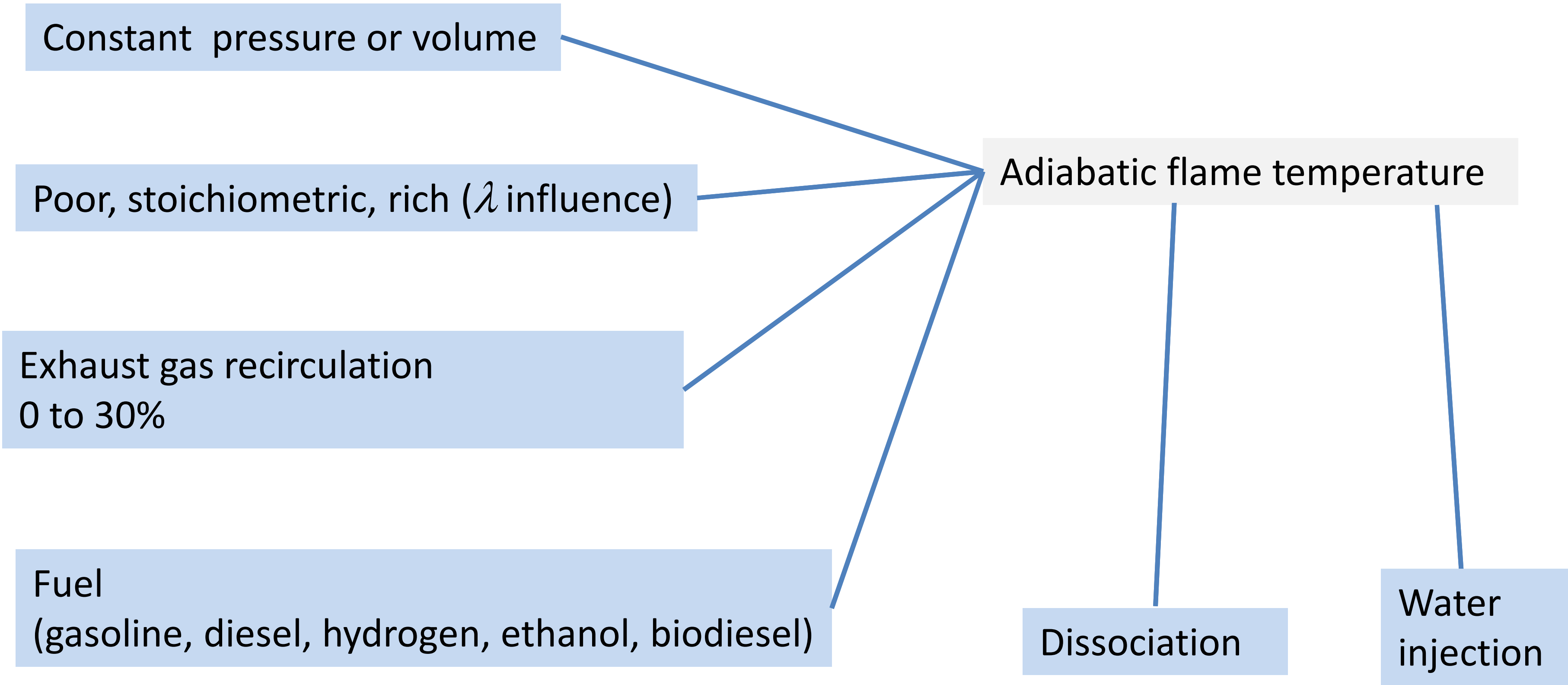
Coal fire power-plants – NOx control- SNCR- Selective non Catalytic Reduction




$$4NO+4NH_3+O_2 \rightarrow 4N_2+6H_2O$$

# Emissions

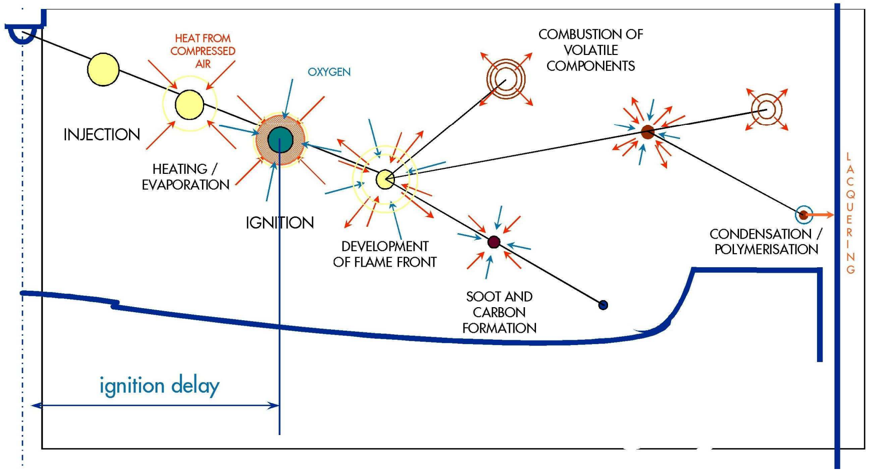
## Adiabatic Flame Temperature

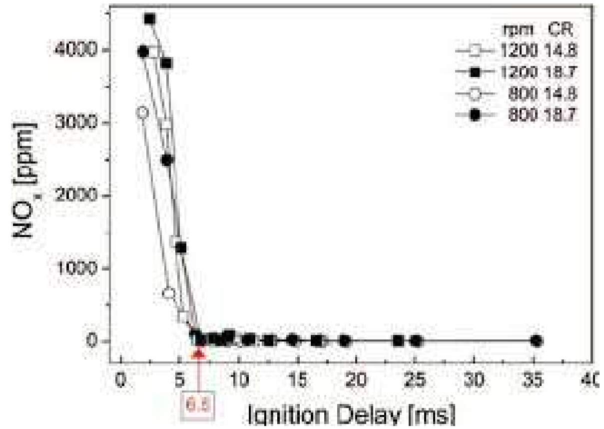


# Emissions

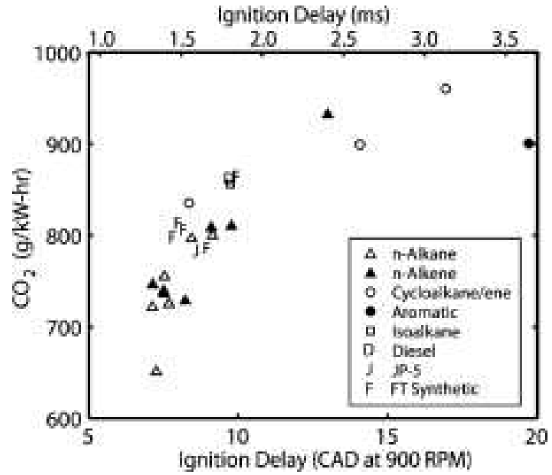
**No pre-mixture**

## Diesel Combustion Process



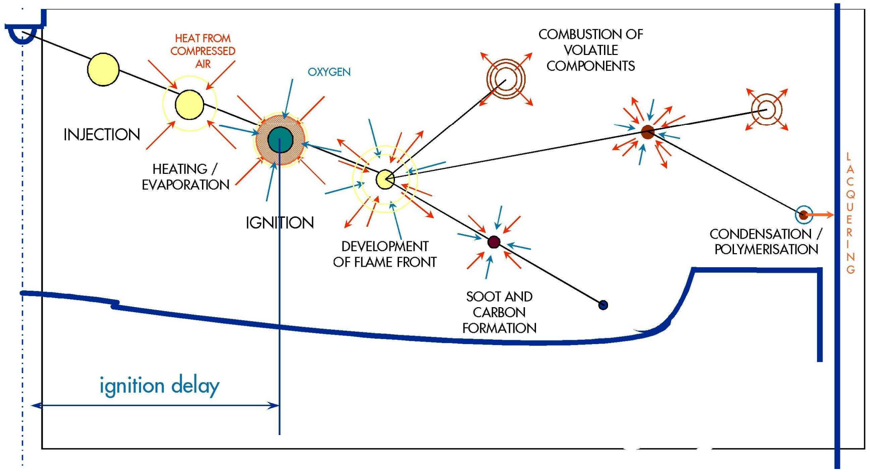

**Influence of ignition delay on emissions**



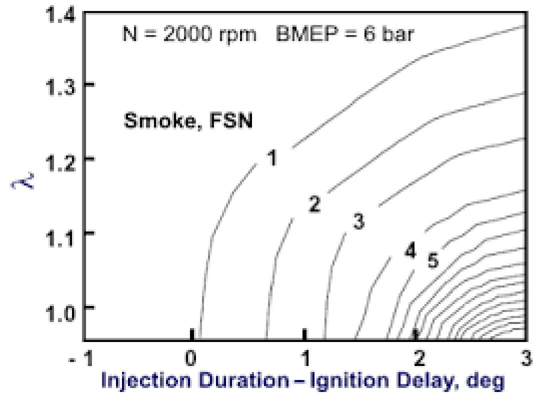
# Emissions

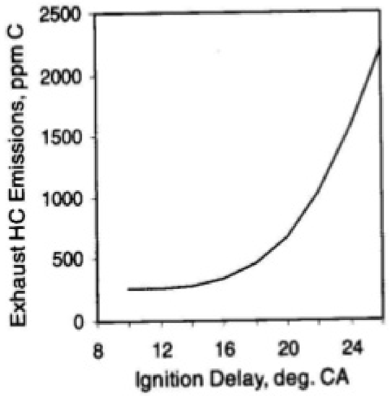
**No pre-mixture**

## Diesel Combustion Process




Visible particles



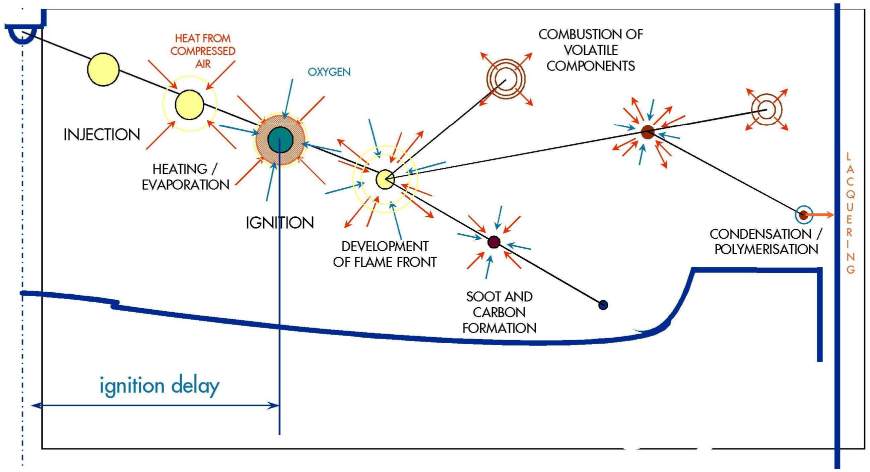



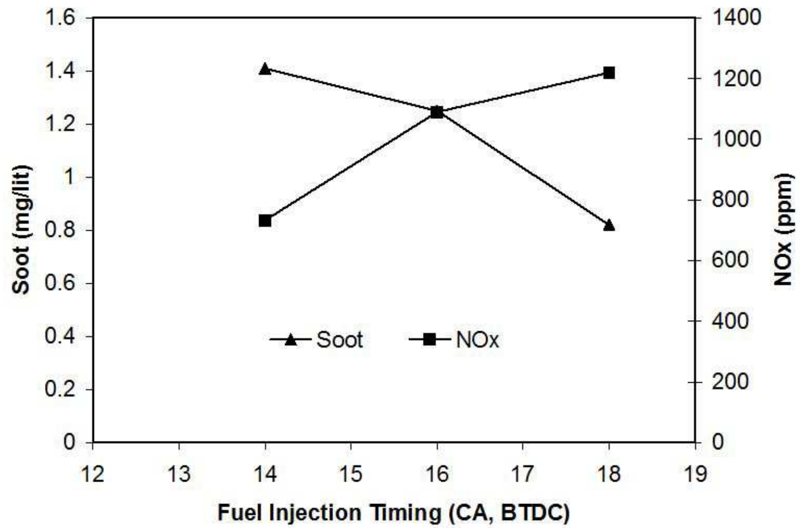

**Influence of ignition delay on emissions**

# Emissions

**No pre-mixture**

## Diesel Combustion Process




**Influence of ignition delay on emissions**

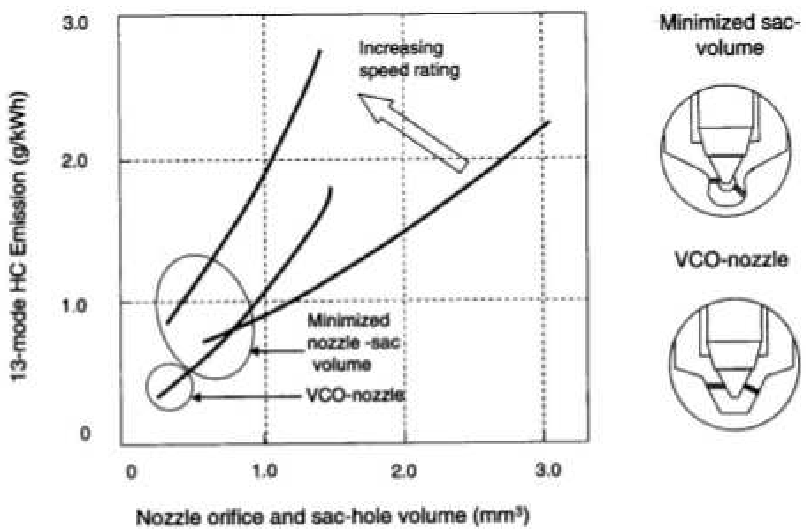
CA-Crank angle (angulos de cambota)

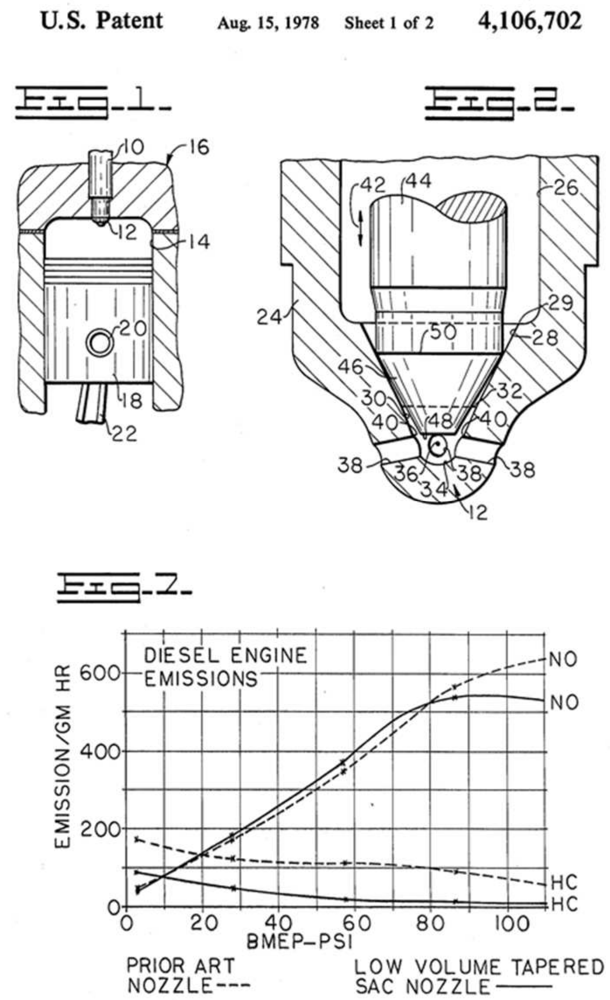
BTDC-Before Top dead centre (antes do ponto morto superior)

# Diesel Engine Emissions : formation, effect of variables and their control

## HC emission from CI Engines

- Effect of nozzle sac volume and hole type



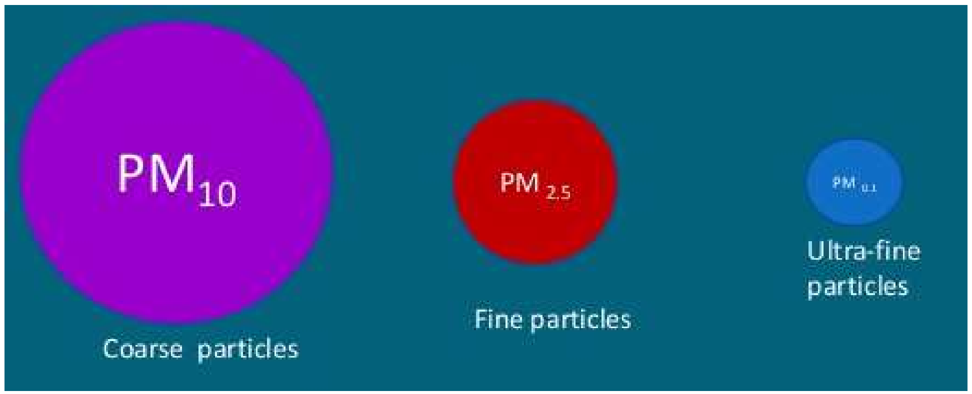

**Influence of injector nozzle**

# Emissions

## Particles and soot formation

**PM1**
**PM2.5**
**PM10**

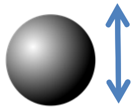
- Lead (Pb in fuel)
- Organic particles (includes soot)
- Sulfates (S in fuel)




Deposit in the extra thoracic/upper tracheo-branchial region → Deposit in deeper lung → Pass into the circulatory system

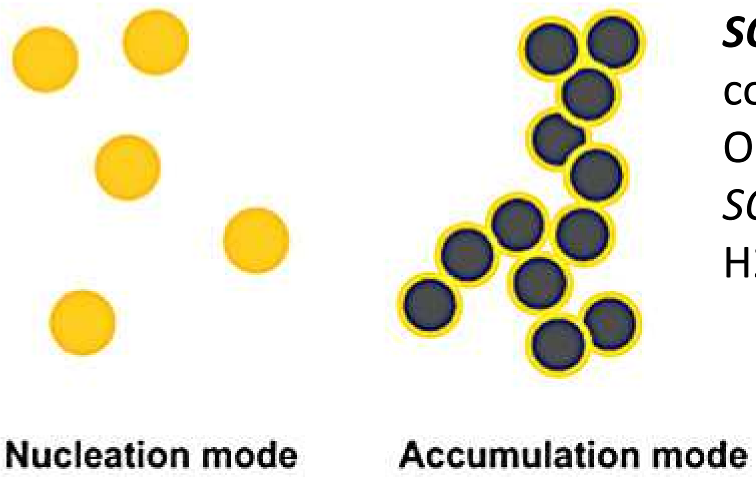
# Emissions

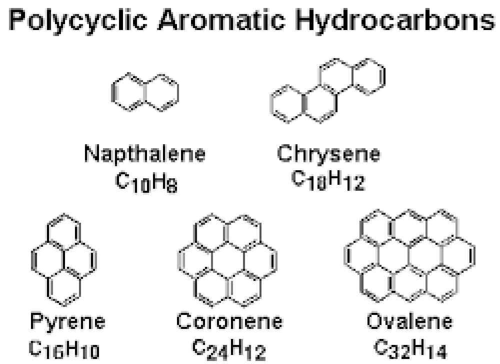
Organic particles (includes soot- carbonaceous material)      H, C, O



**15 nm**< Spherule diameters< **30 nm**

*Solids* – dry carbon particles, commonly known as soot,
***SOF*** – heavy hydrocarbons adsorbed and condensed on the carbon particles, called Soluble Organic Fraction,
*SO4* – sulfate fraction, hydrated sulfuric acid H2SO4.



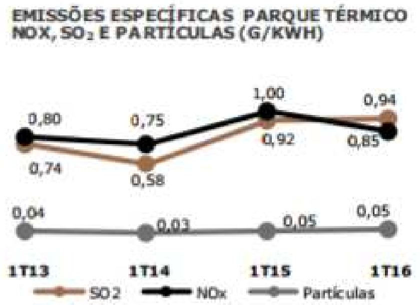

**SOF**-Polynuclear Aromatic Hydrocarbons (PAH) are hydrocarbons containing two or more benzene rings

# Emissions

2012

– **Emissões atmosféricas específicas e resíduos radioativos associados à produção de energia**

| emissões | |
|---|---|
| $CO_2$ (g/kWh) | 279,13 |
| $SO_2$ (g/kWh) | 2,56 |
| NOX (g/kWh) | 1,04 |
| Resíduos Radioativos (µg/kWh) | 18,75 |




[all in mg/km]

| | | | | CO | HC | NOx | PM |
|---|---|---|---|---|---|---|---|
| RENAULT Clio | 1.2 16V 75 | M5 1149 | Petrol | 269 | 49 | 28 | |
| RENAULT Clio | 1.5 dCi 88 | M5 1461 | Diesel | 298 | 23 | 155 | 0.1 |

# low emission zones and the raising of air-quality target

World Health Organization

particulate matter (PM)
ozone ($O_3$)
nitrogen dioxide ($NO_2$)
sulfur dioxide ($SO_2$)

Ambient (outdoor air pollution) in both cities and rural areas was estimated to cause **3 million** premature deaths worldwide in 2012

# Emissions-Outdoor sources

## Ambient Air Quality Directive 2008/50/EC

| Mean | Limit $PM_{10}$ (Particulate Matter) | Limit $NO_2$ (Nitrogen Dioxide) |
|---|---|---|
| 24 h ($PM_{10}$) 1 h ($NO_2$) | 50 µg/m$^3$ not more than 35 violations /year | 200 µg/m$^3$not more than 18 violations/year |
| 1 year | 40 µg/m$^3$ | 40 µg/m$^3$ |

**PM10 and PM2.5 particulates are easily breathed in (causing lung cancer).**

# low emission zones and the raising of air-quality target

**Avenida da Liberdade**

**Dados da Estação**

| | | |
|---|---|---|
| Código: | | 3075 |
| Data de inicio: | | 1994-01-01 |
| Tipo de Ambiente: | | Urbana |
| Tipo de Influência: | | Tráfego |
| Zona: | | Área Metropolitana de Lisboa Norte (a) |
| Rua: | | Avenida da Liberdade |
| Freguesia: | | Santo António |
| Concelho: | | Lisboa |
| Coordernadas Gauss Militar (m) | Latitude: | 195336 |
| | Longitude: | 111902 |
| Coordernadas Geográficas WGS84 | Latitude: | 38°43'13'' |
| | Longitude: | -9°08'45'' |
| Altitude (m): | | 44 |
| Rede: | | Rede de Qualidade do Ar de Lisboa e Vale do Tejo |
| Instituição: | | Comissão de Coordenação e Desenvolvimento Regional de Lisboa e Vale do Tejo |
| Contacto: | | 21 0101 300 |

**(a)** a zona é uma aglomeração

**Poluentes**

| Poluente | Símbolo | Data de Início | Data de Fim |
|---|---|---|---|
| Monóxido de Azoto | NO | 1994-01-01 | |
| Dióxido de Azoto | NO2 | 1994-01-01 | |
| Óxidos de Azoto | NOx | 1994-01-01 | |
| Partículas < 10 µm | PM10 | 1998-02-01 | |
| Monóxido de Carbono | CO | 1994-01-01 | |

<< >>

**Escolha uma outra estação:**

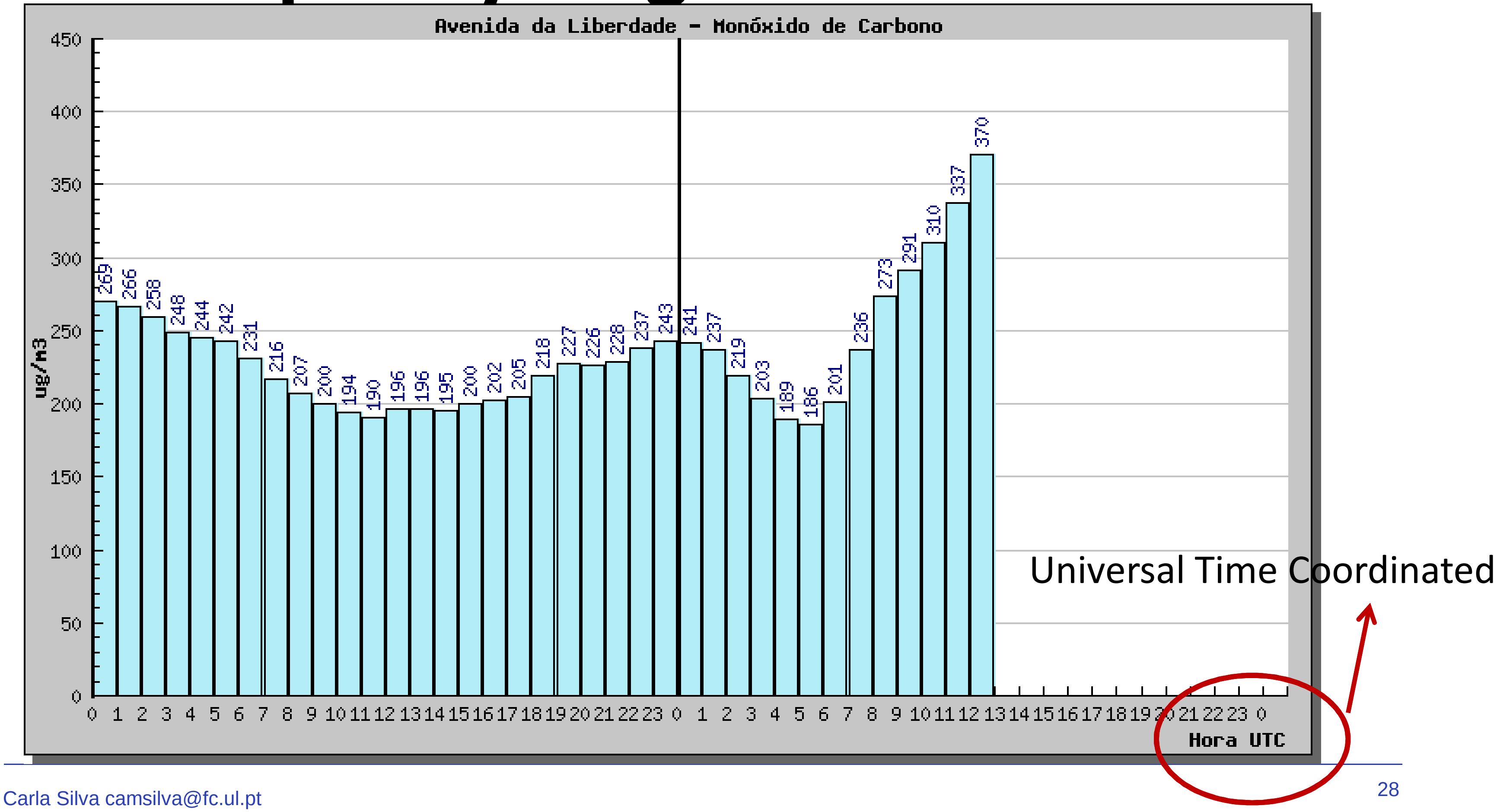
Escolha uma estação ▼ OK ››

**Estatísticas:**

Escolha um poluente ▼

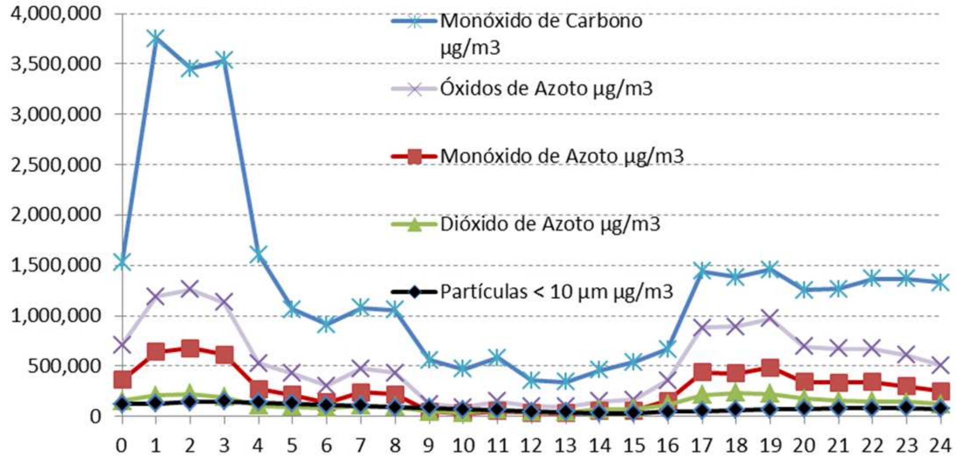
▼ OK ››

# low emission zones and the raising of air-quality target



# Emissions-Outdoor

# Air-quality av. Liberdade

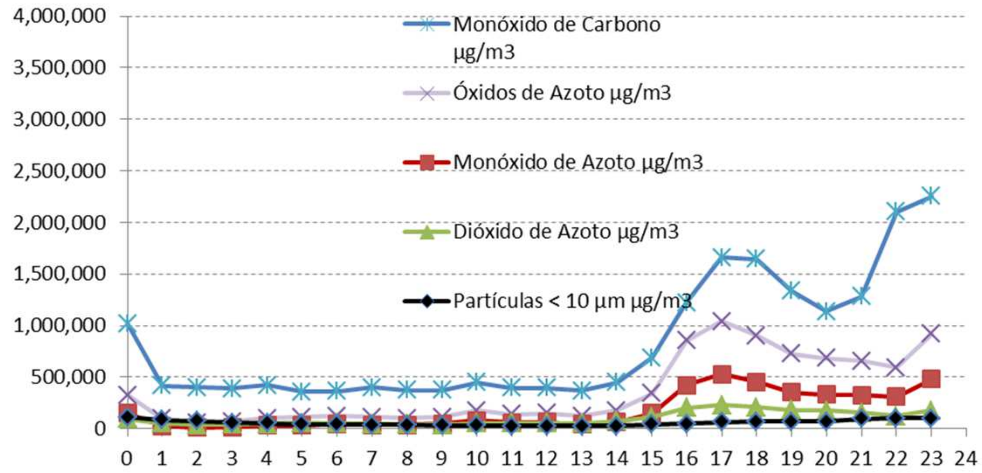



1-1-2015
(Thursday)

QualAr
Base de Dados Online sobre a Qualidade de Ar

AGÊNCIA PORTUGUESA DO AMBIENTE

3-1-2015
(Saturday)



# low emission zones and the raising of air-quality target

| | |
|---|---|
| Estação | Avenida da Liberdade |
| Inflência | Tráfego |
| Ambiente | Urbana |
| Poluente | Dióxido de Azoto (NO2) |
| Ano | 2015 |

**Dados Estatísticos**

| Parâmetro | Valor Anual (base horária) | Valor Anual (base diária) |
|---|---|---|
| Eficiência (%) | 98,7% | 98,4% |
| Dados Validados (n.º) | 8.644 | 359 |
| Média (µg/m3) | 58,6 | 58,5 |
| Máximo (µg/m3) | 247,3 | 128,8 |

**Limiar de Alerta**

(Decreto-lei n.º 102/2010)

| Designação | Valor (µg/m3) | Nº. de Excedencias |
|---|---|---|
| Limiar de Alerta (medido em três horas consecutivas) | 400 | 0 |

**Protecção da Saúde Humana: Base Horária**

(Decreto-lei n.º 102/2010)

| Designação | Valor (µg/m3) | Excedências Permitidas (horas) | N.º Excedências (horas) |
|---|---|---|---|
| VL | 200 | 18 | 20 |

Legenda:
VL - Valor limite: 200 µg/m3.

**Protecção da Saúde Humana: Base Anual**

(Decreto-lei n.º 102/2010)

| Designação | Valor (µg/m3) | Valor Obtido (µg/m3) |
|---|---|---|
| VL | 40 | 58,6 |

# low emission zones and the raising of air-quality target

**Critérios**

| | |
|---|---|
| Estação: | Avenida da Liberdade |
| Poluente: | Partículas < 10 µm (PM10) |
| Ano: | 2015 |

**Dados Estatísticos**

| Parâmetro: | Valor Anual (base horária) | Valor Anual (base diária) |
|---|---|---|
| Eficiência (%) | 94,3% | 93,7% |
| Dados Validados (n.º) | 8.263 | 342 |
| Média (µg/m3): | 36,0 | 36,0 |
| Máximo (µg/m3): | 219,5 | 118,9 |

**Protecção da Saúde Humana: Base Diária**
(Decreto-lei n.º 102/2010)

| Designação: | Valor (µg/m3) | Excedências Permitidas (dias) | N.º Excedências (dias) |
|---|---|---|---|
| VL | 50 | 35 | 66 |

Legenda:
VL - Valor limite: 50 µg/m3.

**Protecção da Saúde Humana: Base Anual**
(Decreto-lei n.º 102/2010)

| Designação: | Valor (µg/m3) | Valor obtido (µg/m3) |
|---|---|---|
| VL | 40 | 36,0 |

Legenda:
VL - Valor limite: 40 µg/m3.

# Emissions-Outdoor sources

**Stationary combustion (limits in mg/m3)**

**Mobile combustion (limits in g/km)**

# Emissions

EN Official Journal of the European Communities L 309/17

ANNEX VII

**EMISSION LIMIT VALUES FOR DUST**

A. Dust emission limit values expressed in $mg/Nm^3$ ($O_2$ content 6 % for solid fuels, 3 % for liquid and gaseous fuels) to be applied by new and existing plants pursuant to Article 4(1) and 4(3), respectively:

| Type of fuel | Rated thermal input (MW) | Emission limit values ($mg/Nm^3$) |
|---|---|---|
| Solid | ≥ 500<br>< 500 | 50 (²)<br>100 |
| Liquid (¹) | all plants | 50 |
| Gaseous | all plants | 5 as a rule<br>10 for blast furnace gas<br>50 for gases produced by the steel industry which can be used elsewhere |

(¹) A limit value of 100 $mg/Nm^3$ may be applied to plants with a rated thermal input of less than 500 MWth burning liquid fuel with an ash content of more than 0,06 %.

(²) A limit value of 100 $mg/Nm^3$ may be applied to plants licensed pursuant to Article 4(3) with a rated thermal input greater than or equal to 500 MWth burning solid fuel with a heat content of less than 5 800 kJ/kg (net calorific value), a moisture content greater than 45 % by weight, a combined moisture and ash content greater than 60 % by weight and a calcium oxide content greater than 10 %.

B. Dust emission limit values expressed in $mg/Nm^3$ to be applied by new plants, pursuant to Article 4(2) with the exception of gas turbines:

*Solid fuels ($O_2$ content 6 %)*

| 50 to 100 MWth | > 100 MWth |
|---|---|
| 50 | 30 |

$mg/Nm^3$

# Emissions

A. $NO_x$ emission limit values expressed in mg/Nm³ ($O_2$ content 6 % for solid fuels, 3 % for liquid and gaseous fuels) to be applied by new and existing plants pursuant to Article 4(1) and 4(3), respectively:

| Type of fuel: | Limit values (1) (mg/Nm³) |
|---|---|
| Solid (2), (3): | |
| 50 to 500 MWth: | 600 |
| >500 MWth: | 500 |
| From 1 January 2016 | |
| 50 to 500 MWth: | 600 |
| >500 MWth: | 200 |
| Liquid: | |
| 50 to 500 MWth: | 450 |
| >500 MWth: | 400 |
| Gaseous: | |
| 50 to 500 MWth: | 300 |
| >500 MWth: | 200 |

(1) Except in the case of the 'Outermost Regions' where the following values shall apply:
Solid in general: 650
Solid with < 10 % vol comps: 1 300
Liquid: 450
Gaseous: 350

(2) Until 31 December 2015 plants of a rated thermal input greater than 500 MW, which from 2008 onwards do not operate more than 2 000 hours a year (rolling average over a period of five years), shall:
- in the case of plant licensed in accordance with Article 4(3)(a), be subject to a limit value for nitrogen oxide emissions (measured as $NO_2$) of 600 mg/Nm³;
- In the case of plant subject to a national plan under Article 4(6), have their contribution to the national plan assessed on the basis of a limit value of 600 mg/Nm³.

From 1 January 2016 such plants, which do not operate more than 1 500 hours a year (rolling average over a period of five years), shall be subject to a limit value for nitrogen oxide emissions (measured as $NO_2$) of 450 mg/Nm³.

(3) Until 1 January 2018 in the case of plants that in the 12 month period ending on 1 January 2001 operated on, and continue to operate on, solid fuels whose volatile content is less than 10 %, 1 200 mg/Nm³ shall apply.

mg/Nm$^3$

N=normal /standard pressure and temperature

Conversion $NO/NO_2$ =(14+16)/(14+32)~1.53

# Emissions



A. $NO_x$ emission limit values expressed in mg/Nm³ ($O_2$ content 6 % for solid fuels, 3 % for liquid and gaseous fuels) to be applied by new and existing plants pursuant to Article 4(1) and 4(3), respectively:

| Type of fuel: | Limit values ([1]) (mg/Nm³) |
|---|---|
| Solid ([2]), ([3]): | |
| 50 to 500 MWth: | 600 |
| >500 MWth: | 500 |
| From 1 January 2016 | |
| 50 to 500 MWth: | 600 |
| >500 MWth: | 200 |
| Liquid: | |
| 50 to 500 MWth: | 450 |
| >500 MWth: | 400 |
| Gaseous: | |
| 50 to 500 MWth: | 300 |
| >500 MWth: | 200 |

([1]) Except in the case of the 'Outermost Regions' where the following values shall apply:
Solid in general: 650
Solid with < 10 % vol comps: 1 300
Liquid: 450
Gaseous: 350

([2]) Until 31 December 2015 plants of a rated thermal input greater than 500 MW, which from 2008 onwards do not operate more than 2 000 hours a year (rolling average over a period of five years), shall:
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([3]) Until 1 January 2018 in the case of plants that in the 12 month period ending on 1 January 2001 operated on, and continue to operate on, solid fuels whose volatile content is less than 10 %, 1 200 mg/Nm³ shall apply.

$NO_2$@6%O2

Convert for the same $\%O_2$:

$$xi_{6\%} = xi * \frac{n}{n_{6\%}}$$

Fuel CxHy

$$n_{xO2} = 4.76 * \left[\frac{x + (1 + xO2)\frac{y}{4}}{1 - 4.76xO2}\right] + \frac{y}{4} \quad \text{(wet)}$$

$$n_{xO2} = 4.76 * \left[\frac{x + (1 - xO2)\frac{y}{4}}{1 - 4.76xO2}\right] - \frac{y}{4} \quad \text{(dry)}$$

# Emissions

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ANNEX VII

**EMISSION LIMIT VALUES FOR DUST**

A. Dust emission limit values expressed in mg/Nm³ ($O_2$ content 6 % for solid fuels, 3 % for liquid and gaseous fuels) to be applied by new and existing plants pursuant to Article 4(1) and 4(3), respectively:

| Type of fuel | Rated thermal input (MW) | Emission limit values (mg/Nm³) |
|---|---|---|
| Solid | ≥ 500<br>< 500 | 50 (²)<br>100 |
| Liquid (¹) | all plants | 50 |
| Gaseous | all plants | 5 as a rule<br>10 for blast furnace gas<br>50 for gases produced by the steel industry which can be used elsewhere |

(¹) A limit value of 100 mg/Nm³ may be applied to plants with a rated thermal input of less than 500 MWth burning liquid fuel with an ash content of more than 0,06 %.

(²) A limit value of 100 mg/Nm³ may be applied to plants licensed pursuant to Article 4(3) with a rated thermal input greater than or equal to 500 MWth burning solid fuel with a heat content of less than 5 800 kJ/kg (net calorific value), a moisture content greater than 45 % by weight, a combined moisture and ash content greater than 60 % by weight and a calcium oxide content greater than 10 %.

B. Dust emission limit values expressed in mg/Nm³ to be applied by new plants, pursuant to Article 4(2) with the exception of gas turbines:

*Solid fuels ($O_2$ content 6 %)*

| 50 to 100 MWth | > 100 MWth |
|---|---|
| 50 | 30 |

$NO_2$@6%O2

Convert kmol/kmol in mg/Nm³

$$X=\text{fraction}=\frac{nNO}{nTotal}*M_{NO}*\frac{1}{\frac{VTotal}{nTotal}}*10^{3}$$

$$X=\text{mg/m3}=\frac{kmol}{kmol}*\frac{kg}{kmol}*\frac{1}{\frac{m3}{kmol}}*10^{3}$$

$$\frac{V}{n}=\frac{RT}{p}=\frac{8.314\frac{\frac{kJ}{kmol}}{K}*298K}{100\ kPa}=$$

$$\frac{8.314\frac{\frac{kJ}{kmol}}{K}*298K}{100\ kNm/m3}=24.8\ \text{m3/kmol}$$

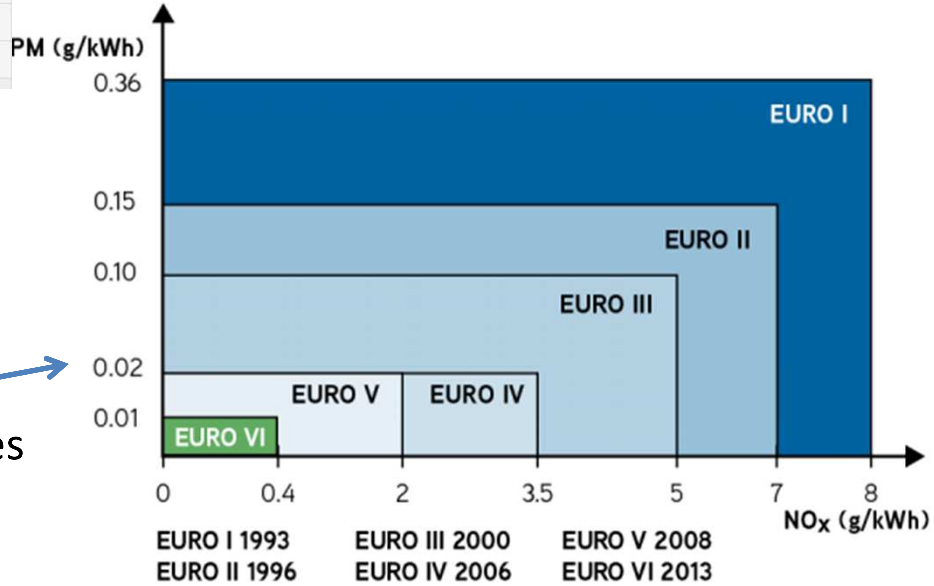
# Emissions

Table 1
EU Emission Standards for Passenger Cars (Category $M_1$*)

| Stage | Date | CO | HC | HC+NOx | NOx | PM | PN |
|---|---|---|---|---|---|---|---|
| | | g/km | | | | | #/km |
| **Compression Ignition (Diesel)** | | | | | | | |
| Euro 1† | 1992.07 | 2.72 (3.16) | - | 0.97 (1.13) | - | 0.14 (0.18) | - |
| Euro 2, IDI | 1996.01 | 1.0 | - | 0.7 | - | 0.08 | - |
| Euro 2, DI | 1996.01[a] | 1.0 | - | 0.9 | - | 0.10 | - |
| Euro 3 | 2000.01 | 0.64 | - | 0.56 | 0.50 | 0.05 | - |
| Euro 4 | 2005.01 | 0.50 | - | 0.30 | 0.25 | 0.025 | - |
| Euro 5a | 2009.09[b] | 0.50 | - | 0.23 | 0.18 | 0.005[f] | - |
| Euro 5b | 2011.09[c] | 0.50 | - | 0.23 | 0.18 | 0.005[f] | $6.0\times10^{11}$ |
| Euro 6 | 2014.09 | 0.50 | - | 0.17 | 0.08 | 0.005[f] | $6.0\times10^{11}$ |

Passenger cars

Truck/bus engines



# Emissions

## low emission zones and the raising of air-quality target

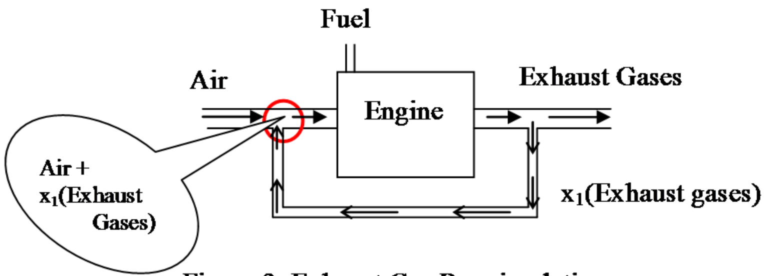


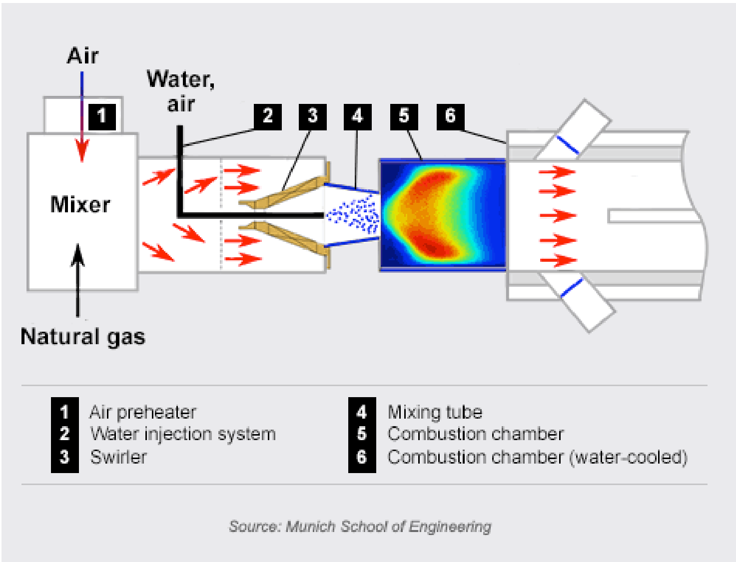

Figure 2: Exhaust Gas Re- circulation

**Combustion alteration not enough!!!!!**

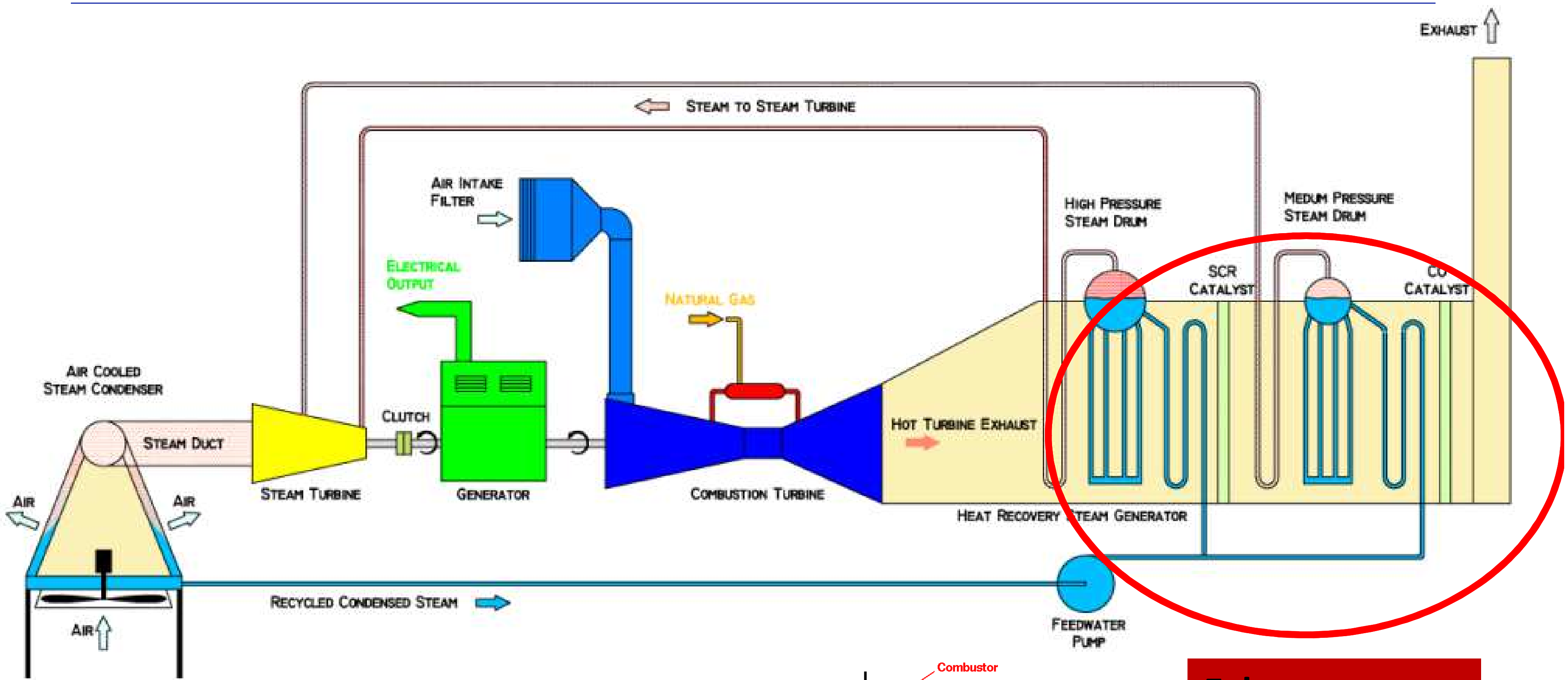
$CO_2$
$H_2O$
$N_2$
CO
HC
NO
NO2
PM

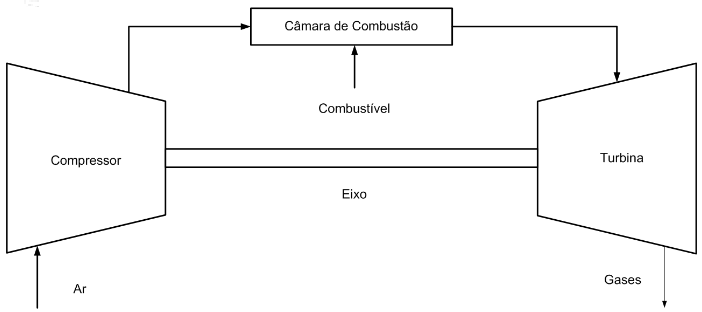
→ **Exhaust gas aftertreatment** →

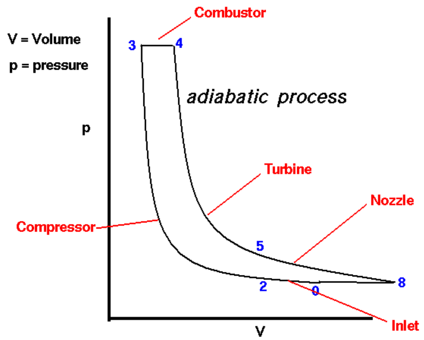
$CO_2$
$H_2O$
$N_2$



# Emissions



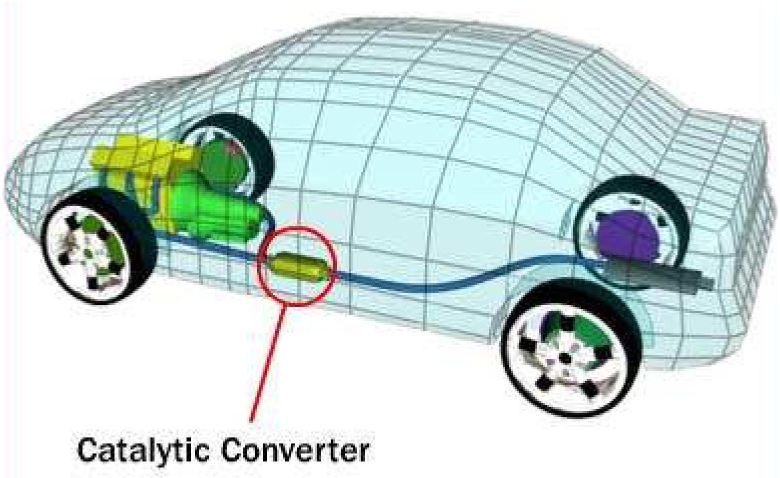

**Exhaust gas aftertreatment**

# low emission zones and the raising of air-quality target

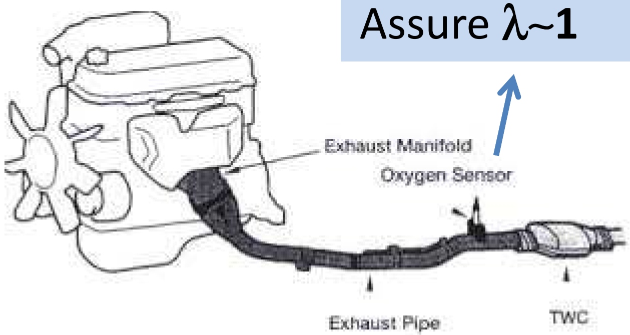

Exhaust gas aftertreatment

# Emissions

## Exhaust gas aftertreatment gasoline



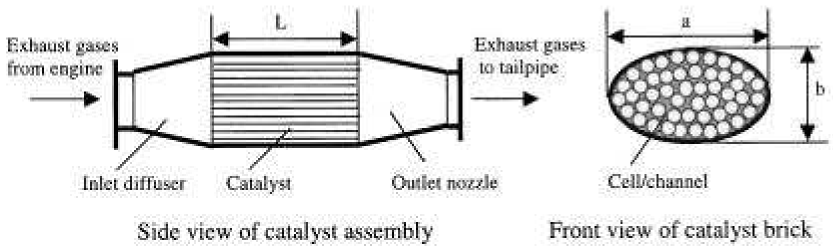

Assure $\lambda$~**1**

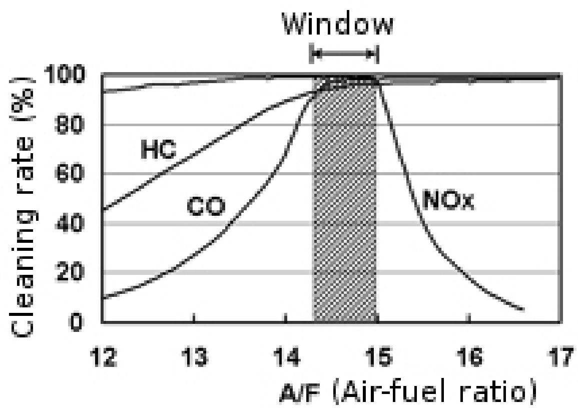



Gasoline engines (spark-ignition) → **TWC-Three Way catalytic converter**

# Emissions

## Exhaust gas aftertreatment



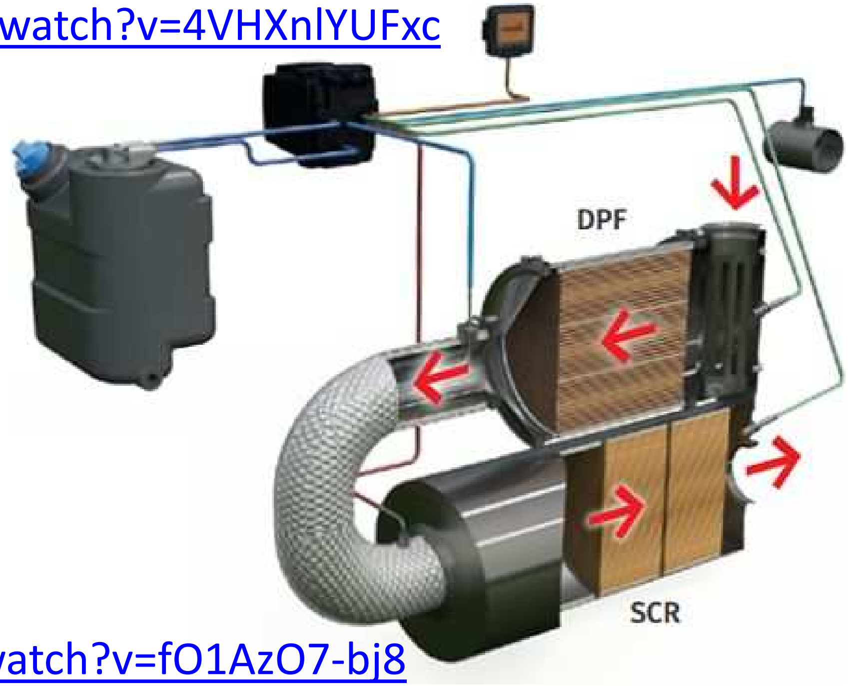

Cleaning rate or catalytic converter efficiency, e.g.,

$$\frac{NOx_{in} - NOx_{out}}{NOx_{in}} x100\%$$

# Emissions

**Exhaust gas aftertreatment Diesel**

https://www.youtube.com/watch?v=4VHXnlYUFxc




https://www.youtube.com/watch?v=fO1AzO7-bj8

Rudolf Diesel engines (compression-ignition) → Oxidation catalyst
Particle filter
Selective catalytic reduction

# Emissions

## Exhaust gas aftertreatment (with SCR)

$CO_2$
$H_2O$
$N_2$
CO
HC
NO
NO2
PM

→ **Exhaust gas aftertreatment** →

$CO_2$
$H_2O$
$N_2$
**NH3 slip**

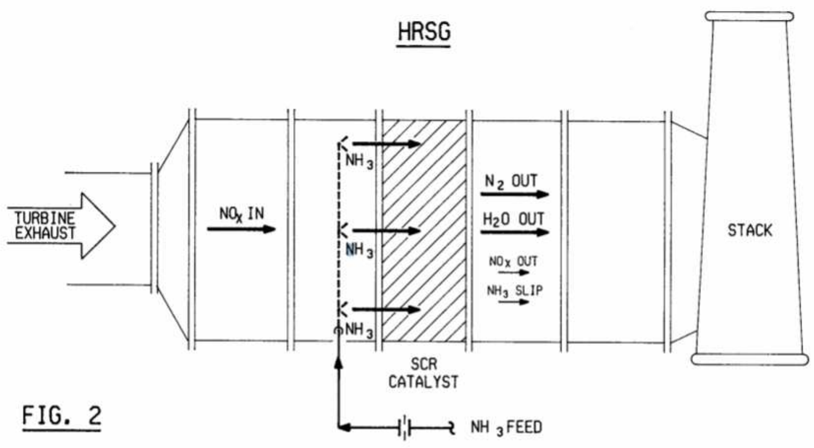


FIG. 2

$$(NH_2)_2CO + H_2O \Rightarrow 2NH_3 + CO_2$$

Urea solution (~ 5% fuel consumption)
Urea 32.5% wt (±0.7%), density of 1.09 g/cm$^3$

$$\mathbf{4NO+4NH_3+O_2 \rightarrow 4N_2+6H_2O}$$

# Emissions

## Exhaust gas aftertreatment (with SCR)

**Central Coal Sines >= 2011**

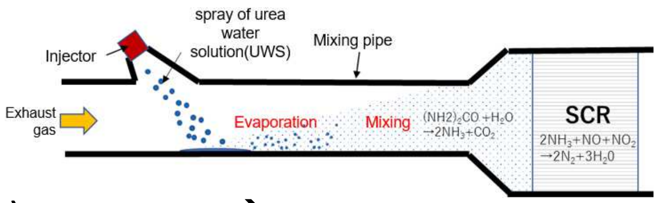
# Exercice

P#11 Consider the molar composition (kmol) of flue gas of a coal furnace with a coal consumption of 90 tonne/h. (power plant with installed power > 500 MW).

$CO_2$=0.052769348
$H_2O$=0.028669893
$N_2$=0.271015989
NO=8.20116x10^-5
$O_2$=0.015955756

SNCR 4NO+4NH3+O2 →4N2+6H2O

SCR

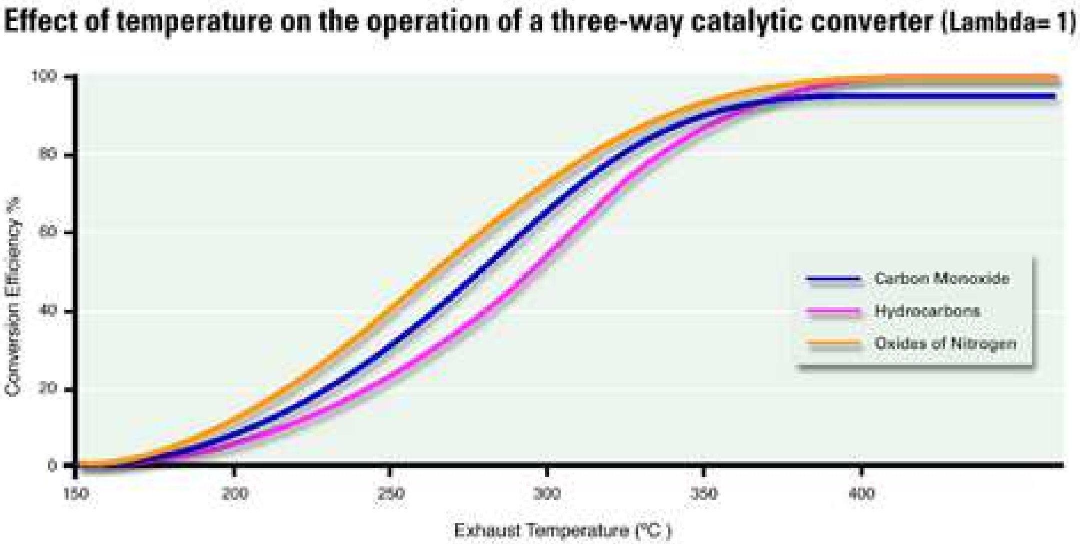



(NH2)2CO+H2O → 2NH3+CO2
4NO+4NH3+O2 →4N2+6H2O

a) Calculate the NO emissions and compare with the limit value imposed by legislation.
b) If you use SNCR (selective non catalytic reduction, 80% conversion efficiency), how much NH3 would you add, and what would be your new NO emissions? Compare with the limit.
c) If you use SCR (selective catalytic reduction, 80% conversion efficiency), how much urea would you add, and what would be your new NO emissions? Compare with the limit.
d) Discuss on weather to use SNCR or SCR.

# Emissions

P#12 A mixture of methane gas and air at 25ºC and 1 atm is burned in a water heater at 100% theoretical air. The mass flow rate of methane is 1.15 kg/h. The exhaust gas temperature was measured to be 500 º C and approximately 1 atm and is subjected to exhaust aftertreatment. The volumetric flow rate of cold water (at 22 º C) to the heater is 4 L/min.




(a) Determine the combustion efficiency.
(b) Calculate the temperature of the hot water if the heat exchanger were to have an efficiency of 1.0, i.e., perfect heat transfer.
(c) Consider the following concentrations of emissions at the combustion products: 5000 ppm NO. Estimate the NO exhaust gas emissions in g/h.

# Emissions

*Table: Air pollutant emission standards for coal-fired power plants in China, European Union and the United States (mg/m$^3$)*

| | | China | EU | US |
|---|---|---|---|---|
| $SO_2$ | New | 100 | 200 | 160 |
| | Existing | 200/400[1] | 400 | 160/640[3] |
| NOx | New | 100 | 500/200[2] | 117 |
| | Existing | 100/200[4] | 500/200[2] | 117/160/640[5] |
| PM | New & existing | 30 | 50 | 22.5 |
| Mercury | New | 0.03 | - | 0.001 |
| | Existing | 0.03 | - | 0.002 |

*1) 400 for four provinces with high-sulphur coal*
*2) 500 until end 2015; 200 as from 2016*
*3) 160 for plants built 1997-2005; 640 for plants built 1978-1996*
*4) 100 for plants built 2004-2011; 200 for plants built before 2004*
*5) 117 for plants built after 2005; 160 for plants built 1997-2005; 640 for plants built 1978-1996*
*Source: WRI (2012)*

**Obrigado**

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