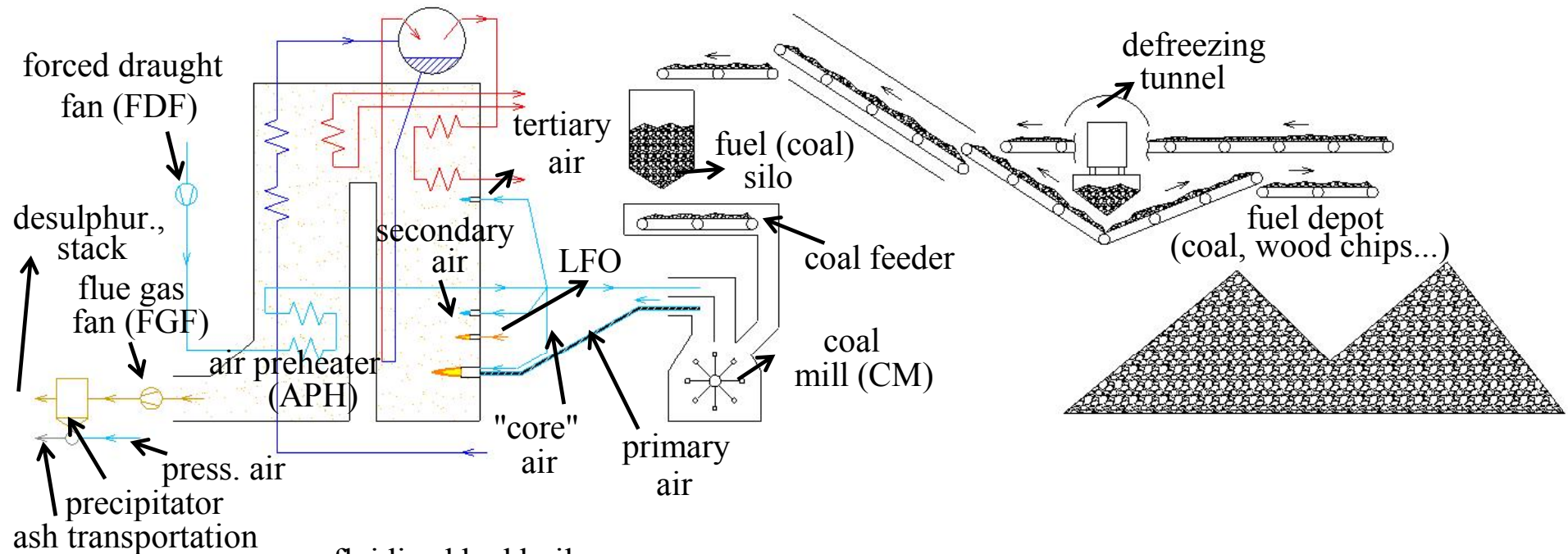# Power Plants
A1M15ENY

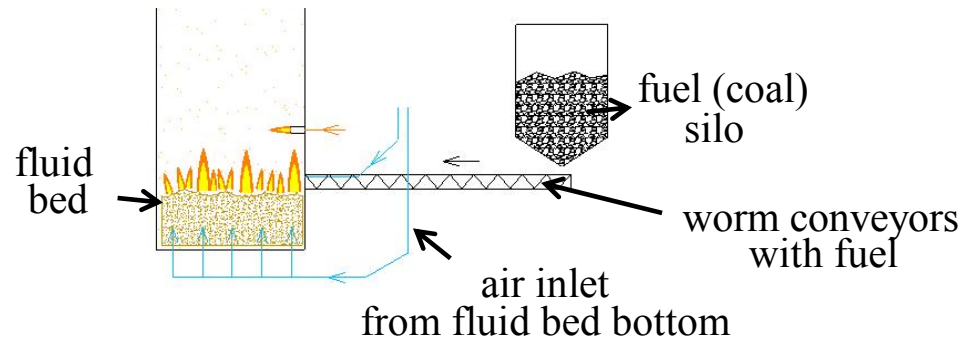# **Lecture No. 9**

Jan Špetlík

spetlij@fel.cvut.cz   - subject in e-mail „ENY"

Department of Power Engineering, Faculty of Eelectrical Engineering CTU, Technická 2, 166 27 Praha 6

Fuel and Flue Gas

forced draught fan (FDF)

desulphur., stack

flue gas fan (FGF)

air preheater (APH)

press. air

precipitator ash transportation

tertiary air

secondary air

LFO

"core" air

primary air

fuel (coal) silo

coal feeder

coal mill (CM)

defreezing tunnel

fuel depot (coal, wood chips...)

fluidized bed boilers:

fluid bed

fuel (coal) silo

air inlet from fluid bed bottom

worm conveyors with fuel

Combustion Principles

Flammable components are determined by element composition of *combustible:*

$$C^{daf} + H^{daf} + N^{daf} + S^{daf} + O^{daf} = 1 \text{ [kg/kg]}$$

It must be taken into account water and ash content in *raw state* :

$$C^{r} + H^{r} + N^{r} + S^{r} + O^{r} + W^{r} + A^{r} = 1 \text{ [kg/kg]}$$

sulfur content   water content   ash content

Basic formulas:

$$C^{r} = C^{daf}.\left(1 - W^{r} - A^{r}\right) \quad H^{r} = H^{daf}.\left(1 - W^{r} - A^{r}\right) \quad N^{r} = N^{daf}.\left(1 - W^{r} - A^{r}\right)$$

$$S^{r} = S^{daf}.\left(1 - W^{r} - A^{r}\right) \quad O^{r} = O^{daf}.\left(1 - W^{r} - A^{r}\right)$$

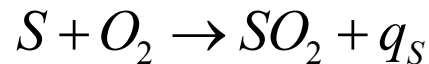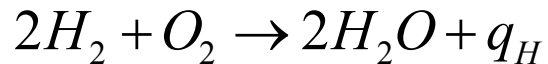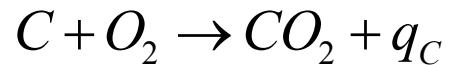Ash content in raw state:

$$A^{r} = A^{d}.\left(1 - W^{r}\right)$$

Index:

r raw

daf dry ash free

d dry

Combustion Principles

In the case of *ideal combustion* is oxidation performed (exotermic reaction) as follows:

oxygen consumption

heat	MJ/mol	MJ/kg	mol/mol	m3/mol	m3/kg
q_C	405,9	33,8	1	22,4	1,87
q_H	572,4	141,9	0,5	11,2	5,55
q_S	29,7	9,25	1	22,4	0,698

$$C + O_2 \rightarrow CO_2 + q_C$$
$$2H_2 + O_2 \rightarrow 2H_2O + q_H$$
$$S + O_2 \rightarrow SO_2 + q_S$$

Taking into consideration oxygen share 21% vol. in the air, total consumption of ideal dry volume air needed for combustion is:

$$V_{adt} = \frac{22,4}{0,21} \cdot \left(\frac{C^r}{12} + \frac{H^r}{4} + \frac{S^r}{32} - \frac{O^r}{32} \right) \ [\text{m}^3/\text{kg fuel}]$$

Under these assumptions it is produced a volume of dry flue gas:

molar volumes

$$V_{fgdt} = \frac{22,3}{12} \overset{CO_2}{\nearrow} \cdot C^r + \frac{21,9}{32} \overset{SO_2}{\nearrow} \cdot S^r + \frac{22,4}{28} \overset{N_2}{\nearrow} \cdot N^r + 0,79 \cdot V_{adt} \ [\text{m}^3/\text{kg fuel}]$$

Index:

a air
fg flue gas
d dry
t theoretical

Combustion Principles
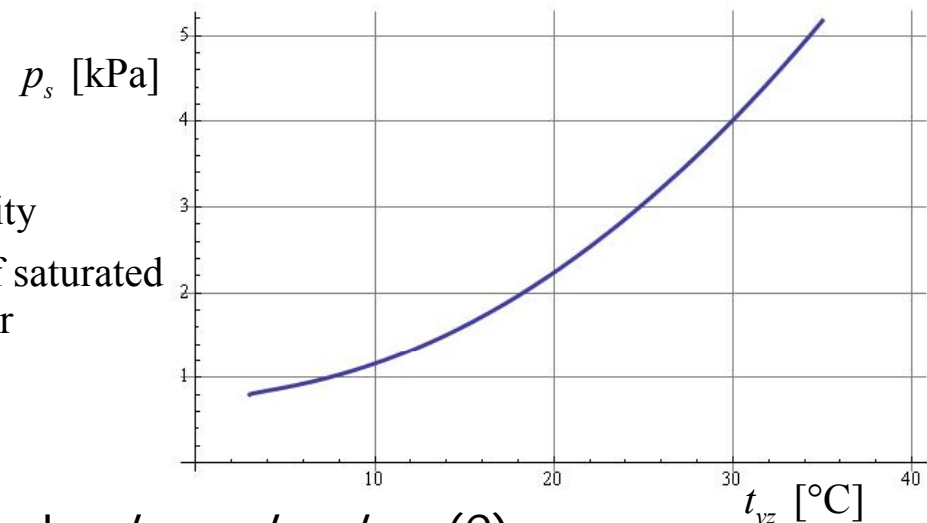
Real air consumption is dependent on:

a) *Air humidity*:

Air humidity factor:

$$\nu = 1 + \frac{\varphi.p_s}{p_c - \varphi.p_s}$$

φ relative air humidity

p_s partial pressure of saturated steam for given air temperature

p_c total air pressure ≈ 1 bar.

p_s [kPa]

t_{vz} [°C]

b) *Incompleteness of combustion* (CO) and *unburned carbon* (C):

Excess air factor for dry air: λ

Real air consumption is then:

$$V_a = \nu.\lambda.V_{adt} \;\; [\text{m}^3/\text{kg fuel}]$$

Fuel moisture must be taken into account for flue gas (water, hydrate water) and air humidity of draft air:

$$V_{H_2O} = 11,11.H^r + 1,24.W^r + (\nu - 1).\lambda.V_{adt} \;\; [\text{m}^3/\text{kg fuel}]$$

Total volume of flue gas:

$$V_{fg} = V_{fgdt} + (\lambda - 1).V_{adt} + V_{H_2O} \;\; [\text{m}^3/\text{kg fuel}]$$

Attention! Oxygen consumption must be taken into account in case of fluid boilers with direct de-sulphurization

$$2.\text{CaSO}_3 + \text{O}_2 \rightarrow 2.\text{CaSO}_4$$

Fuels

Gross calorific value Q_s - the water of combustion is entirely condensed and that the heat contained in the water vapor is recovered (Q_s^{daf})

Net calorific value Q_i - the products of combustion contains the water vapor and that the heat in the water vapor is not recovered

Bituminous coal:

fuel	Q_i^r [MJ.kg^{-1}]	A^d [%]	S^r [%]	W^r [%]
Černé uhlí Důl Lazy	30,06	6,5	0,6	4,0
Ořech 1 Dukla	31,76	5,0	0,4	2,5
OP1 Kladno	23,07	13,5	0,6	14,0

biomass pellets

Biomass:

fuel	Q_i^r [MJ.kg^{-1}]	A^d [%]	S^r [%]	W^r [%]
wood chips dry	9,5	3,0	-	40,0
wood chips wet	7	3,0	-	60,0
triticale pellets	15	5,0	0,2	6,3
compost, sludge from sewage disposal plant	9,5	44,0	0,42	30,0

wood chips

Fuels

Lignite:

fuel	Q_i^r [MJ.kg^{-1}]	A^d [%]	S^r [%]	W^r [%]
HP1AD Bílina	16,4	15,0	0,84	29,7
PS3AD Bílina	15,6	18,6	0,85	29,5
PS3 SD Chomutov	12,5	35,3	0,82	25,5
HP1AD Most	15,9	24,0	1,1	26,0
HP2AD Most	12,9	35,0	1,0	25,5
HP3AD Most	11,0	38,5	1,0	28,3
Ořech 01 Lignit Mikulčice	9,9	24,0	1,1	49,0
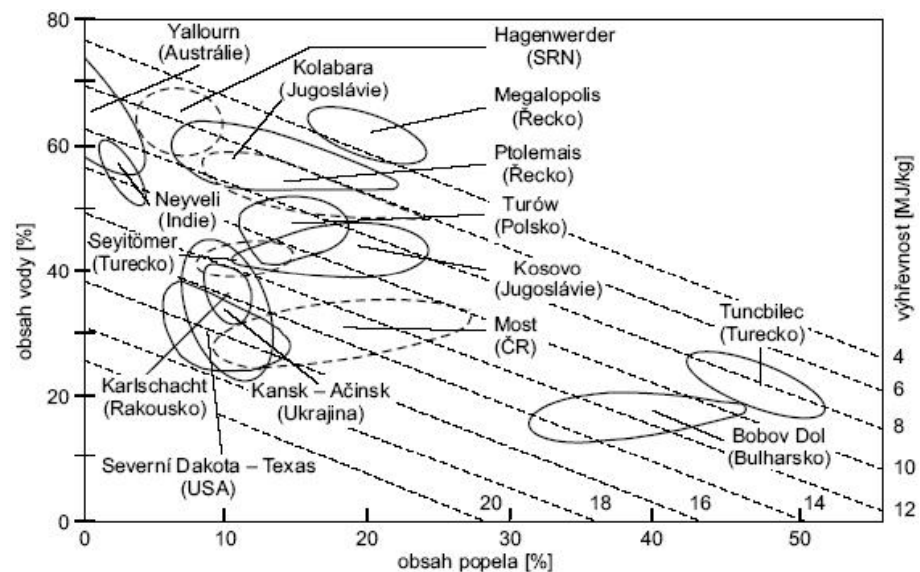
Fuels

Fine fuels:

fuel	Q_i^r [MJ.kg^{-1}]	A^d [%]	S^r [%]	W^r [%]
LFO	42	0,04	0,1-0,5	1,5
mazut	40,5	0,03	1,5	0,6
LPG	50 (39 MJ/m^3)	-	max. 200 mg/kg	-
Natural gas	55 (33-36 MJ/m^3)	-	max. 0,2 mg/m^3	-

Rough values of factor λ :

boiler (furnace)	fuel	λ [-]
pulverized	anthracite	1,2-1,25
	bituminous coal	1,2
	lignite	1,2-1,25
grate	bituminous coal	1,4-1,5
	lignite	1,4-1,5
fluid CFB	bituminous coal	1,2
	lignite	1,2
gas / oil	n. gas / LFO	1,05-1,15

Factor λ computation from excess oxygen in flue gas:

$$\lambda = \frac{0,21}{0,21 - \omega_{O_2}}$$

where

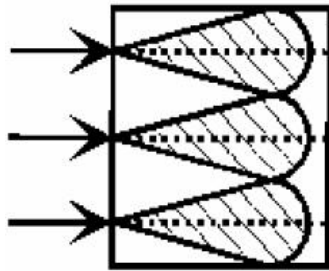$$\omega_{O_2} = \frac{V_{O_2}}{V_{sn}}$$

with rising % volume of oxygen in flue gas, % volume of CO_2 is decreasing!

$$\omega_{CO_2} = \omega_{CO_2 \, max} \frac{0,21 - \omega_{O_2}}{0,21} = \frac{\omega_{CO_2 \, max}}{\lambda}$$
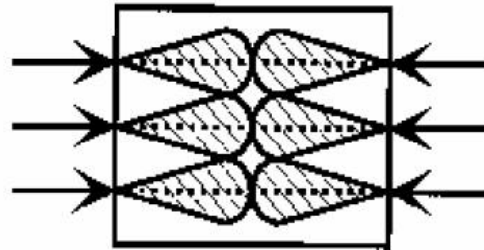
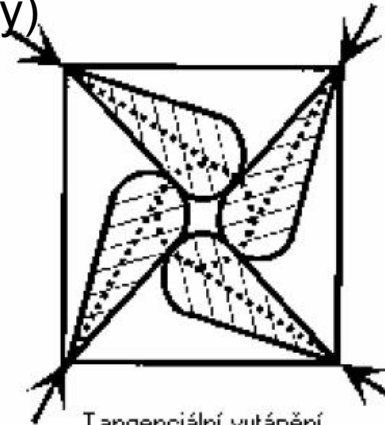# Boilers - Combustion

Combustion chamber:

Fuel-air mixture is flowing through a coal burner into a combustion chamber and then is burnt with additive air (secondary, tertiary)
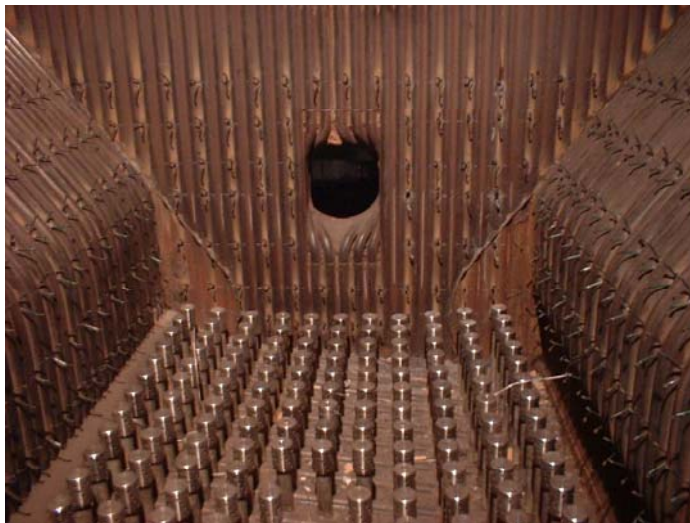

Vytápění z jedné čelní stěny

Vytápění z protilehlých stěn

Tangenciální vytápění (z rohů stěn topeniště)

fluid boiler combustion chamber bottom the air is injected through lower nozzles

pulverized boiler combustion chamber bottom with LFO burner

Boilers - Combustion

- combustion temperature (pulverized ~1400°C, fluid ~750-900°C, gas turbines ~1200-1400°C)
- fuel: coal + stabilization (LFO, gas)
- Flue gas contains **fly ash**, other solid product are present in **bottom ash** (pulverized cca 10%, grate 60-70%)
- whole combustion chamber remains undepressurized (cca -10 – -100 Pa), according to reference value are opening/closing regulační věnce KV

Gross boiler efficiency:

$$\eta = 1 - \zeta_{MN} - \zeta_{CN} - \zeta_f - \zeta_k - \zeta_{sv}$$

ζ_{MN} — heat losses due to incomplete burning from mechanical causes $\approx$ up to 1% pulverized, 5% grate

ζ_{CN} — heat losses due to incomplete burning from chemical causes, 0,3-1,5% pulverized, grate, 3-7% wood combustion

ζ_f — loss due to sensible heat of solid products = heat loss caused by getting cold of f./b. ash, $\approx$ 0,1% to 1%

net specific heat of unburned carbon

$$\zeta_{MN} = \frac{C_i}{1 - C_i} \cdot \frac{A^r}{Q_n^r} \cdot Q_C^r$$

relative carbon content in solid products

Boilers - Combustion

ζ_k stack loss (flue gas heat) - for big boilers THE MOST IMPORTANT
$\approx$ 7% to 15%!

Siegert's (Gumzo's) formula:

$$\zeta_k = \left(\frac{A_1}{\omega_{CO_2}} + B \right) \cdot \left(t_{fg} - t_{amb} \right)$$

ambient air temperature

flue gas temperature

fuel	A₁	B
lignite	1,17	0,0024
hard coal	0,6281	0,0051
fuel oil	0,497	0,0063
natural gas	0,3263	0,0106

ζ_{sv} heat loss to surroundings
$\approx$ 0,1% - 0,8%

Total gross boiler efficiency (without auxiliary):

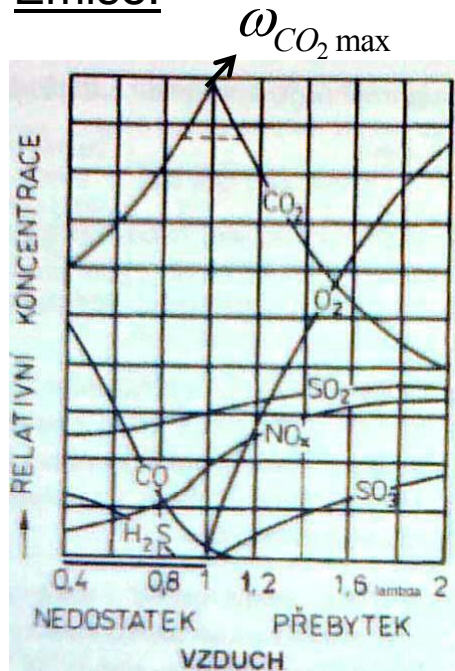| boiler	fuel	η	t_{fg} [°C]
pulverized	Natural gas, mazut	0,94	110 – 125
	Hard coal	0,89 – 0,93	< 135
	Lignite $A^r < 0,13$	0,88 – 0,91	< 150
	Lignite $A^r > 0,13$	0,86 – 0,89	< 160
fluidized	CFB	0,93	130 – 140

Optimal λ selection

Δq_z :
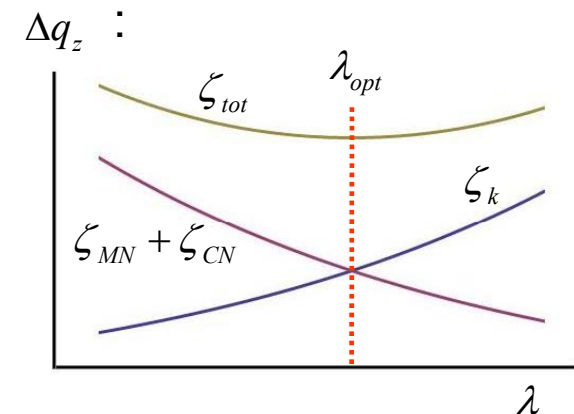
λ_{opt} is dependent on boiler actual output

Boilers - Combustion

Emise:

$\omega_{CO_2 \, max}$

With growing λ is also growing ω_{NO_x}, ω_{SO_2} and ω_{O_2} in flue gas, unlike in the case excess of air $(\lambda > 1)$, ω_{CO_2} is decreasing. With decreasing λ and lack of air $(\lambda < 1)$ ω_{CO} is decreasing.

Emisson limits in the Czech Republic:
Emisní limits are respecting environmental requirements. As an example, newly built 300 MWt source must be in compliance with following:

solid particles	SO$_2$	NO$_x$	CO
30 mg.m^{-3}	200 mg.m^{-3}	200 mg.m^{-3}	250 mg.m^{-3}

limits have to be re-calculated for DRY flue gas with reference volume concentration $\omega_{O_2 ref} = 6\%$. Re-computing to the reference values is following:

$$c_{Xref} = c_{Xmeasured} \frac{0,21 - \omega_{O_2 ref}}{0,21 - \omega_{O_2 measured}}$$

Above mentioned stuffs must be measured *continuously*. Other dangerous substances several times per year:
HCl, PAH, PCB, PCCD, Hg, Cd, As+Pb
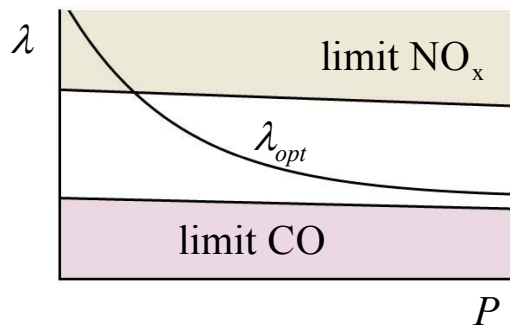
environmental restrictions are influencing selection of air excess

Boilers – Fuel Processing

Grate technology:
With exception of fuel drying process, no special processing required

Fluid technology:
No special processing if the fuel fraction is ok, otherwise the fuel is crushed in crushers. Then the fuel is transported with worm conveyors directly to the boiler.

Pulverized technologies:
Fuel is dried and milled in mills, **pulverized coal** must be at sufficient moisture and fineness level.
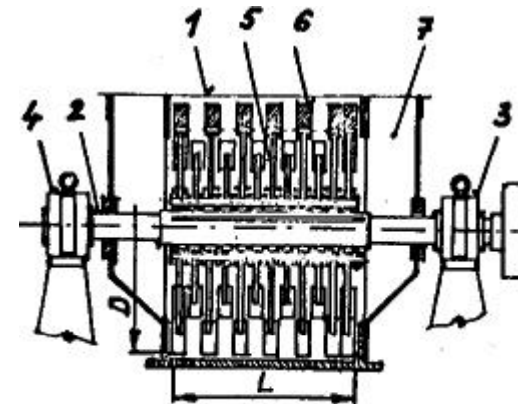
Types of mills:
- Hammer
- Fan
- Ring
- Tubular (ball)
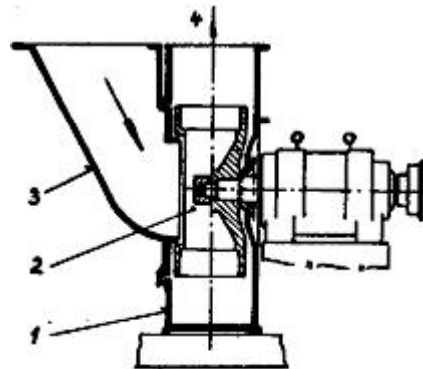
fan mill
1. fan housing, 2. blade wheel, 3. drying and carrying medium and fuel inlet, 4. outlet to the sorter

hammer mill
1. steel housing, 2. shaft, 3. fixed bearing, 4. flexible bearing, 5. branches, 6. hammers, 7. axial glands

Flue Gas Purification

In order to be in compliance with emission limits, flue gas must be purified. Above all from the following stuff:

1. Solid particles (fly ashes)
In precipitators

2. SO_2
Directly in the boiler (CFB) or in de-sulphurization plants

3. NO_x
Not required (good combustion technology) or in DeNOx units (ammonia dosing)

4. CO_2
Due to emission allowances policy, potential removing CO_2 from flue gas is rapidly decreasing total efficiency

Precipitators

Precipitator types:
- Dry mechanical (gravity, inertia, whirling…)
- Wet mechanical (shower, stream, foam…)
- Electrostatic
- Bag filter

Collection efficiency:

Precipitator's ability to separate solid particles from flue gas

$$O_c = \frac{m_p - m_v}{m_p} = \frac{c_p - c_v}{c_p}$$

m_p, c_p mass (or concentration) of solid particles inlet

m_v, c_v mass (or concentration) of solid particles outlet

Typical collection efficiency for large power plants $O_c \geq 0.99$
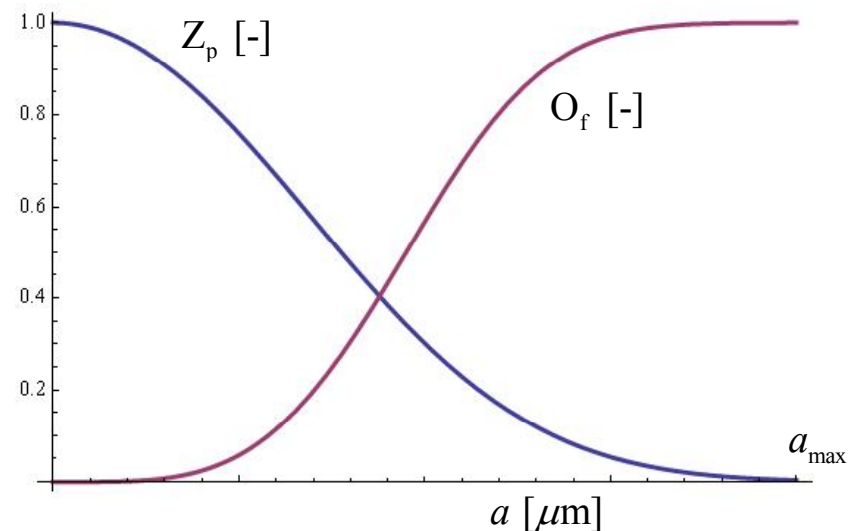
Curve of solid residues content in flue gas:

Expresses how many of mass percents with particle size greater than *a* is present in residue sample:

$$Z_p = Z_p(a)$$

Fractional collection efficiency:

Expresses how many of mass percents with particle size greater than *a* is collected
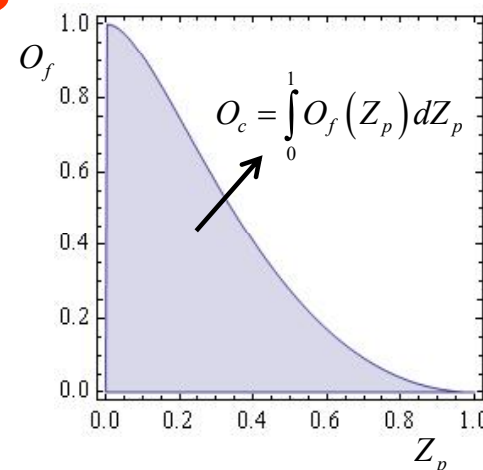
$$O_f = O_f(a)$$

Precipitators

If we express fractional collection efficiency as a function of Z_p: $O_f = O_f(Z_p)$

Final collection efficiency will be:
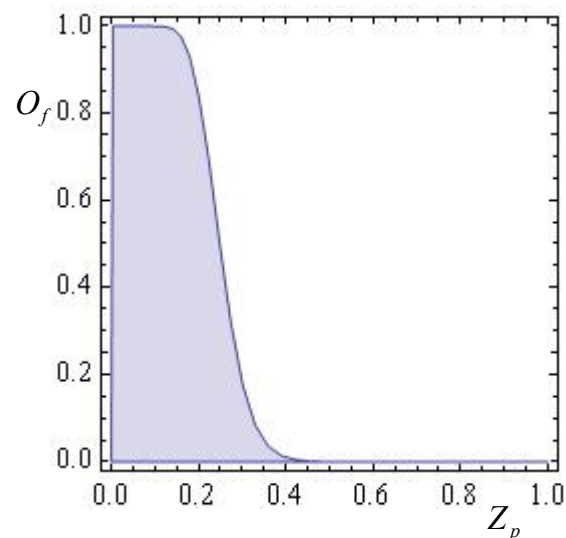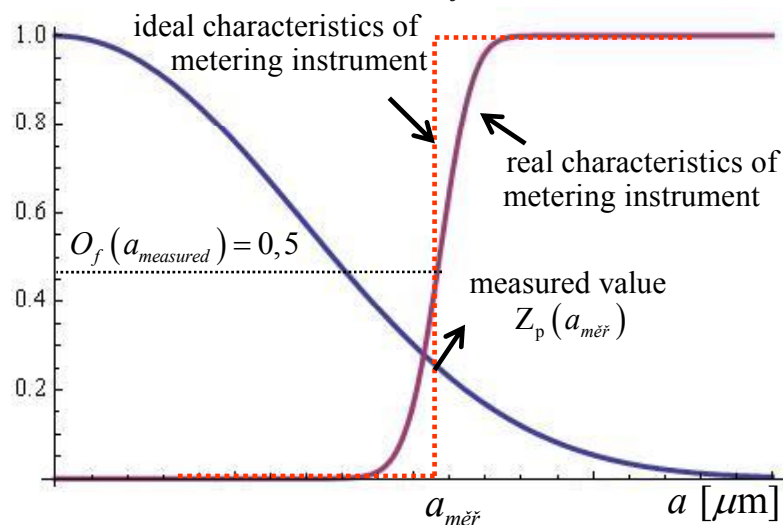
$$O_c = \int_0^1 O_f(Z_p) dZ_p$$

$$O_c = \int_0^1 O_f(Z_p) dZ_p$$

Solid particles fraction measurement:
Fraction PM10 and PM2,5 is measured.
PM10 measurement is performed in precipitating device with $O_f(10\ \mu\text{m}) = 0,5$
Real characteristics $O_f(a)$ is very steep around this point.

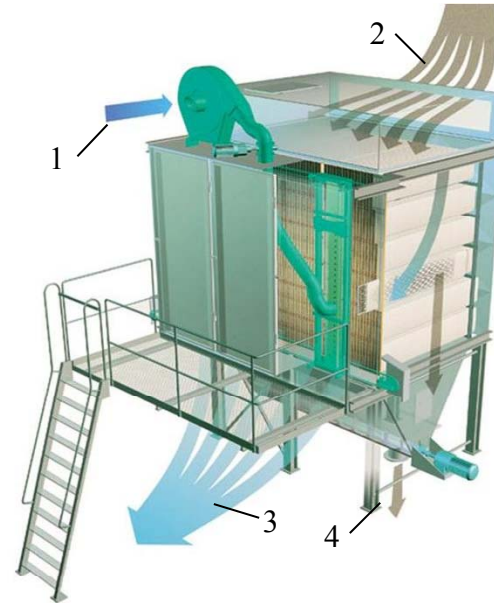

ideal characteristics of metering instrument

real characteristics of metering instrument

$O_f(a_{measured}) = 0,5$

measured value $Z_p(a_{měř})$

$a_{měř}$

$a\ [\mu\text{m}]$

Na stejných principech probíhá měření uhelného prášku, vápence, …

Precipitators
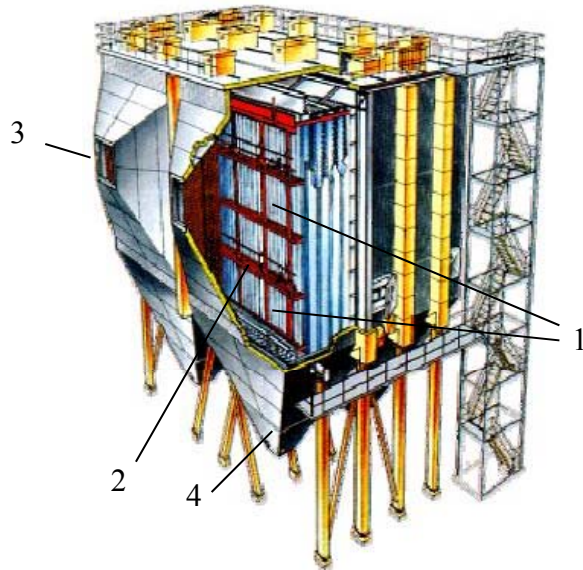
electorstatic precipitator
1. collecting electrodes (grounded), 2. discharging electrodes, 3. flue gas inlet, 4. ash silo

bag filter
1. air for bag shaking, 2. inlet flue gas, 3. purified flue gas, 4. fly ash

De-suplhurization

Desulphurization methods according to way of SO_2 capturing:

Regenerative – active matter is synthesized with sulfur dioxide, in other place is decomposed and then it is repeatedly utilized in the original reaction, decomposed sulfur dioxide enters to further process

Non-**regenerative** – active matter is reacting with SO_2 resulting to exploitable and/or non-exploitable product, but never returns back to the process

wet - SO_2 is captured in the liquid or water suspension with active matter
semi dry - active matter in the form water suspension is injected to hot flue gas flow, the liquid is evaporated and the product is captured in solid form
dry - SO_2 is reacting with active matter in solid form

Power plants in the Czech Republic are using predominantly *wet limestone scrubbing*. Flue gas is flown though absorber with multi-stage shower, which sprinkles limestone suspension, i.e. milled limestone in water. The product of reaction with sulfur dioxide is calcium sulfite ($CaSO_3$), which after oxidation turns into calcium sulfate dihydrate ($CaSO_4.2H_2O$). Resulting product *power plant gypsum* – can be utilized in technologies, civil segments, cement.
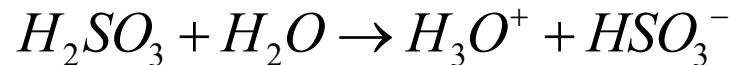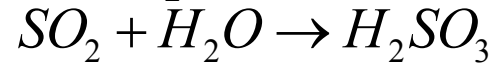
Wet Limestone Scrubbing
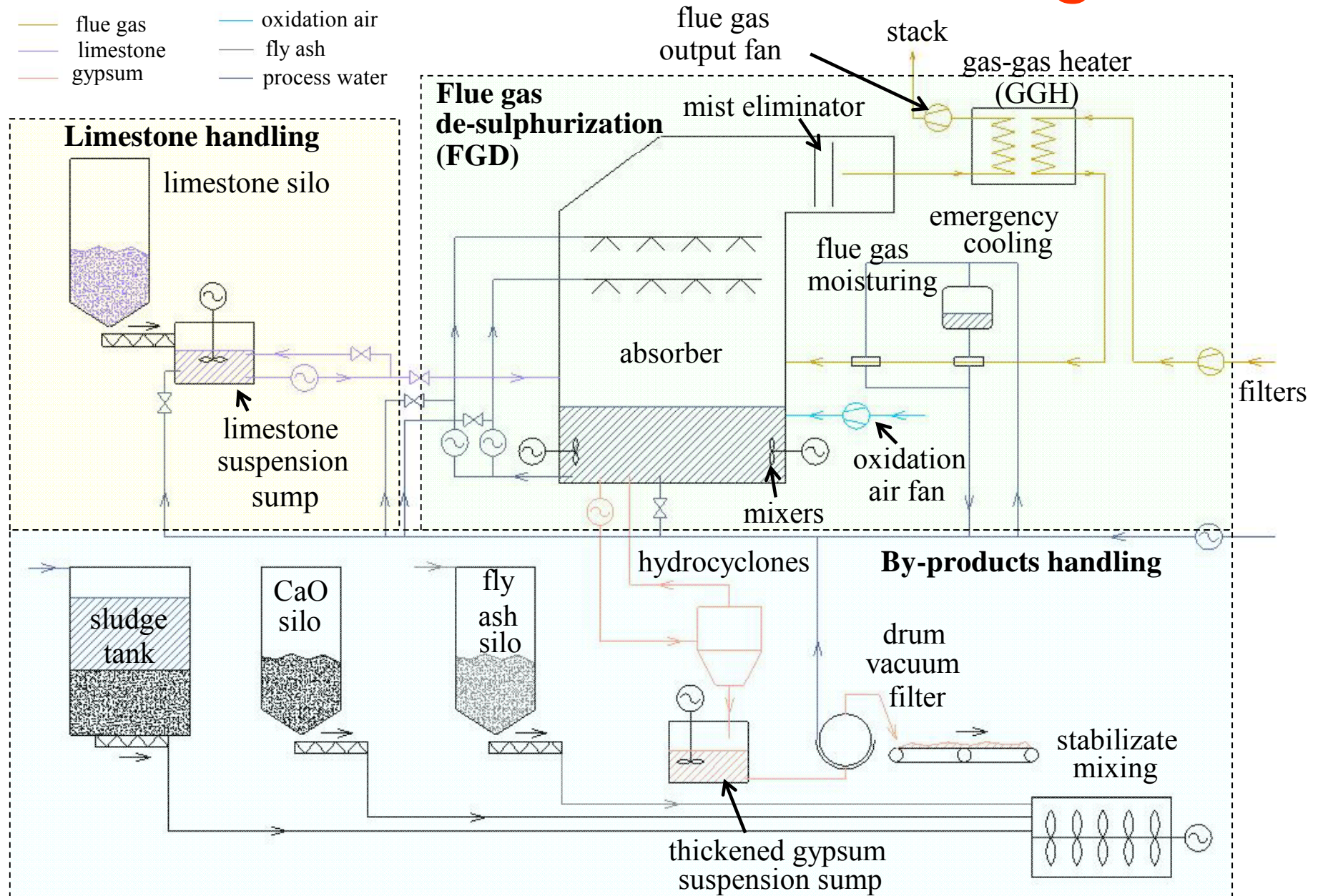
Wet Limestone Scrubbing

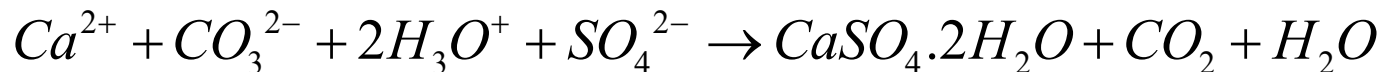**Reactions in Flue Gas Desulphurization (FGD) plant:**

Absorbent suspension absorbs SO_2 as follows:

$$SO_2 + H_2O \rightarrow H_2SO_3$$

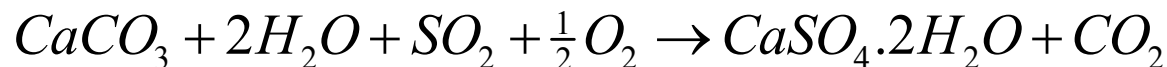$$H_2SO_3 + H_2O \rightarrow H_3O^+ + HSO_3^-$$

A part of HSO_3^- from SO_2 absorption is oxidizing in absorber showers with oxygen in flue gas, the rest of HSO_3^- is oxidizing completely in tank bottom with oxygen present in oxidation air. The reaction is following:

$$HSO_3^- + \tfrac{1}{2}O_2 \rightarrow HSO_4^-$$

$$HSO_4^- + H_2O \rightarrow H_3O^+ + SO_4^{2-}$$
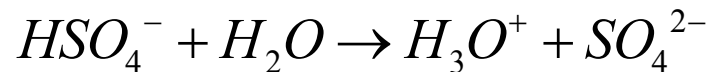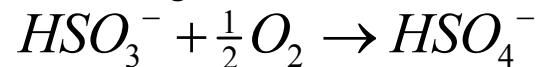
Active suspension is injected from limestone handling system into absorber. It neutralizes the hydrogen ion. Under these conditions the pH value of sorbent remains constant:

$$Ca^{2+} + CO_3^{2-} + 2H_3O^+ + SO_4^{2-} \rightarrow CaSO_4.2H_2O + CO_2 + H_2O$$

Total:

$$CaCO_3 + 2H_2O + SO_2 + \tfrac{1}{2}O_2 \rightarrow CaSO_4.2H_2O + CO_2$$

Limestone consumption is dependent on fraction fineness – i.e. on *reactivity r* and limestone content (normally 90 – 98% of $CaCO_3$, other substances mostly $MgCO_3$)
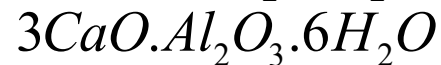
$$\dot{m}_{Limestone} = \frac{\dot{m}_{CaCO_3}}{r.c_{CaCO_3}}$$

With respect to a partial oxidation by flue gas oxygen, the excess of oxygen in dry flue gas at outlet is decreased by 1-2%

Wet Limestone Scrubbing

Reactions in by-products handling:

Within the reaction of fly ash with calcium oxide (CaO), there are produced temporary reactions products such as:

$$3CaO.2SO_2.3H_2O$$
$$3CaO.Al_2O_3.6H_2O$$

The products are very same as in the case of Portland cement, however, the reaction speed is significantly slower. These temporary products can react with other matters of dehydrated gypsum to the terminal products such as etryngite

$$3CaO.Al_2O_3.3CaSO_4.2H_2O$$
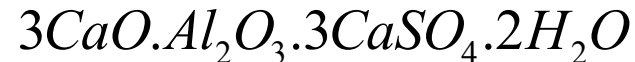
or other compounds with sulfites or sulfates.

Resulting low soluble compounds (*inert compounds*) are exploitable in civil engineering or In the case of storage are classified as the lowest hazardous waste (*inert waste*).

Flue Gas De-nitrification

Flue gas denitrification is supposed to be more technically difficult than desulphurization

Flue gas is containing various nitrogen oxides:

- cca 95 % of nitric oxide NO
- cca 5 % of nitrogen dioxide NO_2
- nitrous oxide N_2O is present if combustion temperature is under 900 °C
- a small content of organic compounds of nitrogen
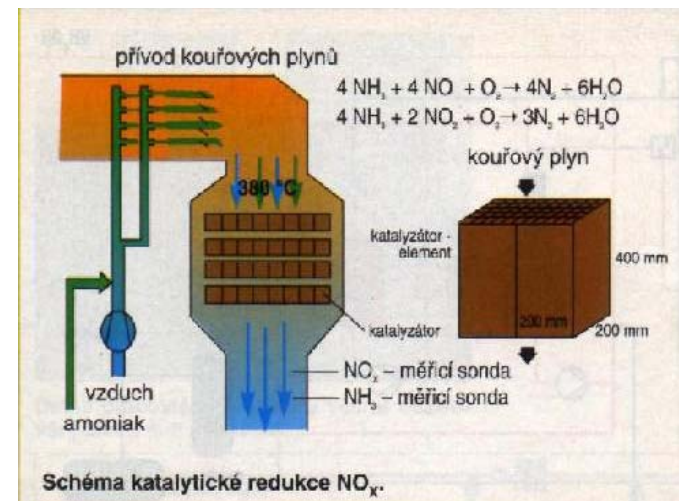
NO_x content reducing methods:

Primary

A content of nitrogen oxides can be reduced by way of combustion and boiler construction (possibility reduction of Nox by 40-60 %)

Secondary

Selective catalytic reduction

Performed in special reactor, vanadium, molybdenum or wolfram oxides serve as a catalyst. Ammonium is injected into flue gas and the mixture enters to catalysts part where nitrogen oxides are decayed to elementary oxygen and nitrogen. This method is more expensive, however NOx content can be reduced by 80-90 %

přívod kouřových plynů

$4 NH_3 + 4 NO + O_2 \rightarrow 4N_2 + 6H_2O$
$4 NH_3 + 2 NO_2 + O_2 \rightarrow 3N_2 + 6H_2O$

kouřový plyn

380 °C

katalyzátor - element

400 mm

katalyzátor

200 mm   200 mm

NO_x – měřicí sonda
NH_3 – měřicí sonda

vzduch
amoniak

Schéma katalytické redukce NO_x.

Carbon Capture & Storage Technology

CCS technologies:

post combustion capture
combustion of fuel with air followed by separation of CO_2 from flue gas

oxy-fuel technology
combustion of fuel with pure oxygen followed by separation of CO_2 from flue gas
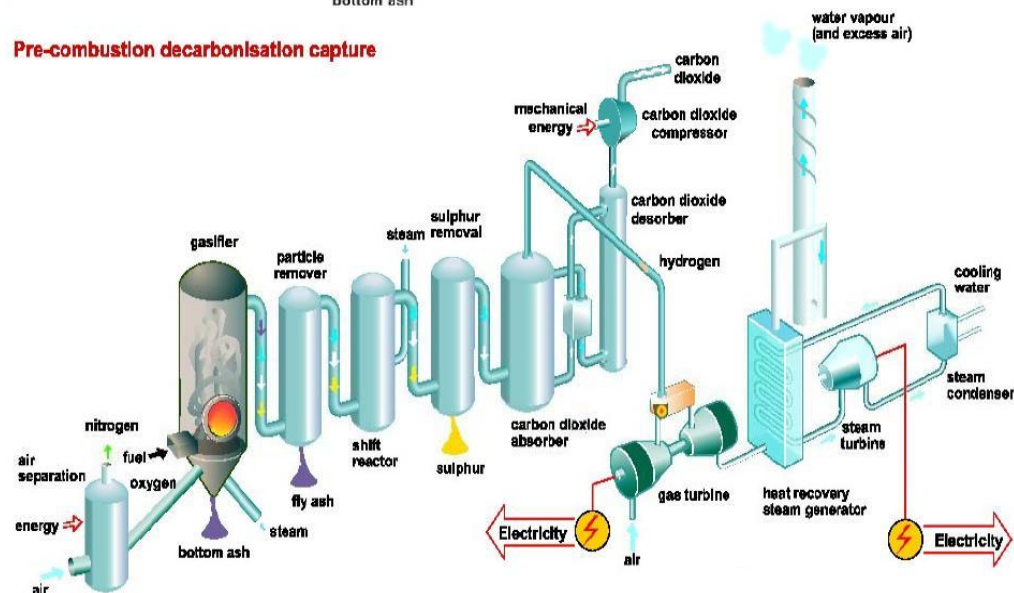
pre combustion capture
fuel gasification before combustion, CO (in the gas) to CO_2 conversion, CO_2 and hydrogen separation followed by pure hydrogen combustion (IGCC – Integrated Gasification Combined Cycle).

O₂/CO₂ recycle (oxyfuel) combustion capture
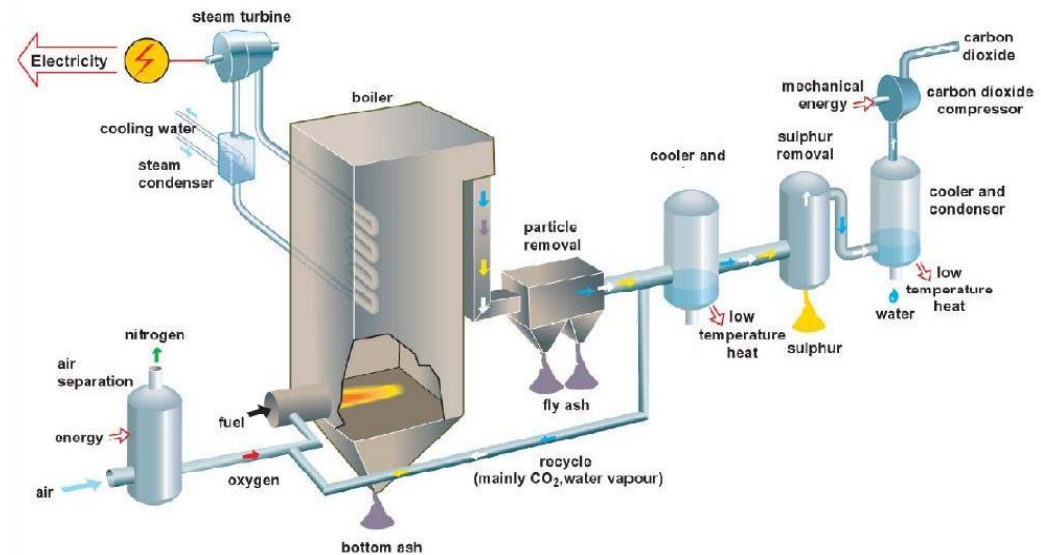
Pre-combustion decarbonisation capture

Carbon Capture & Storage Technology

Efficiency

- Significant auxiliary rise, i.e. reduction of net efficiency by 6-14% and growth of fuel consumption by 20-40%
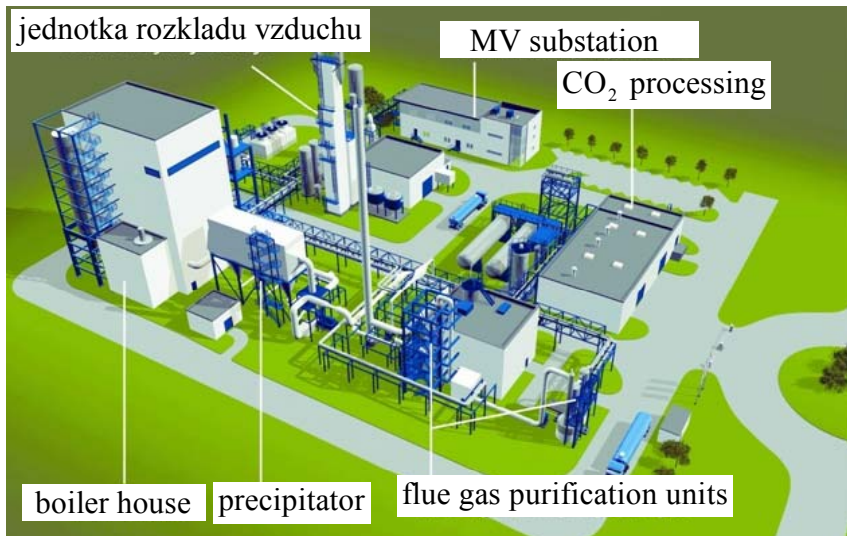
Carbon balance

- CO_2 emissions caused by storage and transportation in total balance have to be considered!

Potential storages' capacity and exploitation

- potential of the storages (exhausted deposits) is expected to be 70x CO_2 annual production
- former deposits won't be exploitable for possible gas extraction renewal in the future after CO_2 injection

Safety risks

- CO_2 can leak around geological fractures
- compressed CO_2 can cause micro-earthquakes with upside layers disruption risk
- CO_2 volume concentration about 8% is mortally dangerous for human in 30-60 minutes

jednotka rozkladu vzduchu
MV substation
CO_2 processing
boiler house
precipitator
flue gas purification units

Pilot project: 30 MWt power plant Schwarze Pumpe (technology: CCS - oxy-fuel)

Tagebau
CO_2
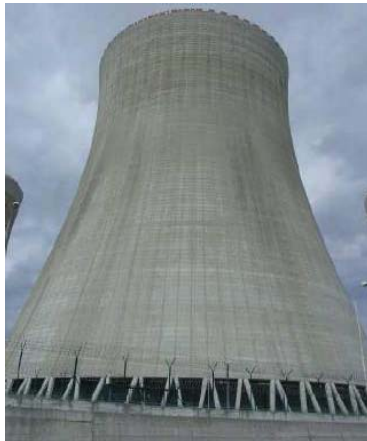CO_2
CO_2
CO_2
Öl/Gas
saline Aquifere
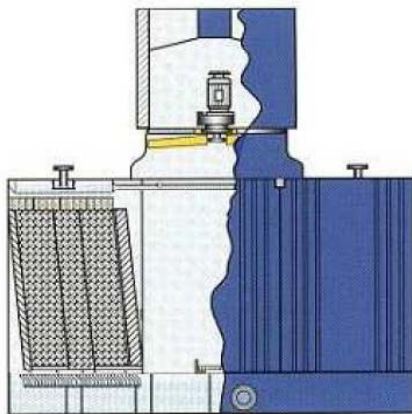Öl-/Gasfeld

Storage of CO_2 to underground deposits

Cooling Circuit

Cooling towers
- with natural draft
- forced draft (fan)

cooling tower
with natural draft

fan cooling tower

cooling tower

warm circulating water

cold water

feeder - natural flow cooling

warm water of natural flow cooling

cold water for the next units

Cooling tower balance

$T_{out} \approx T_T$ $\dot{m}_{odp}$ $\dot{m}_{un}$

$\dot{m}_T$

$\dot{m}'_S$ $\dot{m}_S$

T_{ok}

$\dot{m}_{vz}$ $\dot{m}_d$

$\dot{m}_{un}$ blow-out losses
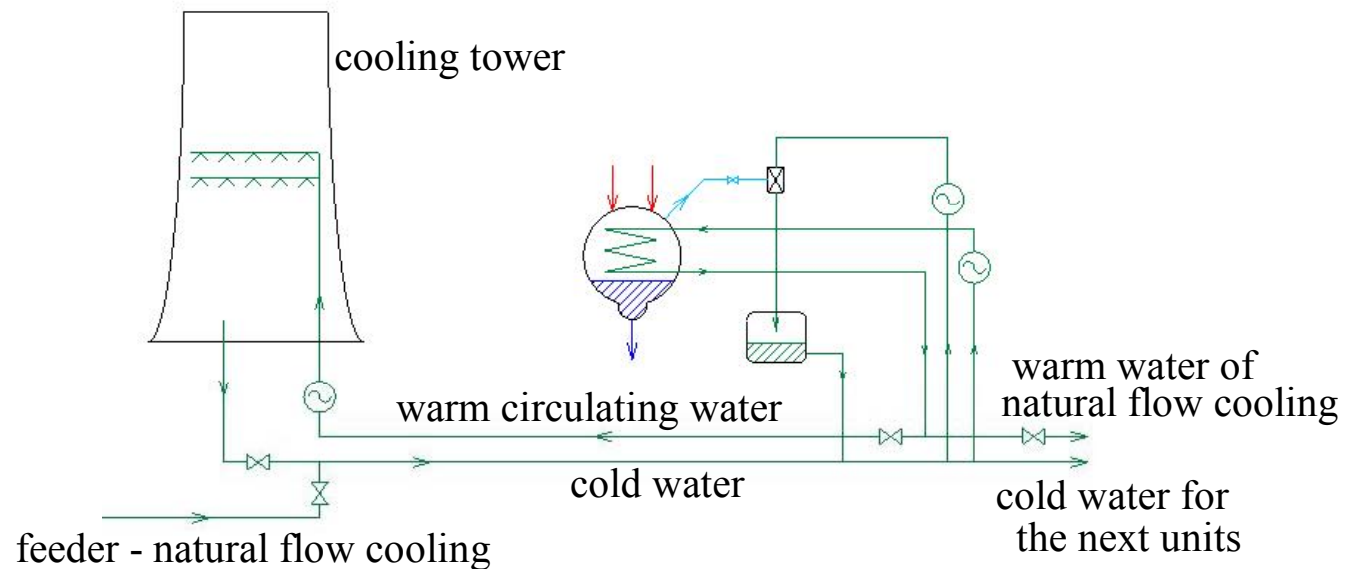
$\dot{m}_{odp}$ evaporation losses
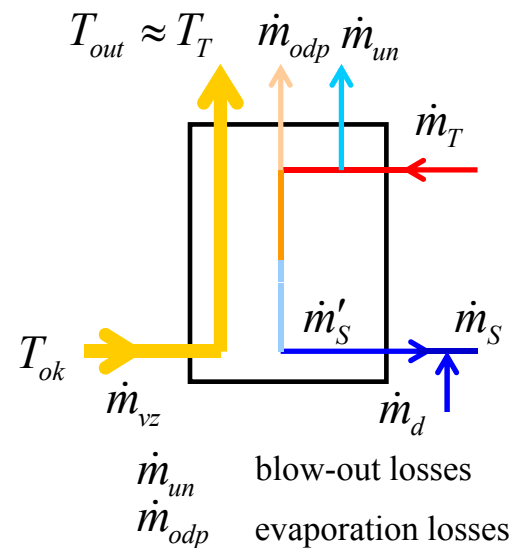
Mass flows:

$$\dot{m}_T - \dot{m}_{odp} - \dot{m}_{un} - \dot{m}_d = \dot{m}_S$$

Simplified heat balance:

$$\dot{m}_T . c_v . \left(T_T - T_S \right) = \dot{m}_{odp} . \Delta i_{(p,T)odp}$$
$$+ \dot{m}_{vz} . c_{vz} . \left(T_T - T_{ok} \right)$$

Evaporation loss (neglecting heat transfer to air):

$$\frac{\dot{m}_{odp}}{\dot{m}_T} = \frac{c_v . \left(T_T - T_S \right)}{\Delta i_{(p,T)odp}} \approx 1 - 3\%$$

Blow-out loss:

$$\frac{\dot{m}_{un}}{\dot{m}_T} \approx 0,1\%$$

Cooling Circuit

Cooling towers with natural draft
- "chimney effect"
- monolith, reinforced concrete
- height 30 – 150 m
- warm water distribution with sprinkler heads
- mist eliminators above them for blow-out losses limitation
- bottom part – basin with outlet of cold water

Fan cooling towers
- inside: cooling tower fill
- above: sprinkler heads
- above: mist eliminators
- forced draft given by fan
- directioning the flow by diffuser

Note:
The air as a coolant might be used in the case of inaccessibility of water. Air cooled condensers are of larger size and higher investment costs.

cooling tower with integrated flue gas outlet from FGD

Fan cooling tower

Diffuser

Mist eliminators

Sprinkler head

Cooling tower fill

Technological Waters

DEMI water

- utilized in Rankine cycle (boiler water)
- processed in Water Treatment Plant (WTP)
- stuff purity requirement, sediments in the tubes can significantly reduce the heat transfer (= *demi*neralized water)

typické parametry DEMI vody:

parameter		max.	$\varnothing$
Conductivity	(μS/cm)	0,5	0,2
pH		8 - 9	
SiO_2 content	(μg/kg)	100	20
iron content	(μg/kg)	200	20
$Ca^{2+} + Mg^{2+}$ content	(μg/kg)	3	1
COD (chem. oxygen demand)	(mgO_2/kg)	1	0,5

Filtered water (heating system)

- Power plants with district heating
- Processed in WTP

Cooling tower (from river, sea)

- Basic inflow filtration

Addendum No. 9

Coal-fired TPP has following parameters
Unit rated power: 1000 MW (net generation)
Efficiency: 0,33 (net efficiency subjected to fuel net calorific value)
Lignite parameters:

Q_i^r [MJ.kg^{-1}]	A^d [%]	S^r [%]	W^r [%]
15	15	2	30

Excess of air: 1,3   Efficiency of de-sulphurization: 0,95
Fly ash / bottom ash: 0,9 / 0,1   Precipitator's collection efficiency: 0,999

Emission limits (related to 6% excess of O_2 in flue gas):

Solid particles	SO_2
30 mg.m^{-3}	200 mg.m^{-3}

1. Decide whether TPP operation is in compliance with solid particles and SO_2 limits
2. Calculate mass flows of coal, limestone, gypsum and CO_2 emissions
3. What additional costs means CO_2 allowances for 1 MWh of generated electricity. Compare it with standard electricity price (el. price 60 EUR/MWh and CO_2 allowances price 25 EUR/t)

Neglect: other non-specified fuel components (nitrogen, chlorine, hydrate water etc.) with exclusion of carbon, air humidity, collection efficiency of FGD, reactivity and chemical purity of limestone, consider only oxidation by oxidation air in resulting balance