FACULTY
OF MECHANICAL
ENGINEERING
CTU IN PRAGUE

DEPARTMENT OF
ENVIRONMENTAL
ENGINEERING

Ventilation

1. Introduction and basic principles

Bachelor degree course

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Principle of ventilation

Ventilation

- is intentional supply of outdoor air into the buildings (cars, trains …)
- to dilute and remove indoor air contaminants
- affect the indoor air quality (IAQ)
- good indoor air quality (IAQ) is necessary for maintaining health and high productivity !!!

- healthy buildings

Principle of ventilation

Natural ventilation

- ➢ is driven by pressure differences across the building envelope, caused by wind and air density differences because of temperature differences between indoor and outdoor air
- ➢ the flow of air through open windows, doors, grilles and other planned building envelope penetrations

Mechanical (forced) ventilation

- ➢ intentional movement of air into and out of building using mechanical force
- ➢ is driven by fans

Hybrid ventilation

Terminology

Nominal air exchange rate (ventilation rate)

$$\boxed{I = \frac{\dot{V}_o}{V_r}} \qquad [1/h]$$

Space air exchange rate

$$I_S = \frac{\dot{V}_s}{V_r} \qquad [1/h]$$

$$\dot{V}_s = \dot{V}_o + \dot{V}_{rec} \qquad [m^3/h]$$

V_o … outdoor air volume air flow rate [m^3/h]

V_{rec} … recirculation air flow rate [m^3/h]

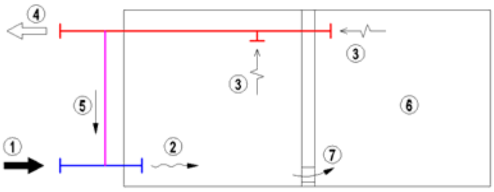
V_r…interior volume of space [m^3]

Terminology

Airflows

1 Outdoor air
2 Supply air
3 Return air
4 Exhaust air
5 Recirculated air
6 Indoor air
7 Transfer air

8 Mixed air
9 By-pass air



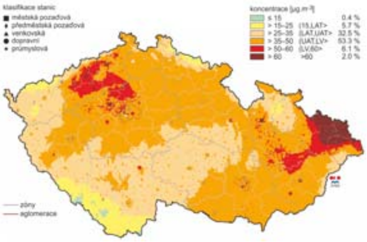
Pollutants

Internal sources (people, …)

- ➢ CO_2
- ➢ water vapour
- ➢ VOC
- ➢ formaldehyde
- ➢ Asbestos
- ➢ tobacco smoke
- ➢ combustion products
- ➢ …

Outdoor air

- ➢ SO_2
- ➢ NO_x
- ➢ CO
- ➢ benzen
- ➢ particles PM_{10} a $PM_{2,5}$
- ➢ Benzo[*a*]pyren, …



Ventilation Requirements

Requirements

- hygienic – for the people
- **technological** – for technology processes
- **biological** – agricultural processes
- micro-biological
- safety
- fire

Parameters of the pollutants

Concentration of pollutants

- mass [mg/m^3]
- volumetric [cm^3/m^3]
- ppm (parts per million) 1 ppm = 10^{-4} %
- number of particles in m^3 – clean rooms

Dimension of the particles

- $a = 0 – 100\ \mu\text{m}$

Conversion X [mg/m^3] → Y [ppm]

$$Y\ [\text{ppm}] = X\ [\text{mg/m}^3]\frac{24,44}{M}$$

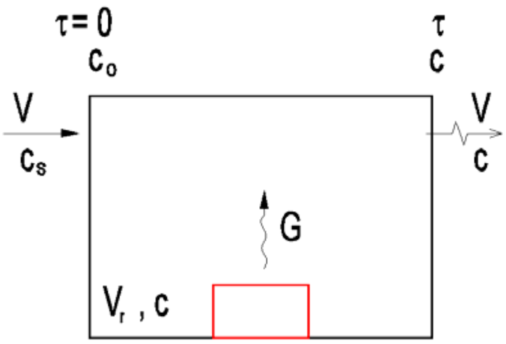
where M ...molar weight of the gas [g/mol]

Example 1: CO_2
C = 9000 mg/m3
C = ? ppm

M_C = 12 g/mol
M_O = 16 g/mol

1 000 ppm = 0,1 % vol.

Mass Balance of Pollutants



$$\underbrace{\dot{G}d\tau}_{\text{gain}} + \underbrace{\dot{V}c_s d\tau}_{\text{supply}} = \underbrace{\dot{V}c\ d\tau}_{\text{exhaust}} + \underbrace{V_r dc}_{\text{storage}}$$

Mass Balance of Pollutants

- solution

$$\left(\dot{G} + \dot{V}c_s - \dot{V}c\ \right)d\tau = V_r dc$$

$$\int_{c_0}^{c} \frac{dc}{\frac{\dot{G}}{\dot{V}} + c_s - c} = \frac{\dot{V}}{V_r}\int_{0}^{\tau} d\tau$$

$$\ln\frac{\frac{\dot{G}}{\dot{V}} + c_s - c_0}{\frac{\dot{G}}{\dot{V}} + c_s - c} = \frac{\dot{V}}{V_r}\tau \quad \Rightarrow \quad \boxed{\tau = \frac{V_r}{\dot{V}}\ln\frac{c_s + \frac{\dot{G}}{\dot{V}} - c_0}{c_s + \frac{\dot{G}}{\dot{V}} - c}}$$

Mass Balance of Pollutants

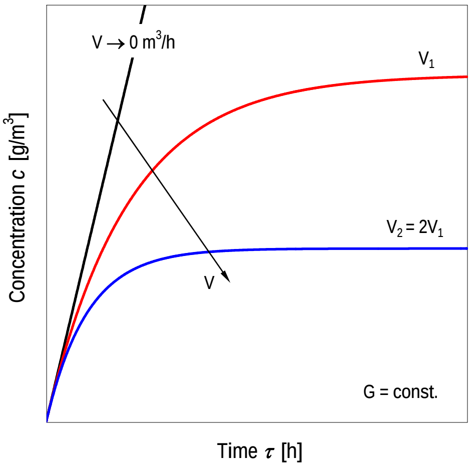
$$\boxed{c = c_0 e^{-\frac{\dot V}{V_r}\tau} + \left(\frac{\dot G}{\dot V} + c_s\right)\left(1 - e^{-\frac{\dot V}{V_r}\tau}\right)}$$

- $\tau \to \infty$; steady state

$$\dot G \cancel{d\tau} + \dot V c_s \cancel{d\tau} = \dot V c \cancel{d\tau} + \cancel{V_r dc}$$

$$\boxed{\dot V = \frac{\dot G}{c - c_s}}$$

Concentration of the pollutants



Limit Concentrations

Maximum permission concentration (MPC)

$c < MPC$

… in any time !!

for $\tau \to \infty$ and steady state

$$c_{max} = \frac{\dot{G}}{\dot{V}} + c_s$$

Ventilation

Permission exposure limit *PEL*

$c_{avg} \leq PEL$

- for $\tau \to \infty$ and steady state

$$\boxed{\dot{V} = \frac{\dot{G}}{PEL - c_s}}$$

!

Limit Concentrations

Permission exposure limit *PEL*

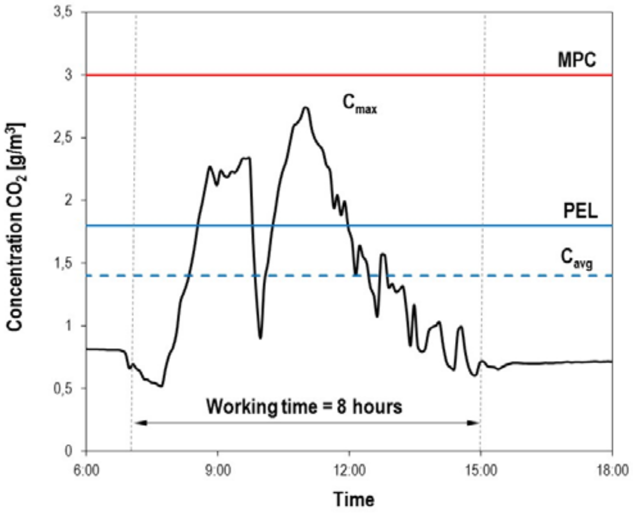
$$\boxed{c_{avg} = \frac{1}{\tau}\int_0^{\tau} c_{\tau}\, d\tau}$$

$$c_{avg} = \frac{1}{\tau \cdot I}\left(c_0 - \frac{\dot{G}}{\dot{V}} - c_s\right)\left(1 - e^{-\tau \cdot I}\right) + \left(\frac{\dot{G}}{\dot{V}} + c_s\right)$$

$$c_{avg,8} \leq PEL$$

…where τ = 8 hours

Limit Concentrations



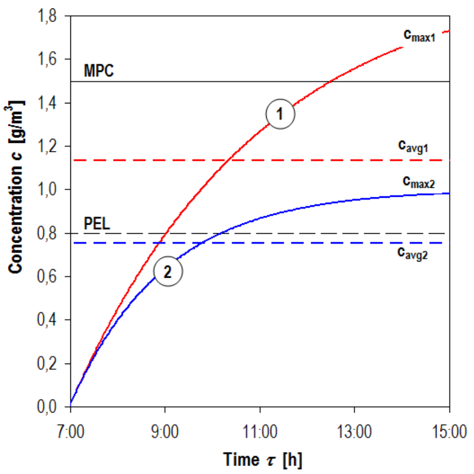
$$c_{max} < MPC$$

$$c_{avg} \leq PEL$$

!

Example 1

Permanent pollutant generation



Ventilation strategy:

1) $c_{max,1}$ > MPC
$c_{avg,1}$ > PEL

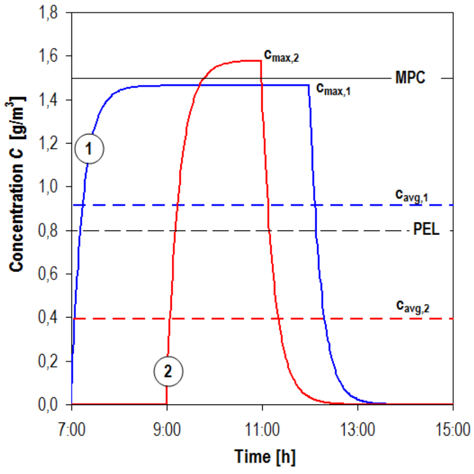
!!! V_o ↑

2) $c_{max,2}$ < MPC
$c_{avg,2}$ < PEL

OK

Example 2

Variable pollutant generation



Ventilation strategy:

1) $c_{max,1}$ < MPC
$c_{avg,1}$ > PEL

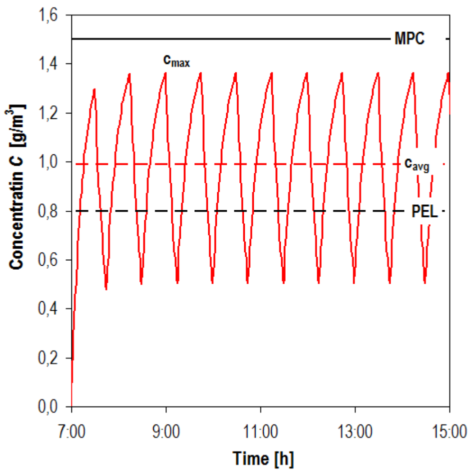
!!! V_o ↑, τ↓

2) $c_{max,2}$ > MPC
$c_{avg,2}$ < PEL

!!! V_o ↑ , τ↓

Example 3

Periodical pollutant generation



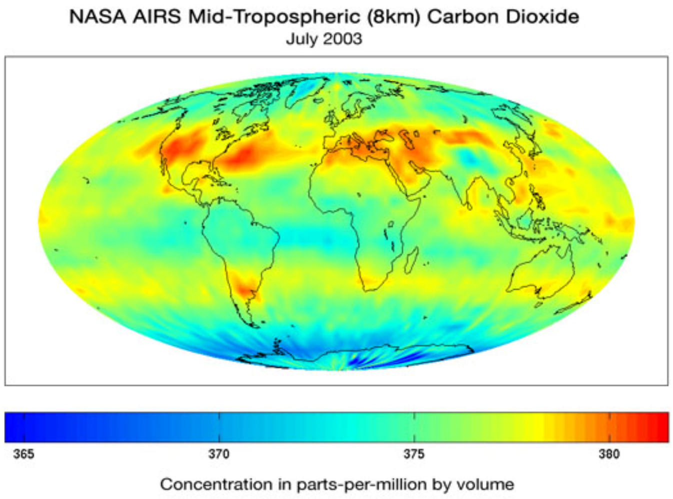
Ventilation strategy:

c_{max} < MPC ...OK
c_{avg} > PEL ...!!!

!!! $V_o \uparrow, \tau \downarrow$

Carbon dioxide CO_2

Mauna Loa
(Havaj)
> 380 ppm



Carbon dioxide CO_2

360 - 600 ppm: concentration in outdoor air

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800 - 1 200 ppm: recomended indoor air concentration

1 500 ppm: maximum indoor air concentration

> 1 500 ppm: tideness, sleepiness, lethargy, headache…

< 5 000 ppm: maximum safety concentration without health risk

> 5 000 ppm: sickness, higher pulsation (sick building syndromme - SBS)

> 10 000 ppm: health hazards

> 40 000 ppm: dangerous to live (caves, wine-cellar, water well …)

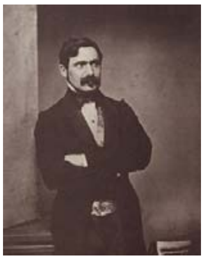
1 000 ppm = 0,1 % obj.

Carbon dioxide CO_2

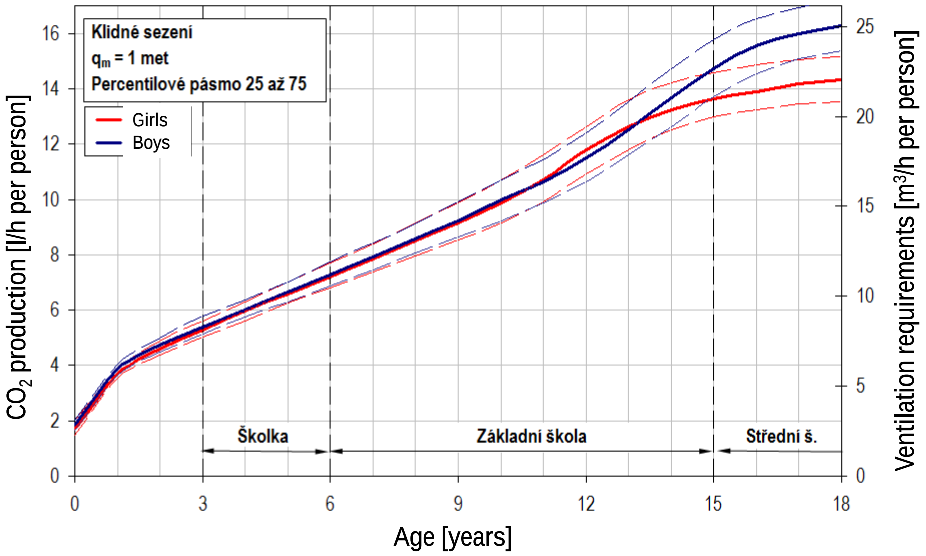
Max von Pettenkofer (1818 - 1901)

- main metabolite: CO_2 a water vapour
- CO_2 production depends on activity level and age
- Adults - 16 dm³/h CO_2 for unsleeping person (10 dm³/h when sleeping)
- CO_2 concentration in indoor environments informs about quality of ventilation
- max. concentration 0,1 vol. % = 1000 ppm

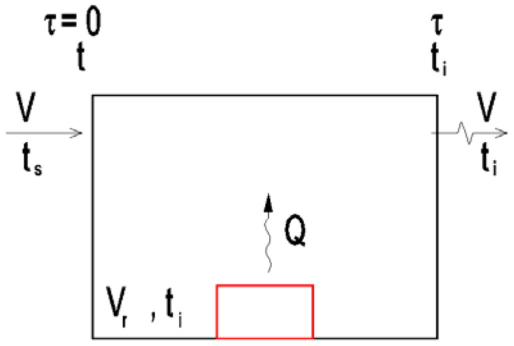
  → Pettenkofer criterion
- ventilation rates 25 m³/h per person



CO$_2$ production



Thermal balance



$$\dot{Q}d\tau + \dot{V}\rho c t_s d\tau = \dot{V}\rho c t_i d\tau + V_r \rho c\ dt$$

Thermal balance

- only for $\tau \rightarrow \infty$ steady state

$$\dot{Q}\cancel{d\tau} + \dot{V}\rho c t_p \cancel{d\tau} = \dot{V}\rho c t_o \cancel{d\tau} + \cancel{V_r \rho c dt}$$

$$\boxed{\dot{V} = \frac{\dot{Q}}{\rho c\left(t_i - t_s\right)}}$$

c	...specific heat of the air = 1010 [kJ/kgK]
ρ	...density of the air = 1.2 [kg/m^3]

Moisture balance

$$\dot{M}_w d\tau + \dot{V}\rho x_s d\tau = \dot{V}\rho x_i d\tau + V_r \rho dx$$

$$x_{i,\tau} = x_{i,0} e^{-\tau I} + \left(\frac{\dot{M}_w}{\dot{V}\rho} + x_s\right)\left(1 - e^{-\tau I}\right)$$

$$\boxed{\dot{V} = \frac{\dot{M}_w}{\rho\left(x_i - x_s\right)}}$$

Ventilation Requirements

Czech Republic regulation

- minimal ventilation air flow rate per person

25 m^3/h per person – sitting

50 m^3/h per person – sitting work

70 m^3/h per person – standing work

90 m^3/h per person – hard work

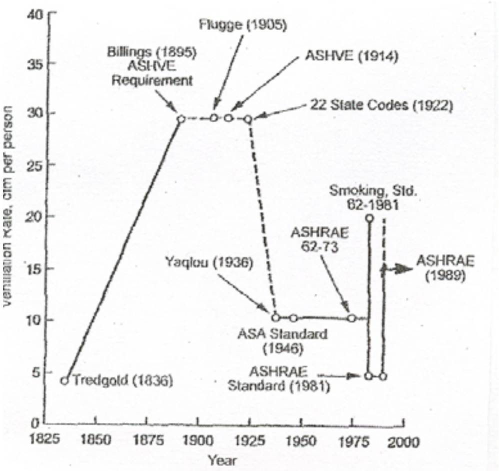
Ventilation Requirements

EN 15251 - Indoor environmental input parameters for design and assessment of energy performance of buildings- addressing indoor air quality, thermal environment, lighting and acoustics

Space	Occupancy [m^2/person]	Required air flow rate [m^2/h.person]
Office spaces	10	36
Land-scape office	15	36
Classroom	2	29
Kidergarten	2	30
Conference room	2	36
Department store	7	23

Ventilation Requirements

ASHRAE



10 cfm = 17 m^3/h

Examples

Example 2: Calculation of volume air flow rate

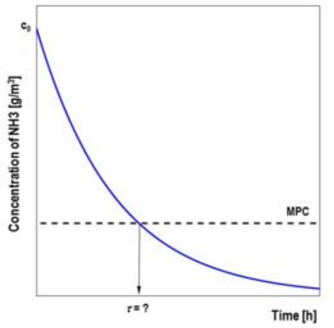
Mass flow of pollutant	G = 0.2 kg/h of Fe_xO_y
Permission exposure limit	PEL = 0.015 g/m^3
Concentration in outdor air	$c_s = 0$
Calculate volume air flow rate	$V = ?$

Examples

Example 3: Calculate time τ after accident of NH_3 in machine room.

Volume of the machine room	$V_r = 500\ m^3$
Amount of escaped NH_3	$m = 1.2$ kg
Max. permission concentration	$MPC = 0.036\ g/m^3$
Ventilation rate	$I = 5\ h^{-1}$

How long it takes achieving of *MPC* ...
τ = ?



Examples

Example 4: Pettenkoffer‘s criterion

1 people exhale 0.42 m^3/h of air

Concentration of CO_2 in exhaled air is 4 % vol.

Concentration of CO_2 in outdoor air C_{CO2} = 0.035 % vol. = 350 ppm

Max. concentration of CO_2 in the room C_{max} = 0.1 % vol. = 1000 ppm

Calculate volume air flow rate of outdoor air V_o = ? [m^3/h]

Examples

Example 5: Calculate V_o = ?, V = ?, V_{rec} = ?

Cooling load	Q_{cl} = 30 kW
Indoor air temperature	t_i = 26 °C
Temp. of supply air	t_s = 16 °C
Occupancy	200 person
Air flow rate	25 m^3/h per person

Examples

Example 6:

$V_{ex} = V_s$ = 8 000 m^3/h

V_r = 1 000 m^3

G = 60 g/h

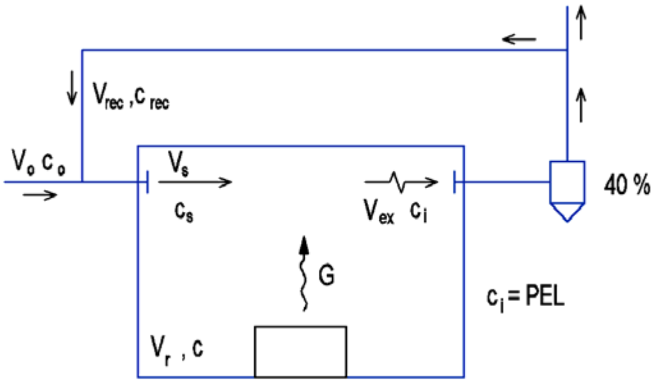
C_o = 0.0001 g/m^3

PEL = 0.01 g/m^3

C_s = ?

V_o = ?

V_{rec} = ?



Examples

Example 7:

V_r = 1 600 m^3
G = 1000 g/h (aceton)
I = 0.5 h^{-1}
C_s = 0
C_0 = 0
PEL = 0.8 g/m^3
MPC = 1.5 g/m^3

Calculate:

C_{max} = ?
C_{avg} = ?
Compare with *PEL* and *MPC*

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Thank you for your attention

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