



FACULTY
OF MECHANICAL
ENGINEERING
CTU IN PRAGUE



DEPARTMENT OF
ENVIRONMENTAL
ENGINEERING

Environmental Engineering

3. Ventilation

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

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■ Terminology



Nominal air exchange rate (ventilation rate)

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

Space air exchange rate

$$I_s = \frac{\dot{V}_s}{V_r} \quad [1/h]$$

\dot{V}_o ... outdoor air volume air flow rate [m^3/h]

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

\dot{V}_{rec} ... recirculation air flow rate [m^3/h]

V_r ... interior volume of space [m^3]

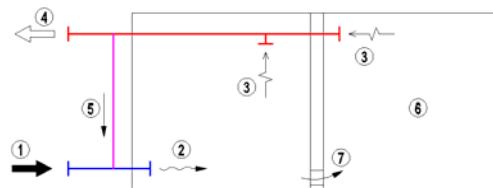
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■ Terminology



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

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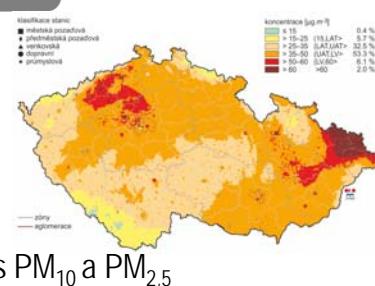
■ Pollutants



Internal sources (people, ...)

- CO₂
- water vapour
- VOC
- formaldehyde
- Asbestos
- tobacco smoke
- combustion products
- ...

Outdoor air



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■ Ventilation Requirements



Requirements

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

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■ Parameters of the pollutants



Concentration of pollutants

- mass [mg/m³]
- volumetric [cm³/m³]
- ppm (parts per million) 1 ppm = 10⁻⁴ %
- number of particles in m³ – clean rooms

Example: CO₂

Dimension of the particles

- $a = 0 - 100 \mu\text{m}$

Conversion X [mg/m³] → Y [ppm]

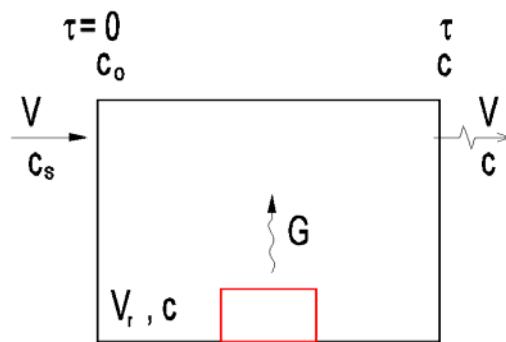
$$Y [\text{ppm}] = X [\text{mg/m}^3] \frac{24,44}{M}$$

where M ...molecular weight of the gass [g/mol]

1 000 ppm = 0,1 % obj.

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■ Mass Balance of Pollutants



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

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■ Mass Balance of Pollutants



➤ solution

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

$$\int_{c_0}^c \frac{dc}{\dot{G} + c_s - c} = \frac{\dot{V}}{V_r} \int_0^\tau d\tau$$

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

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■ Mass Balance of Pollutants



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

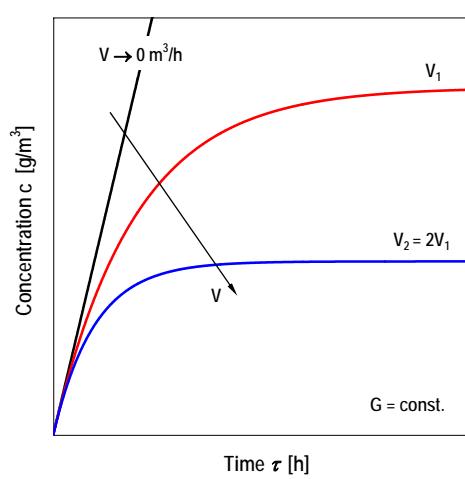
➤ $\tau \rightarrow \infty$; steady state

$$\cancel{\dot{G}} \cancel{dt} + \cancel{\dot{V}} \cancel{c_s} \cancel{dt} = \cancel{\dot{V}} \cancel{c} \cancel{dt} + \cancel{\dot{V}} \cancel{dc}$$

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

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■ Concentration of the pollutant



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■ Limit Concentrations



Maximum permission concentration (MPC)

$$c \leq MPC$$

... in any time !!

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

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

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■ Ventilation



Permission exposure limit PEL

$$c_{avg} \leq PEL$$

➤ for $\tau \rightarrow \infty$ and steady state

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

!

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■ Limit Concentrations



Permission exposure limit *PEL*

$$C_{avg} = \frac{1}{\tau} \int_0^{\tau} C_{\tau} d\tau$$

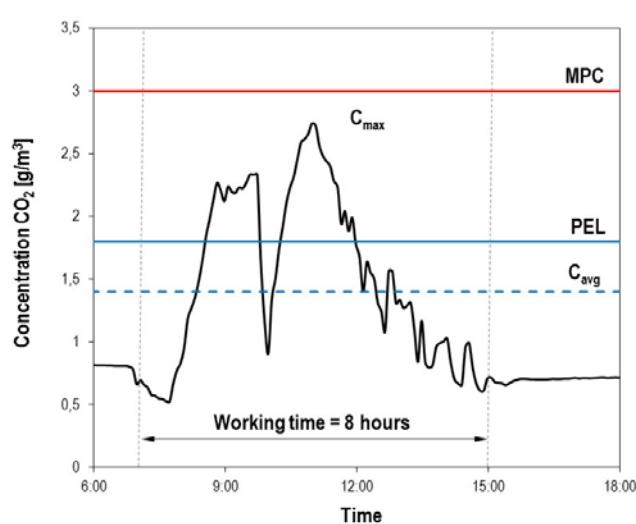
$$C_{avg} = \frac{1}{\tau \cdot I} \left(C_0 - \frac{\dot{G}}{\dot{V}} - C_s \right) \left(1 - e^{-\tau \cdot I} \right) + \left(\frac{\dot{G}}{\dot{V}} + C_s \right)$$

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

...where $\tau = 8$ hours

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■ Limit Concentrations



$C_{max} < MPC$

$C_{avg} \leq PEL$



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■ Example



Example 1: Calculation of volume air flow rate

Mass flow of pollutant

$$G = 0.2 \text{ kg/h of } \text{Fe}_x\text{O}_y$$

Permission exposure limit

$$PEL = 0,015 \text{ g/m}^3$$

Concentration in outdoor air

$$c_s = 0$$

Calculate volume air flow rate

$$V = ?$$

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■ Example



Example 2: Calculate time τ after accident of NH_3 in machine room.

Volume of the machine room

$$V_r = 500 \text{ m}^3$$

Amount of escaped NH_3

$$m = 1.2 \text{ kg}$$

Max. permission concentration

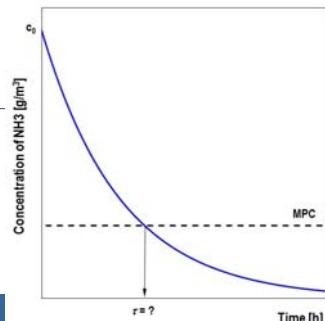
$$MPC = 0.036 \text{ g/m}^3$$

Ventilation rate

$$I = 5 \text{ h}^{-1}$$

How long it takes achieving of MPC ...

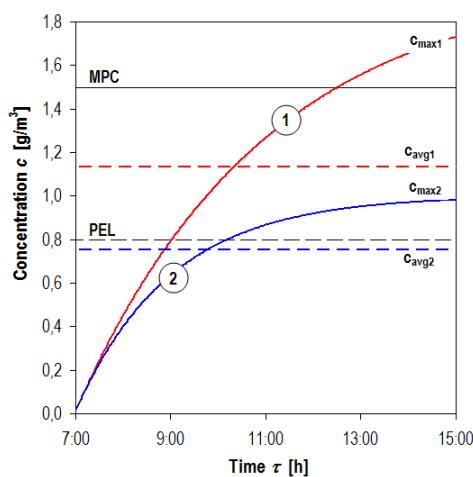
$$\tau = ?$$



■ Example 1



Permanent pollutant generation



Ventilation strategy:

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

!!! $V_o \uparrow$

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

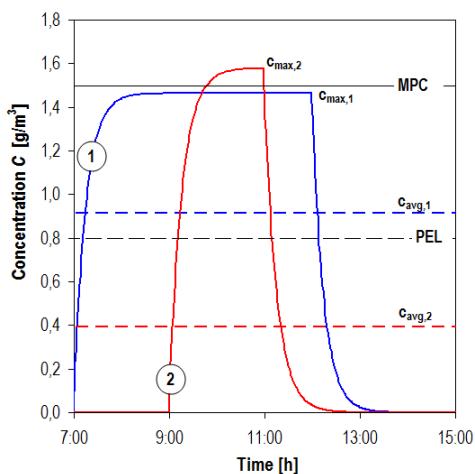
OK

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■ Example 2



Variable pollutant generation



Ventilation strategy:

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

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

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

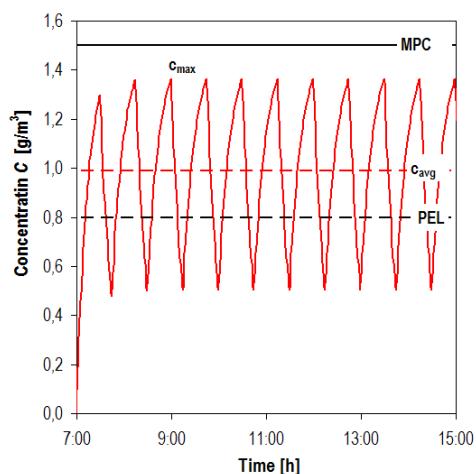
!!! $V_o \uparrow, \tau \downarrow$

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■ Example 3



Periodical pollutant generation



Ventilation strategy:

$C_{max} < MPC$...OK
 $C_{avg} > PEL$...!!!

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

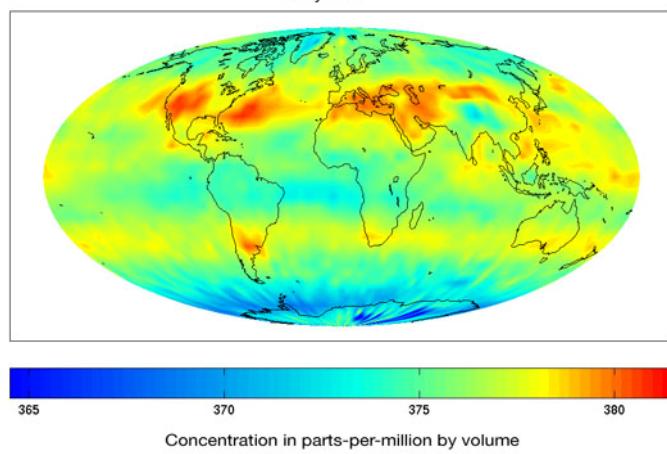
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■ Carbon dioxide CO₂



NASA AIRS Mid-Tropospheric (8km) Carbon Dioxide
July 2003

Mauna Loa
(Hawaii)
> 380 ppm



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■ Carbon dioxide CO₂



360 - 600 ppm: concentration in outdoor air

800 - 1 200 ppm: recommended indoor air concentration

1 500 ppm: maximum indoor air concentration

> 1 500 ppm: tiredness, sleepiness, lethargy, headache...

< 5 000 ppm: maximum safety concentration without health risk

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

> 10 000 ppm: health hazards

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

1 000 ppm = 0,1 % obj.

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■ Example



Example 3: Pettenkoffer's criterion

1 people exhale 0.42 m³/h of air

Concentration of CO₂ in exhaled air is 4 % vol.



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

Max. concentration of CO₂ in the room C_{max} = 0.1 % vol. = 1000 ppm

Calculate volume air flow rate of outdoor air V_o = ? [m³/h]

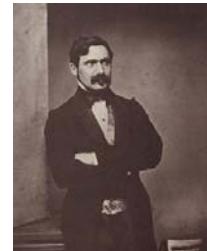
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■ Carbon dioxide CO₂



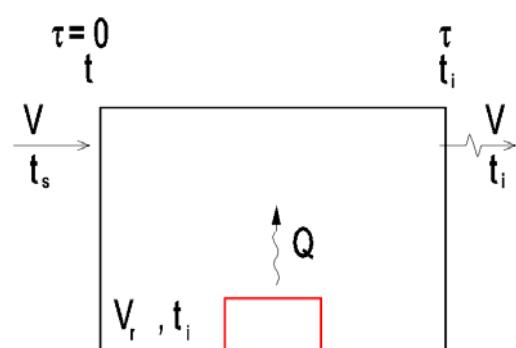
Max von Pettenkofer (1818 - 1901)

- main metabolite: CO₂ a water vapour
- CO₂ production depends on activity level and age
- Adults - **16 dm³/h CO₂** for unsleeping person (10 dm³/h when sleeping)
- CO₂ 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



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■ Thermal balance



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

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■ Thermal balance



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

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

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

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■ Moisture balance



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

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

$$x_i = \frac{\dot{M}_w}{V \rho} + x_s$$

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Mechanical ventilation



Example 4: Calculate $V_o = ?$, $V = ?$, $V_{rec} = ?$

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

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Example



Example 5:

$$V_{ex} = V_s = 8000 \text{ m}^3/\text{h}$$

$$V_r = 1000 \text{ m}^3$$

$$G = 60 \text{ g/h}$$

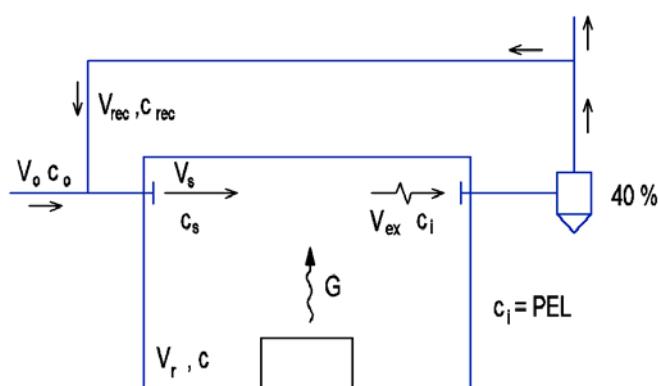
$$C_o = 0.0001 \text{ g/m}^3$$

$$PEL = 0.01 \text{ g/m}^3$$

$$C_s = ?$$

$$V_o = ?$$

$$V_{rec} = ?$$



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■ Example



Example 6:

$$\begin{aligned}V_r &= 1\,600 \text{ m}^3 \\G &= 1000 \text{ g/h (acetone)} \\I &= 0.5 \text{ h}^{-1} \\C_s &= 0 \\C_0 &= 0 \\PEL &= 0.8 \text{ g/m}^3 \\MPC &= 1.5 \text{ g/m}^3\end{aligned}$$

Calculate:

$$\begin{aligned}C_{max} &=? \\C_{avg} &=? \\&\text{Compare with PEL and MPC}\end{aligned}$$

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■ 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

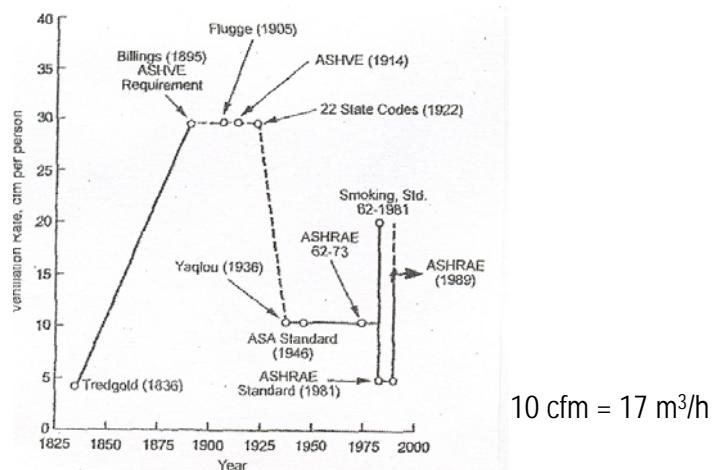
Space	Occupancy [m ² /person]	Required air flow rate [m ² /h.person]
Office spaces	10	36
Landscape office	15	36
Classroom	2	29
Kindergarten	2	30
Conference room	2	36
Department store	7	23

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Ventilation Requirements



ASHRAE



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Thank you for your attention



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