Building ventilation systems

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Outline of following three lectures

- Fundamentals of building ventilation
- Basic principles
  - Natural ventilation
  - Mechanical ventilation
  - Hybrid ventilation
- Typical examples of natural ventilation
- Typical systems of mechanical ventilation
  - Central and local systems
- Requirements and applications for specific buildings
  - Residential, office, commercial and special buildings
Fundamentals of building ventilation

- Why is it necessary to ventilate?
  - **Air for breathing**
    - Adult man has frequency of breathing typically 16 times per minute – 8 \( \text{l/min} \).
  - Oxygen consumption varies between 250 – 350 \( \text{ml/min} \)
  - **Respiration**
    - Into lungs (atmospheric air) - 21 % \( \text{O}_2 \), 78 % \( \text{N}_2 \), 0,03 % \( \text{CO}_2 \)
    - Out from lungs - 16 % \( \text{O}_2 \), 79 % \( \text{N}_2 \), 4 % \( \text{CO}_2 \) (plus water vapor)
Fundamentals of building ventilation

- Why is it necessary to ventilate?
  - Pollutants production
  - Men activity
    - Carbon dioxide – $CO_2$, water vapor
  - Equipment
    - Furniture, flooring, –VOC - Volatile Organic Compounds (carbon-based compounds that easily evaporate)
  - Technology
  - Animals
  - Outside pollutant sources
    - Traffic – CO, NH$_x$, …
    - Earth – radon released from soil, dangerous in case of accumulation in homes and long exposure to it
Fundamentals of building ventilation

- Why is it necessary to ventilate?
  - Indoor environment in a room has to meet level suitable for people and their activity.
  - In an industrial building ventilation requirements may relate also to industrial processes.
  - In an agricultural building all focus aims to animals.
  - Ventilation is one of systems keeping habitable environment.
Fundamentals of building ventilation

• **How much air?**
  • Breathing – 8 l/min (adult person in low activity)
    • Rising activity causes increasing air volume rate

• **Pollutants**
  • Rate of pollutant production
  • Maximum permissible concentration
  • Mean concentration in a supply air
  \[
  \text{Air flow rate} \quad [\text{kg/s, m}^3/\text{h}]
  \]
Fundamentals of building ventilation

• **Calculation of supply air flow rate**

  • Ventilation intensity
    • Simplified approach
    • Preliminary design or buildings with typical operation (residential buildings)

  \[
  V_s = n \cdot V_o
  \]

  \[V_s\] supply air flow rate \([\text{m}^3\cdot\text{h}^{-1}]\)

  \[V_o\] room volume \([\text{m}^3]\)

  \[n\] ventilation intensity \([\text{h}^{-1}]\)
Calculation of supply air flow rate

Gas pollutants (carbon dioxide as example)

\[ V_s = \frac{m_{CO_2}}{\Psi_{max} - \Psi_e} = \frac{19l/h}{(1200 - 350) ppm \cdot 10^{-3}} = 22.4 \text{ m}^3\text{h}^{-1} \text{ per person} \]

- \( V_s \): supply air flow rate necessary to keep \( CO_2 \) concentration on required level \([\text{m}^3\text{h}^{-1}]\)
- \( m_{CO_2} \): \( CO_2 \) production \([\text{l.h}^{-1}]\)
- \( \Psi_{max} \): maximum concentration in interior 1200 ppm (EN 13 779 for class „B“) \([\text{g.g}^{-1}]\)
- \( \Psi_e \): outside air concentration of \( CO_2 \) (350 ppm) \([\text{g.g}^{-1}]\)

<table>
<thead>
<tr>
<th>Activity</th>
<th>CO(_2) production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seated man</td>
<td>13 l. h(^{-1})</td>
</tr>
<tr>
<td>Light activity</td>
<td>19 l. h(^{-1})</td>
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<tr>
<td>Medium activity</td>
<td>60 l. h(^{-1})</td>
</tr>
<tr>
<td>Heavy labor</td>
<td>77 l. h(^{-1})</td>
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</tbody>
</table>
Fundamentals of building ventilation

- Calculation of supply air flow rate

- Water vapor
  - Evaporation from skin, breathing

\[ V_s = \frac{G}{\rho \cdot (x_i - x_s)} = \frac{40 \, g/h}{1,205 \, kg/m^3 \cdot (6-3,5) \, g/kg} = 13,28 \, m^3/h^{\text{-1}} \text{ per person} \]

<table>
<thead>
<tr>
<th>Activity</th>
<th>Water vapor production [g.h(^{-1})]</th>
<th>Source</th>
<th>Water vapor production [g.h(^{-1})]</th>
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</thead>
<tbody>
<tr>
<td>Seated man</td>
<td>30</td>
<td>Bathroom with bath</td>
<td>cca 700</td>
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<tr>
<td>Light activity</td>
<td>40-200</td>
<td>Bathroom with shower</td>
<td>cca 2600</td>
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<tr>
<td>Medium activity</td>
<td>120 až 300</td>
<td>Kitchen during cooking</td>
<td>600 až 1500</td>
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<tr>
<td>Heavy labor</td>
<td>200 až 300</td>
<td>Kitchen with gas cooker</td>
<td>1500 g per 1 m(^3) gas</td>
</tr>
</tbody>
</table>

G - total moisture gain of a space [g.s\(^{-1}\)]
\( \rho \) - density of air [1.2 kg.m\(^{-3}\)]
\( x_i \) - moisture content of indoor air [g.kg\(^{-1}\) d.a.]
\( x_s \) - moisture content of supply air [g.kg\(^{-1}\) d.a.]
Fundamentals of building ventilation

- Calculation of supply air flow rate
  - Heat or cold demand
    - Purpose of cooling or warm air heating
    - Cooling - supply colder air than air in an interior for purpose of elimination of excessive heat gains.
    - Heat could be a pollutant in case of overheating a room.
    - Heating – supply of warmer air than in an interior for purpose of covering heat losses.
Fundamentals of building ventilation

- Calculation of supply air flow rate

- Heat or cold demand

\[ V_s = \frac{Q_{load\,(loss)}}{\rho \cdot c_a \cdot \Delta t} = \frac{900W}{1,2\,kg/m^3 \cdot 1010\,J/kg \cdot K \cdot 6K} = 0,123\,m^3/s = 445,5\,m^3/h} \]

- \( Q \) total thermal load or heat loss of a space [kW]
- \( c_a \) specific heat of air [kJ.kg\(^{-1}\).K\(^{-1}\)]
- \( \rho \) density of air [1.2 kg.m\(^{-3}\)]
- \( \Delta t \) temperature difference
- \( t_i \) indoor air temperature [°C] \( t_s > t_i \) - heating
- \( t_s \) supply air temperature [°C] \( t_s < t_i \) - cooling
Estimation of supply air flow rate

- A room with CO$_2$ production:

\[
V_s = \frac{m_{co2}}{\Psi_{max} - \Psi_e} = \frac{19l/h}{(1200 - 350) \text{ppm} \cdot 10^{-3}} = 22.4 \text{ m}^3\text{h}^{-1} \text{ per person}
\]

Only fresh exterior air \( V_s = V_e \)

- A room with water vapor production:

\[
V_s = \frac{G}{\rho \cdot (x_i - x_s)} = \frac{40g/h}{1.205kg/m^3 \cdot (6 - 3.5)g/kg} = 13.28m^3h^{-1} \text{ per person}
\]

Fresh exterior air \( V_s = V_e \)

Dehumidifying device \( V_s = V_c \)

\( V_c \) – circulation air, reused air extract from a room (for this case needs dehumidification)
Fundamentals of building ventilation

- **Estimation of supply air flow rate**
  - A room with CO$_2$ and water vapor production:
    \[
    V_s = \frac{m_{co2}}{\Psi_{max} - \Psi_e} = \frac{19 l/h}{(1200 - 350) ppm \cdot 10^{-3}} = 22.4 \text{ m}^3\text{h}^{-1} \text{ per person}
    \]
    \[
    V_s = \frac{G}{\rho \cdot (x_t - x_s)} = \frac{40 g/h}{1,205 kg/m^3 \cdot (6 - 3,5) g/kg} = 13.28 \text{ m}^3\text{h}^{-1} \text{ per person}
    \]
    Maximum of $V_s$  $\Rightarrow$  $V_s = V_e$

- A room with heat loss or heat load:
  \[
  V_s = \frac{Q_{load(loss)}}{\rho \cdot c_a \cdot \Delta t} = \frac{900 W}{1,2 kg/m^3 \cdot 1010 J/kg \cdot K \cdot 6 K} = 0,123 \text{ m}^3\text{s}^{-1} = 445.5 \text{ m}^3\text{h}^{-1}
  \]
  Air heating or cooling  $\Rightarrow$  $V_s = V_c$

In air heating (cooling) device is necessary to keep temperature difference $\Delta t$. 
Fundamentals of building ventilation

- Estimation of supply air flow rate
  - A room with heat loss or heat load and CO₂ and water vapor production:

  
  \[
  V_s = \frac{m_{\text{co}2}}{\Psi_{\text{max}} - \Psi_e} = \frac{19 l / h}{(1200 - 350) \, \text{ppm} \cdot 10^{-3}} = 22,4 \, m^3 h^{-1} \text{ per person}
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  \[
  V_s = \frac{G}{\rho \cdot (x_i - x_s)} = \frac{40 g / h}{1,205 kg / m^3 \cdot (6 - 3,5) g / kg} = 13,28 m^3 h^{-1} \text{ per person}
  \]

  Maximum of \( V_s \)

  \[
  V_s = V_e
  \]

  \[
  V_s = \frac{Q_{\text{load(loss)}}}{\rho \cdot C_a \cdot \Delta t} = \frac{900 W}{1,2 kg / m^3 \cdot 1010 J / kg \cdot K \cdot 6K} = 0,123 \, m^3 s^{-1} = 445,5 m^3 h^{-1}
  \]

  \[
  V_s = V_e + V_c
  \]
Fundamentals of building ventilation

- Estimation of supply air flow rate
  - A room with heat loss or heat load and CO₂ and water vapor production:

\[ V_s = V_e + V_c \]

\[ V_e \quad t_e \quad V_c \quad t_i \]

\[ V_s \quad t_s \]
Basic principles

- *General definition*: Ventilation provides exchange of polluted air for fresh outside air or clean air from neighboring rooms.
- *How ventilation works?* Ventilation requires air flowing between interior and exterior. Thus it is necessary to start and maintain air flow according to requirements in a ventilated space.
  - Basically pressure difference is a force starting an air flow.
Basic principles

- **Natural ventilation**
  - Pressure difference is caused by
    - difference between densities of interior and exterior air given by temperature difference.
    - wind velocity providing on windward façade positive pressure and on leeward negative pressure.

- **Mechanical ventilation**
  - Pressure difference is caused by dynamic pressure of a fan.

- **Hybrid ventilation**
  - Combines both natural and mechanical.
  - If natural ventilation is not able to provide required air flow rate, than supporting mechanical element starts it operation.
Basic principles

- **Natural ventilation**
- Pressure difference is caused by
  - difference between densities of interior and exterior air given by temperature difference.
  - wind velocity providing on windward façade positive pressure and on leeward negative pressure.
Basic principles

- Mechanical ventilation
- Dynamic pressure of a mechanical device – fan, blower
  - Overpressure ventilation
  - Balanced ventilation
  - Underpressure ventilation
Natural ventilation
Natural ventilation

- Natural ventilation
- Influence of terrain
  - Wind velocity, turbulence, flow pattern
Natural ventilation

- Natural ventilation
- Influence of neighboring buildings
  - Building exposure and orientation

![Diagram showing wind direction in winter and summer, and the effect of building orientation on natural ventilation.](Image)
Natural ventilation

- Natural ventilation
- Influence building shape
  - Flow direction through building, ventilation intensity
Typical examples of natural ventilation

**Infiltration** – air permeates through leaking structural joints, window gaps, etc.
- Historically the most widely used ventilation in residential and small office buildings.
- Modern windows are tight, so infiltration is too small to keep ventilation requirements.

**Interrupted ventilation** – ventilation through openings
- Suitable only for auxiliary increase of ventilation rate.
Natural ventilation

• Typical examples of natural ventilation
  • Aeration – air supply and exhaust is caused through inlets with proper high difference
    • Industrial halls, stables
    • Regulation of inlets and outlets opening
Natural ventilation

- Typical examples of natural ventilation
- *Shaft ventilation* – combination of inlets and shafts
Natural ventilation

- Principle of automatic control of natural ventilation
- Evaluation of indoor air quality - sensors
- Meteorological data
- Smart control system
Natural ventilation

- **Existing natural ventilation systems**
- British Inland Revenue Service in Nottingham (1994)
  - Ventilation towers in building corners
  - Driving air from halls and corridors in each floor

Ventilation towers
Natural ventilation

- Existing natural ventilation systems
- School of Engineering, De Montfort University, Leicester, GB.
  - System features variety of ventilation towers, skylights, sunroofs, etc.

Necessary to consider local occurrence of draft.
Natural ventilation

- **Passive cooling**
- Heat gains – avoid of building overheating
- mechanical components like pumps and fans are not used
- Suitable for mild climates with cool dry nights - can be done with simple ventilation

Enhanced passive cooling systems
- Air humidification spraying water into fresh air flow
- Indirect cooling in wet cooler

Pictures from: http://www.thefarm.org/charities/i4at/lib2/aircool.htm
Mechanical ventilation
Mechanical ventilation

- Mechanical ventilation
  Dynamic pressure of a mechanical device – fan, blower

- Basic purposes
  Ventilation operable independent (less) on exterior conditions.
  High ventilation demand – high rate of pollutants production.
  Precise operation control
  Temperature and humidity control
Mechanical ventilation

- **Categories**

  *Air pressure in a ventilated room:*

  - *Pressure balanced system* — into a ventilated room is being supplied the same amount of air as it is exhausted from it. No pressure difference to neighboring rooms.
Mechanical ventilation

• Categories

*Air pressure in a ventilated room:*

• *Underpressure system* - into a ventilated room is being supplied less amount of air than it is exhausted from it. Negative pressure difference to neighboring rooms – air permeates into room.
Mechanical ventilation

- **Categories**

  *Air pressure in a ventilated room:*

- Overpressure system - into a ventilated room is being supplied more amount of air than it is exhausted from it. Positive pressure difference to neighboring rooms – air permeates from room.
Mechanical ventilation

- **Categories**

  *Purpose of a system*

- *Ventilation* — waste air exchange for fresh air, pollutants production

- *Warm air heating* — air exchange controlling required indoor air temperature. Supply air temperature is higher than indoor air temperature. Coverage of entire or partial of a room heat loss. May be in combination with ventilation.

- *Air-conditioning* — complex control of indoor air parameters through supplied air. Maintenance of temperature, moisture parameters and quality of supply air.
Mechanical ventilation

• Categories

  *Purpose of a system*

  • *exhaustion* – forced exhaust of gas and solid pollutants directly from location of their production. To prevent contamination of neighborhood filtration, particles separation or neutralization may be necessary.

  • *Industrial ventilation* – belong to group of specialized equipment of unique function. Connects direct requirements of technology and room ventilation.

  • *Other* – emergency and fire ventilation, air showers and curtains, etc.
Mechanical ventilation

- Categories
  
  *another categorization:*

- Relation between ventilated building and system:
  - Central
  - Local

- Air flow rate:
  - Constant
  - Variable

- pressure:
  - Low pressure
  - High pressure
Mechanical ventilation

- What ventilation system consist of?

AHU – air-handling unit
Ductwork – supply and exhaust of air
Air distribution – supply grills, diffuser

Other elements – fan-coils, VAV box
Control devices - dampers

Overpressure reduction
- Decrease of air velocity
- High pressure systems only

Overpressure reduction - Decrease of air velocity - High pressure systems only

Main vertical ductworks

Waste air exhaust

Room air exhaust

Distribution network

Fresh air

Air distribution elements – air supply
Mechanical ventilation

• **Basic central systems**

**Underpressure system**

- air exhaust only
- air supply through a zone boundary (exterior, neighboring rooms)
- simple ductwork (one pipe)
- Suitable to avoid transfer of pollutants to surrounding.

- **Used in:** auxiliary, hygiene rooms
  - toilets, bathrooms, kitchens in residential buildings
  - underground garages
- may be in combination with other system providing air supply and its treatment.
- ventilation only
**Basic central systems**

**Standard system**
- the most common ventilation system providing air supply and exhaust,
- central AHU, no differences between building zones,
- appropriate for buildings with uniform pollutants production, heat loss/load,
- inappropriate for variable loaded rooms in a building in time,
- simple maintenance

**Typical for:**
- small administrative buildings, single large offices
- large shopping centers – „supermarkets“
- small independent premises – restaurant, cafeteria etc.

Possibly also VAV system
**Basic central systems**

**Fancoil (FCU) system**

- probably the most typical system for large buildings (new also rebuild)
- AHU transfer and maintain parameters of fresh air only (no air circulation)
- in each zone is a unit which:
  - secure final air temperature (moisture exceptionally),
  - mix fresh air with room air - circulation
- includes coils for air heating and cooling
- connection to drainage (condensing water vapor on cooler)

**Typical for:**
- Administrative buildings
- Commercial buildings, shopping centers with different variety of shops
**Mechanical ventilation**

- **Basic central systems**
  
  Fancoil (FCU) system

  - autonomous unit with fan and coils (air cooling and heating)
  - Main parts – one or two coils, fan, damper, filters
  - typical variants:
    - centralized – primary air is processed in AHU
    - decentralized – direct transfer of fresh air from exterior
    - circulation – circulation of indoor air only
  - locations: wall mounted, under ceiling, sill mounted, integrated in suspended ceiling, in ductwork, etc.
  - heat exchanger (coil) – water-to-air, refrigerant-to-air
  - regulation – central system featuring FCU is capable of simultaneous cooling and heating in different zones according to immediate requirements
• Air distribution

Ductwork system

Rectangular ducts
• Galvanized steel
• 0.6 – 1.1 mm for pressure +1000/-630 Pa
• Dimensions AxB e.g. 500x315 mm
• Connection – bolt flanges
• Categories according to operating pressure, required tightness (A – regular, B, C)

AxB: 125, 200, 250, 300, 315, 400, 500, 600, 630, 710, 800

Pictures from technical parameters http://www.azklima.com
**Mechanical ventilation**

**Air distribution**

**Ductwork system**

Circular ducts
- Galvanized steel
- 0.6 – 1.25 mm for pressure +1500/-630 Pa
- Dimensions D e.g. 500 mm
- Categories according to operating pressure, required tightness (A – regular, B, C)

D: 80, 100, 125, 140, 160, 180, 200, 225, 250, 315, 355, 400, 450, 500, 560, 630, 710, 800

Pictures from technical parameters http://www.azklima.com
Mechanical ventilation

- **Air distribution**

  **Air mixing**
  - Supplied air is mixed with indoor air
  - Fresh air quickly get contaminated
  - High supply air velocities 2-8 m/s
  - Most common system

  **Unidirectional displacement ventilation**
  - No mixing, limited turbulence of supply air
  - Fresh air like piston push out contaminated air
  - Clean rooms

  **Displacement ventilation**
  - Low velocity up to 0.5 m/s
  - Temperature difference 1 to 3 K
  - No turbulence
  - Cooling only
  - Cold supplied air flows on floor and warms up from heat sources
  - Large supply air elements
Mechanical ventilation

- Air distribution

Examples of distribution elements
**Mechanical ventilation**

- **Air handling units**

  **Categories**
  - Modular units
    - AHU consists of typical chambers representing functions of air processing
      - fan chamber, heater or cooler chamber, etc.
    - chambers are mounted together – variable system
    - functional and shape variability
    - size range starts at hundreds to hundred thousand m$^3$/h
Mechanical ventilation

• **Air handling units**

**Categories**

• Compact units
  - compact units has one integrated frame in which all parts are inserted
  - units are less internally variable – usually each part has specific location
  - less shape variable
  - allows very compact AHU solution with the lowest outer dimensions and lower weight than modular units
Mechanical ventilation

• **Air handling units**

  **Positions (compact units only)**

  • sill
  • vertical
  • floor
  • under ceiling – small units, depends on weight (up to 5000 m$^3$/h)
  • window integrated – very small units (10 to 100 m$^3$/h)
# Mechanical ventilation

## Air handling units

What AHU includes?

- AHU is defined based on required air processes
- greater variety of air processes causes:
  - larger unit – dimensions, weight
  - costs – investment, operation
  - connections to other HVAC systems

<table>
<thead>
<tr>
<th>Ventilation unit</th>
<th>Warm air heating unit</th>
<th>Air conditioning unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>filters</td>
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<tr>
<td>Supply air fan</td>
<td>Supply air fan</td>
<td>Supply air fan</td>
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<tr>
<td>Exhaust air fan</td>
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<td>Exhaust air fan</td>
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<tr>
<td>Heat recovery exchangers</td>
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<tr>
<td>Fresh air heater</td>
<td>Mixing chamber</td>
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<td>Supply air heater</td>
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<td></td>
<td>Supply air cooler</td>
<td>Humidifying system</td>
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<td></td>
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<td>Water drop eliminator</td>
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<td>Dehumidifying system</td>
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</tbody>
</table>
Mechanical ventilation

- Air handling units

Ventilation unit

- Connection to heating system
- Air heater of supply air
- Heat recovery exchanger
- Filter
- Supply air
- Exhausted air
- Exhaust air fan
- Connection to electrical network
- Supply air fan
- Connection to electrical network
- Wasted air
- Filter
- Fresh air
Mechanical ventilation

- Air handling units

Warm air heating unit
Mechanical ventilation

- Air handling units

Air conditioning unit
- Connection to heating system
- Connection to cooling system
- Connection to water supply
- Humidification chamber
- Air heater of supply air
- Heat recovery exch.
- Mixing chamber
- Exhaust air fan
- Supply air fan
- Connection to electrical network
- Connection to heating system
- Connection to cooling system

Supply air
- Filter
- Exhausted air
- Connection to water supply

Exhausted air
- Filter
- Exhaust air fan
- Connection to heating system

Fresh air
- Filter

Connection to electrical network
# Mechanical ventilation

- **Air handling units**

  **Summary of AHU connection to other systems**

  - according to design air processes
  - more processes = more connections to systems

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<td>- cooler</td>
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Mechanical ventilation

• **Air handling units**

  How to define AHU?

  • Basic approach to size definition:
    • fundamental idea of AHU functions and requirements
    • design air flow rate of supply air
    • design air flow rate of fresh and circulated air

  • Detail design and certain type definition:
    • while ventilation system is mostly defined
    • air quality - filters
    • thermal and cooling outputs of heat exchangers – hxs size
    • pressure drop of ductwork system – fan performance
    • humidification requirements – hum. chamber
    • controlled air properties - control requirements
    • aj.
Local/decentralized systems

- large buildings, halls, industrial halls, warehouses, markets, etc.
- basic functions ventilation and warm air heating
- possible combination with cooling
- allows diverse conditions
- temperature stratification
- economical warm air heating up to height 8 ÷ 10 m
Mechanical ventilation

• Local/decentralized systems

Simple local unit

a – ventilation, no circulation
b – ventilation with partial circulation,
c – only circulation, temporary state

1 – damper for control of circulation (mixing),
2 – open grill for shortened indoor air access (summer),
3 – closed grill (winter),
4 – fan
Mechanical ventilation

- Local/decentralized systems

Modern units

- Pressure balanced ventilation with heat recovery
- Circulation regime – heating up
- Summer regime bypass of heat recovery
Mechanical ventilation

• Local/decentralized systems

Advantages:
• institution of local zones with different parameters (even in one air volume of a hall),
• without ductwork,
• avoid degradation of fresh air in compare to central system (in case of poor maintenance),
• local control and automation of units,
• reuse of warmer air layers bellow roof,

Disadvantages:
• higher number of smaller units (maintenance),
• more complicated connection to other systems.
Hybrid ventilation

- **Hybrid ventilation system**
- Controlled combination of mechanical and natural ventilation including also night cooling.
- Mainly $\text{CO}_2$, (relative humidity)
- All air inlets and outlets - low pressure drop
- Fans – auxiliary function
- Fans and other motorized devices – low energy input
- Heat recovery – usually not used, heat pipes heat exchangers are possible
- Simpler system, low required service and maintenance
Hybrid ventilation

- Hybrid ventilation system
- Example

Operation while natural ventilation provides sufficient pressure difference

Transient states operated by mechanical system (heat recovery)
Applications and requirements

- **Residential buildings**
  - IAQ achieved depends mainly on three criteria:
  - Exhaust of pollutions in wet rooms (bathroom, kitchen, toilets).
  - General ventilation of all rooms in the dwelling.
  - General ventilation of all rooms in the dwelling with fresh air criteria in the main room (bed and living rooms).
Applications and requirements

- Residential buildings
- Sources of pollutants:
  - Outside environment, such as climate, earth (which can provide radon);
  - Human respiration, odours;
  - Human behaviour, such as cooking, bathing, drying machine, cleaning;
  - Emissions of building materials and furniture;
  - Emissions of cleaning material;
  - Combustion appliance.

- Causes risk for:
  - The building - condensation, risk of dryness, mould growth, fungi’s, dust mites
  - For humans health and comfort
Applications and requirements

- Residential buildings
- Main pollutants causing risk to humans:
  - CO₂, water vapor, odors, germs, microorganisms, formaldehydes, VOC, CO (burning appliances!)
  - Max CO₂ concentration – Pettenkofer criteria 1200 ppm

<table>
<thead>
<tr>
<th>Country</th>
<th>Limit concentration of CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Czech Republic</td>
<td>Exterior concentration + 800 ppm (ČSN EN 15251 )</td>
</tr>
<tr>
<td>Finland</td>
<td>Exterior concentration + 1500 ppm</td>
</tr>
<tr>
<td></td>
<td>Controlled ventilation - exterior +800 ppm</td>
</tr>
<tr>
<td>Germany</td>
<td>1000 ppm</td>
</tr>
<tr>
<td>Great Britain</td>
<td>5000 ppm (Health service executive)</td>
</tr>
<tr>
<td></td>
<td>1000 ppm (CIBSE)</td>
</tr>
<tr>
<td>Norway</td>
<td>1000 ppm</td>
</tr>
<tr>
<td>Estonia</td>
<td>1000 - 1500 ppm</td>
</tr>
</tbody>
</table>
Applications and requirements

- **Residential buildings**
  - Permanent ventilation – Living room, bedrooms
    - Continual supply of fresh air
  - Occasional ventilation – Kitchen, Bathrooms, Toilets
    - Temporal exhaust during pollutants production (room is used for it’s purpose)
Applications and requirements

• **Residential buildings**

• **Suitable systems**
  - Continual mechanical exhaust of air from bathroom (and/or toilet), underpressure causes fresh air to permeate through air inlets in outer walls. Occasional ventilation – increase of fan power.
  - Hybrid ventilation – temporarily fan assisted natural ventilation
  - Balanced mechanical ventilation – AHU, heat recovery
Applications and requirements

- Residential buildings
- Inappropriate system
  - Infiltration – air do not permeates through structural joints and tight window gaps, etc.
  - Ventilation through openings – windows

- Provide continues air exchange in main rooms!
Applications and requirements

• Residential buildings
• Air change rate - ACH
  • air change per hour for each room - outside air supply to achieve a requirement in the main rooms.

\[ ACH = \frac{V_e}{room\ volume} \] \quad [\text{--}]
Applications and requirements

- **Residential buildings**
- **Requirements according to CSN EN 15251**
  - Calculate total ventilation rate for the residence based on:
    - a. Floor area, column (1).
    - b. Number of occupants or number of bedrooms, column (2) and (3).
  - Select the higher value from above a) or b) for the total ventilation rate of the residence

<table>
<thead>
<tr>
<th>Category</th>
<th>Air change rate a</th>
<th>Living room and bedrooms, mainly outdoor air flow</th>
<th>Exhaust air flow, l/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>l/s.m²</td>
<td>ach</td>
<td>l/s, pers</td>
</tr>
<tr>
<td>I</td>
<td>0.49</td>
<td>0.7</td>
<td>10</td>
</tr>
<tr>
<td>II</td>
<td>0.42</td>
<td>0.6</td>
<td>7</td>
</tr>
<tr>
<td>III</td>
<td>0.35</td>
<td>0.5</td>
<td>4</td>
</tr>
</tbody>
</table>

This is Table B.4 from CSN EN 15251
Applications and requirements

- Residential buildings
- Requirements according to CSN EN 15251
  - Adjust the exhaust air flows from the kitchen, bathroom and toilets, columns (4) accordingly:
    - a. in residences with small floor area exhaust air flow rates become smaller;
    - b. in large residences higher.
  - Outdoor air should be supplied primarily to living rooms and bedrooms

<table>
<thead>
<tr>
<th>Category</th>
<th>Air change rate ( \text{ach} )</th>
<th>Living room and bedrooms, mainly outdoor air flow</th>
<th>Exhaust air flow, l/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \text{l/s, m}^2 )</td>
<td>( \text{l/s, pers}^b )</td>
<td>( \text{l/s/m}^2 )</td>
</tr>
<tr>
<td>I</td>
<td>0.49 0.7</td>
<td>10 1.4</td>
<td>28</td>
</tr>
<tr>
<td>II</td>
<td>0.42 0.6</td>
<td>7 1.0</td>
<td>20</td>
</tr>
<tr>
<td>III</td>
<td>0.35 0.5</td>
<td>4 0.6</td>
<td>14</td>
</tr>
</tbody>
</table>

*This is Table B.4 from CSN EN 15251*
Applications and requirements

- **Residential buildings**
- **Req. according to National Amendment to CSN EN 15665**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Permanent ventilation (outside air supply)</th>
<th>Occasional ventilation (exhaust air)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirement</td>
<td>ACH ([\text{h}^{-1}])</td>
<td>Amount of fresh air per person ([\text{m}^{3}/(h\cdot\text{per})])</td>
</tr>
<tr>
<td>Minimum value</td>
<td>0,3</td>
<td>15</td>
</tr>
<tr>
<td>Recommended value</td>
<td>0,5</td>
<td>25</td>
</tr>
</tbody>
</table>
Applications and requirements

- **Residential buildings**
- **Suggestions to design**
  - Outdoor air should be supplied primarily to living rooms and bedrooms.
    - Air supply inlets
    - Location obstructing a cold air draft – behind/close to heating body
  - Exhaust air should be withdrawn from bathroom and toilet (kitchen)
  - Kitchen – a hood above cooker, exhaust to exterior. Circulation hoods only in case of AHU mechanical ventilation
  - Mechanical system with AHU – heat recovery
  - System HASTO respect Fire Codes and regulations!
  - Noise – from exterior, from system
  - Gas and other combustible appliances – air pressure, combustion air
Applications and requirements

- Non-residential buildings
- Requirements according to CSN EN 15251
- Total ventilation rate for a room:
  - ventilation rate for occupancy per person $q_p$, l/(s.person)
  - ventilation rate for emissions from building $q_B$, l/(s.m$^2$)

$$q_{tot} = n \cdot q_p + A \cdot q_B$$

$n$ - design value for the number of the persons in the room
$A$ - room floor area, m$^2$

This is Table B.1 from CSN EN 15251
Applications and requirements

- Non-residential buildings
- Requirements according to Czech Government regulation
  - All values based on humans activity
  - Minimum amount of fresh air
    - 50 m$^3$/h.person - light labor, mostly sitting
    - 70 m$^3$/h.person - medium labor, walking, (e.g. assembly line)
    - 90 m$^3$/h.person – heavy labor (e.g. mining)
    - +10 m$^3$/h.person if smoking is allowed
  - Min 15 % of supply air (air conditioning systems)
  - Efficient ventilation – avoid pollutants transfer between rooms
Applications and requirements

- **Office buildings**
- **Main pollutants:**
  - CO$_2$, water vapor, odors, germs, microorganisms, formaldehydes, VOC,
  - Heat load from office equipment
- SBS – sick building syndrome, physical symptoms without clearly identifiable causes. Some of these symptoms include dry mucous membranes and eye, nose, and throat irritation.
  - HVAC systems that are improperly operated or maintained.
- Working environment – basic criteria are usually defined in a law
Applications and requirements

- **Office buildings**
- **Approach to IAQ:**
  - Control of pollutants at the source is the most effective means of promoting indoor air quality.
  - An adequate supply of outdoor air is essential to diluting indoor pollutants.
  - In the absence of adequate ventilation, irritating or harmful contaminants can build up, causing worker discomfort, health problems and reduced performance levels.
  - Air cleaning is an important part of an HVAC system, but is not a substitute for source control or ventilation.
Applications and requirements

- **Office buildings**
- **Requirements according to Czech Government regulation**
  - All values based on humans activity
  - Minimum amount of fresh air
    - 50 m$^3$/h.person - light labor, mostly sitting
    - +10 m$^3$/h.person if smoking is allowed
    - Min 15 % of supply air (air conditioning systems)
  - Efficient ventilation – avoid pollutants transfer between rooms
Applications and requirements

- **Office buildings**
- **Suitable systems**
  - Natural ventilation + hybrid ventilation, passive and night cooling
  - Mechanical ventilation
    - Most common
    - Often together with air-conditioning
    - Precise control of IAQ parameters
    - Provide ventilation rate in conformity with local needs.
Applications and requirements

- **Office buildings**
- **Suitable systems**
- **Principle of mechanical ventilation system**

![Diagram of office ventilation systems]

- **Centralized AHU**
- **Fire ventilation**
- **Smoke and heat ventilation**
- **Independent exhaust system**

**Applications and requirements**

- An office
- Corridor
- Toilets
Applications and requirements

- **Public garages**
  - Main pollutant – CO
  - Natural ventilation – possible for floors above ground, down to 1st ground floor
    - Permanent openings – 0.15 m² per parking place
  - Mechanical ventilation – all other cases,
    - underpressure only, independent system from other
    - Calculation of CO production according to car number, motion, route from entrance to parking place
    - Max CO concentration 87 ppm (Czech standard), 50 – 100 ppm (Austrian, German standard)
  - Czech standard require 300 m³/h per parking place (too high)
  - Austrian standard calculate approx. 100 – 200 m³/h (ÖNORM H 6003)
Moist air

- **Definition of moist air**
- What is moist (humid) air?
  - mixture of dry air and water
  - homogenous mixture – dry air and low-pressure water vapour
  - heterogeneous mixture – dry air and:
    - water vapour plus liquid water particles (droplets, rain, etc.)
    - water vapour plus solid water particles (ice, snow etc.)
    - water vapour plus combination of liquid and solid particles
Moist air

- **Perfect gas equation of state**
- dry air characteristics are close to ideal gas
- for proper determination of moist air are used perfect gas relationships, this simplification is sufficiently accurate for most engineering calculations.

\[ p_d V = m_d R_d T \]

\[ p_w V = m_w R_w T \]

for the mixture

\[ p.V = m.R_{dw}.T \]

\[ m = m_d + m_w \]

\[ R_{dw} = \frac{m_d}{m} R_d + \frac{m_w}{m} R_w \]

\( d, \text{ d.a.} \) – dry air; \( w, \text{ w.v.} \) – water vapour; \( m.a. \) – moist air (also no subscript)

- \( p_d \) – partial pressure of dry air [Pa]
- \( p_w \) – partial pressure of water vapour [Pa]
- \( V \) – volume of mixture [m³]
- \( T \) – absolute temperature [K], temperature of mixture

\( m_d \) – mass of dry air [kg]

\( m_w \) – mass of water vapour [kg]

\( R_d \) – gas constant of dry air; 287,11 [J/kgK]

\( R_w \) – gas constant of water vapour; 461,5 [J/kgK]
Moist air

- **Dalton’s law**

  total pressure of mixture is given as sum of partial pressures of its components

\[ p = p_d + p_w \quad [\text{Pa}] \]

\( p_d \) – partial pressure of dry air [Pa]
\( p_w \) – partial pressure of water vapour [Pa]

**Saturation water pressure** \( p_w^* \)

The amount of water vapour in moist air is variable, from zero up to maximum at saturation. Saturation water pressure is function only of temperature and is the ultimate water pressure.

\( p_w < p_w^* \) – non-saturated moist air

\( p_w = p_w^* \) – saturated moist air

\( p_w > p_w^* \) – supersaturated moist air – heterogeneous mixture
Moist air

- Thermodynamics properties of moist air
- Two independent properties plus barometric pressure are required to establish the thermodynamic state.
- Necessary for determination of all moist air processes.
Moist air

- Thermodynamics properties of moist air
- TEMPERATURE
- **Dry air temperature** $t$ [°C]
- **Dew point temperature** $t_d$ [°C]
  - The dew point temperature is the temperature of moist air at the saturation with the same pressure and moisture content $x$ as the given state.
- **Thermodynamics wet-bulb temperature** $t^*, t_{WB}$ [°C]
  - The moist air temperature, at which water evaporating into moist air, can bring mixture to the saturation adiabatically. The lowest temperature that is possible to reach during adiabatic cooling of air.
Moist air

- Thermodynamics properties of moist air
- HUMIDITY

- **Moisture content** $x$ [kg/kg d.a., g/kg d.a.]
  - defined as the ratio of the mass of water vapour $m_w$ to the mass of dry air $m_d$

  $$x = \frac{m_w}{m_d} = 0.622 \frac{p_w}{p - p_w}$$

- **Relative humidity** $rh$ [-; %]
  - defined as the ratio of the partial pressure of water vapour in the moist air to the saturation vapour pressure at the same temperature.
  - express spacing (“distance”) to saturation state

  $$rh = \frac{p_w}{p_{w}}$$
Moist air

- Thermodynamics properties of moist air
- HEAT CONTENT, SPECIFIC HEAT
- Specific enthalpy $h$ [J/kg d.a.]
  - defined as sum of partial enthalpies of the components

$$h = h_d + x.h_w = c_{p,d}.t + x.(c_{p,w}.t + l_{2,3})$$

$c_{p,d}$ – specific heat of dry air; 1 010 [J/kgK]
$c_{p,w}$ – specific heat of water vapour; 1 850 [J/kgK]
t – temperature of state [°C]
l$_{2,3}$ – latent heat of water; 2 500 000 [J/kg] (2→3 means phase change from liquid to vapour)
Moist air

- Mollier’s chart (psychometric chart)
Moist air

- Mollier’s chart (psychometric chart)
- Definition of dew point and wet bulb temperature
Moist air

- Mollier’s chart (psychometric chart)
- Heat exchange during process
  - Total heat = Sensible and latent heat
    \[ \vartheta = \frac{Q_C}{Q_S} = \frac{c_p \Delta t}{\Delta h} \]

\[ Q_T = Q_S + Q_L \]

- Sensible heat
  \[ Q_S = m_a (h_1' - h_1) \]

- Latent heat
  \[ Q_L = m_a (h_2 - h_1') \]
Moist air

- Mollier’s chart (psychometric chart)
- Heating

\[ x_1 = x_2, \quad t_2 > t_1, \quad rh_2 < rh_1, \quad h_2 > h_1 \]

Thermal output

\[ Q = m_a.(h_1 - h_2) \quad [W] \]
Mollier’s chart (psychometric chart)

Cooling

<table>
<thead>
<tr>
<th>Sensible cooling</th>
<th>Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_1 = x_2$, $t_2 &lt; t_1$, $j_2 &gt; j_1$, $h_2 &lt; h_1$</td>
<td>$x_1 &gt; x_2$, $t_2 &lt; t_1$, $j_2 &gt; j_1$, $h_2 &lt; h_1$</td>
</tr>
</tbody>
</table>

Thermal output

$$Q = m_a(h_1 - h_2) \quad [W]$$

Amount of condensing water vapor

$$m_w = m_a(x_1 - x_2) \quad [kg/s]$$
Moist air

- Mollier’s chart (psychometric chart)
- Humidification

- Spray chamber, steam injection

\[
m_w = m_a (x_2 - x_1) \quad \text{[kg/s]}
\]

Spray of water
\[x_1 < x_2, t_2 < t_1, j_2 > j_1, h_2 = h_1\]

Steam injection
\[x_1 < x_2, t_2 = t_1, j_2 > j_1, h_2 > h_1\]
Moist air

- Mollier’s chart (psychometric chart)
- Air mixing

\[
\frac{m_{a1}}{m_{a2}} = \frac{h_3 - h_2}{h_1 - h_3} = \frac{x_3 - x_2}{x_1 - x_3} \Rightarrow \frac{h_3 - h_2}{x_3 - x_2} = \frac{h_1 - h_3}{x_1 - x_3} = \delta_{13} = \delta_{23}
\]
Thank you for your attention!

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