Ventilation strategies for good indoor climate and energy performance in schools

Air distribution and temperature control in classrooms

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Introduction

• Many studies have reported poor ventilation and thermal comfort in schools worldwide

• Recent studies have investigated the linkage of ventilation rates and temperature to objectively measured school work performance:
  – Norwegian study (Myhrvold and Olesen 1997)
  – U.S. study (Shaughnessy et al. 2006)
  – Japanese study (Ito et al. 2006 and Murakami et al. 2006)
  – Danish study (Wargocki & Wyon 2006)
  – Dutch study (TNO 2006)
  – UK intervention (Bakó-Biró et al. 2007)

• All these studies have quite similar outcome indicating:
  1. the need for higher ventilation rates than used today, as positive effects are shown at least up to 10 L/s per person (about 5 L/s per floor m²)
  2. and the need for more strict temperature control than commonly used, as temperature increase has lead to performance decrement of about 2% per 1°C
Normal office situation

15 m² per person

(Thanks to C. Derikx and Atze Boestra)
Translated to school situation...

2–3 m² per person
Contents of the presentation

• What should be done to achieve healthy and productive indoor environment quality (IEQ) in classrooms?
• “Ventilate well and strictly control the temperature” IEQ differs quite from IEQ in a typical school with ventilation rate ≤4 L/s per person and no special attention to temperature control
• Alternative solutions for ventilation systems
• Main IEQ-problems in schools
• Measurement and simulation results

• **Special attention to air distribution solutions capable for low air velocities and supply air temperature at high ventilation rates:**
  – air distribution measurements to assess do we have presently available cost efficient solutions for good IEQ
  – all studied cases without mechanical cooling in common classrooms
In office buildings we use a lot of effort for good IEQ
And we accept the need of HVAC as essential…
In schools we often discuss is the ventilation really needed…

- We often believe that window opening compensates ventilation,
- or natural ventilation does the task,
- or very simple mechanical solutions are enough…
- Such discussions are typically held in air conditioned rooms…
Basic question of IEQ: how to manage temperature and air distribution in classrooms with highly varying loads?

South classroom:
30 students + solar radiation = cooling need

North classroom,
15 students: heating need

The same system should serve all classrooms

No air conditioning, cost efficient ventilation system:
- Constant ventilation or demand controlled ventilation
- Supply air temperature compensation (cooling with outdoor air)
Control in AC-system

In AC system:
- Room controller for cooling and room conditioning device
- Thermostat for heating and radiator
- CAV ventilation very often

The room

Air-handling unit
Air cooled condenser
Water chiller
District heating supply
District heating return
District heating substation

Chilled water tank
Chilled beam
Radiator and thermostatic valve

Room controller for cooling and room conditioning device
Control in a simple ventilation and heating system

- Thermostat/radiator in the heating mode
- Supply air temperature and air flow rate control for cooling (with outdoor air + night ventilative cooling) – T and CO₂ controlled ventilation (DCV)
Alternatives for ventilation systems

- Natural ventilation – was used before mechanical and hybrid systems
- Mechanical exhaust ventilation – cannot be used in cold climate in classrooms due to draft (as well as noise, dust, PM$_{2.5}$)
- **Mechanical supply and exhaust ventilation (balanced ventilation) with heat recovery:**
  - Constant air volume (CAV) system
  - Demand controlled ventilation (DCV or VAV)
  - Low pressure DCV + night time ventilative cooling
- Hybrid ventilation system:
  - Fan assisted natural ventilation systems
  - Mechanical supply and exhaust ventilation + natural ventilation (double system)
  - Stack and wind assisted mechanical ventilation system (more or less the same as the low pressure system)
- No AC (air conditioning) in common classrooms in cold climate (computer classrooms/server rooms need AC)
Energy performance

- EP-target values are as essential as IEQ-target values, i.e. design objective
- Good IEQ and EP are not conflicting requirements

- Good energy performance can be ensured by:
  - **Heat recovery** – exhaust air heats up supply air in the heat exchanger
  - **Demand controlled ventilation** – shorter operation time and lower fan speeds
  - **Low pressure design and high efficiency components** (fans, pumps etc.) – less electricity for running of ventilation
  - As well as overall design quality regarding **solar protection, windows and thermal insulation**, building shape etc.
Examples of ventilation systems
Fan assisted natural ventilation system, Ruusutorppa school, Espoo, Finland

- Fan assisted natural ventilation
- Supply air fan operates when needed
- No exhaust fans, no heat recovery
- Cold climate => preheated and filtered supply air
- Cross ventilation may be used between lessons
Ventilation principle in Ruusutorppa school, Helsinki
Main problems in Ruusutorppa school

- Balancing and tuning of the system took about 1.5 years
- Backflow due to height difference of exhaust chimneys – was fixed with outdoor temperature controlled dampers (damper position in the bottom end allowed chimneys to cool down)
- Connection to the main building problematic – opening the door might turn natural air flows due to negative pressure in the hall; solution: the hall was balanced and the doors kept closed
- Not as good performance as in common mechanical system
Examples of ventilation systems
Hybrid ventilation, Mediå School, Grong, Norway

Architects: Letnes Arkitekter A/S

(Thanks to Per Heiselberg)
Mediå Primary School

• Typical hybrid ventilation system in Nordic countries
• Architect driven design, from natural to mechanical ventilation
• Demonstrates the evolution of these systems:
  – First systems were natural ventilation systems (and failed)
  – The last ones are stack and wind assisted low pressure mechanical systems with heat recovery

• Brief description of ventilation strategy
  – The hybrid ventilation system (Stack and wind assisted mechanical ventilation) is a balanced, low-pressure mechanical system with both central air supply and exhaust. The system includes filtering, heat recovery, preheating in underground culvert and heating. The system is demand controlled by CO$_2$ sensors in each classroom.
Air Supply System
Air Exhaust System

- More complicated systems than common mechanical ones
- Less controlled air distribution and less stable airflows in classrooms
- Lower fan energy use, but higher heating energy use due to less effective heat recovery
Poikkilaakso school, Helsinki, Finland

- One of modern schools in Helsinki, completed 2001
- Well designed and construction integrated mechanical ventilation system – no compromises between indoor climate and architecture
Poikkilaakso school, ventilation concept

• low pressure mechanical ventilation with heat recovery
• the building serves as an air flow route => no visible ducts inside
• central spaces ventilated with transfer air from classrooms where the CO\textsubscript{2} sensors are located

![Diagram of ventilation system]

- Large exhaust air ducts 2.5 m by 1.6 m on the roof
- Large supply air ducts 2.0 m by 1.6 m on the roof
- Air extract in the central hall
- Transfer air
- Vertical ducts, 200 mm
Supply air ducts in Poikkilaakso school

- No visible equipment
- Very quiet operation

**Horizontal ducts (2 m by 1.6 m) are part of the roof structure**

**Vertical ducts from the roof to the classrooms**

**Displacement air supply**
• Silent and invisible mechanical ventilation system – many users have pointed out that the building has a feeling of natural ventilation but also superior air quality
What are most common IEQ-problems and complaints in schools?
Most common IEQ-problems in schools 2007 vs. 1996

460 schools, Finland (Putus & Rimpelä 2007)

1164 schools, Finland (Kurnitski et al. 1996)
IEQ-problems according to ventilation system
(Kurnitski et al. 1996)

- Inadequate ventilation, winter: 62%
- Inadequate ventilation, spring/autumn: 50%
- Draught, winter: 52%
- Draught, spring/autumn: 28%
- Stuffy air, winter: 43%
- Stuffy air, spring/autumn: 30%
- Unpleasant odors, winter: 23%
- Unpleasant odors, spring/autumn: 14%

Weekly prevalence [%]

- Natural ventilation
- Mechanical exhaust
- Mechanical supply and exhaust
Ventilation rates [l/s, person; m²]

- Average value of all measurements: 3.5 [l/s, person] 1061 [l/s m²]
- Natural ventilation: 1.2 [l/s, person] 0.4 [l/s m²]
- Mechanical exhaust: 2.3 [l/s, person] 0.9 [l/s m²]
- Mechanical supply and exhaust: 5.5 [l/s, person] 1.9 [l/s m²] 836 [ppm]

CO₂ concentrations [ppm]

- Average value of all measurements: 1285 [ppm]
- Natural ventilation: 1181 [ppm]

(Kurnitski et al. 1996)
Outcome of Finnish school studies

- Most common IEQ-problems in schools:
  1. Inadequate ventilation (41%)
  2. Room temperature (27%)
  3. Lack of space (25%)

- Much more problems in natural and mechanical exhaust ventilation relative to mechanical supply and exhaust ventilation
Situation in 11 Dutch schools

(van Dijken 2004)
Room temperature and CO₂ performance (Kurnitski et al. 2008)

• Sample of schools:
  – 6 schools 1910-1960
  – 10 schools 1960-1970
  – 10 schools 1970-1980
  – 6 schools 2000-

• Room temperature data during one week in May (21-25.5.2007, mean outdoor temperature 13°C) from 63 classrooms. Data from the school time, from 8:00 to 14:00 on week-days.
Temperature fluctuations during one week

- only occupied hours from 8:00 to 14:00 from Monday to Friday considered (21-25.5.2007)
- results from three classrooms represent 10th, 50th (median) and 90th percentile of the weekly temperature difference
- the temperature variation is from 1 to 3 °C during couple of hours

Good design, stable temp.
Outdoor temperature dependency – typical temperature patterns in classrooms

- $y = 0.02x + 21.66$
  - $R^2 = 0.01$

- $y = 0.09x + 20.25$
  - $R^2 = 0.13$

- $y = 0.17x + 19.89$
  - $R^2 = 0.36$

- $y = 0.02x^2 - 0.28x + 22.70$
  - $R^2 = 0.54$
Temperature in August (warm period)  
14-30.8.2007, just after summer holidays

![Graph showing the relationship between outdoor and indoor temperature with equations and R² values.]

- **Indoor temperature, °C**
  - Equation: $y = 0.39x + 18.92$
  - $R^2 = 0.84$

- **Indoor temperature, °C**
  - Equation: $y = 0.23x + 20.96$
  - $R^2 = 0.79$
Temperature simulations

- 2 or 6 classroom simulations with part load vs. full load occupancy
- Determining air flow rate and the control curve needed for the temperature control (no cooling!)
- CAV vs. DCV and heating season vs. summer performance
• Two ventilation rates, 6 L/s per person, 180 L/s per classroom in total or 10 L/s per person, 300 L/s per classroom in total.
• For both rates CAV system and DCV system with CO₂ and temperature control was simulated. DCV system had two air flow steps, 100 % and 40% of total airflow.
Results, heating season

- Excess degree-hours over 22°C should be less than 100°Ch
- (excess of 2°C during 5 hours is 2*5=10°Ch)
Which system works in all conditions?

<table>
<thead>
<tr>
<th>Sum of degree hours in weekdays at 08:00-15:00, °Ch</th>
<th>Heating season</th>
<th>Summer period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation system and classroom orientation</td>
<td>Over 22°C</td>
<td>Below 20°C</td>
</tr>
<tr>
<td></td>
<td>Over 25°C</td>
<td>Below 22°C</td>
</tr>
<tr>
<td></td>
<td>Criterion, °Ch</td>
<td>100</td>
</tr>
<tr>
<td><strong>CAV</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>South classroom 300 L/s</td>
<td>181</td>
<td>0</td>
</tr>
<tr>
<td>South classroom 300 L/s, with solar protection glasses</td>
<td>92</td>
<td>0</td>
</tr>
<tr>
<td>North classroom 300 L/s, with low occupancy</td>
<td>0</td>
<td>56</td>
</tr>
<tr>
<td><strong>CAV + heating coil in supply duct for each classroom</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>South classroom 300 L/s, with solar protection glasses</td>
<td>96</td>
<td>0</td>
</tr>
<tr>
<td>North classroom 300 L/s, with low occupancy</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>DCV 40-100%</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>South classroom 120-300 L/s, with solar protection glasses</td>
<td>99</td>
<td>0</td>
</tr>
<tr>
<td>North classroom 120-300 L/s, with low occupancy</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>DCV 40-100% + night ventilative cooling</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>South classroom 120-300 L/s, with solar protection glasses</td>
<td>99</td>
<td>0</td>
</tr>
<tr>
<td>North classroom 120-300 L/s, with low occupancy</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Effective temperature control was possible by:

1. Supply air temperature going down to 14-15 °C with free cooling
2. Demand controlled ventilation (T and CO₂ control to avoid excessive cooling in North facade classrooms at part load)
3. Ventilation rate of 10 L/s per person (5 L/s per m²)

![Supply air temperature control curve](image)
Which air distribution solutions are capable for 15°C supply air temperature and 5 L/s per m² airflow rate without draft?
Many solutions for air distribution

- Intake air (not in use any more)
- Wall diffusers (ref. case)
- Ceiling or duct diffusers (many available options)
- Displacement ventilation
How about suitable air distribution solutions for 15°C/300 L/s supply air?

- Air velocity, room temperature and CO₂ measurements in 6 schools
- All schools relatively new or renovated, having modern mechanical supply and exhaust ventilation systems with ventilation rates, corresponding at least to Finnish minimum code requirements
- Air distribution in schools A to F:

  A  Perforated duct

  B  Wall diffusers (ref.)
C
Duct diffusers

D
Ceiling diffusers

E
Duct diffusers

F
Displacement diffusers
Results – airflow rates

<table>
<thead>
<tr>
<th>School</th>
<th>Occupancy, pers.</th>
<th>Supply air flow rate, L/s per pers.</th>
<th>Supply air flow rate, L/s</th>
<th>Design supply air flow rate, L/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>20</td>
<td>7</td>
<td>138</td>
<td>210/150/90</td>
</tr>
<tr>
<td>B</td>
<td>27</td>
<td>7</td>
<td>186</td>
<td>210/30</td>
</tr>
<tr>
<td>C</td>
<td>22</td>
<td>6</td>
<td>136</td>
<td>175</td>
</tr>
<tr>
<td>D</td>
<td>20-25</td>
<td>6.8-8.2</td>
<td>168</td>
<td>170</td>
</tr>
<tr>
<td>E</td>
<td>348</td>
<td>348</td>
<td>340</td>
<td>340</td>
</tr>
<tr>
<td>F</td>
<td></td>
<td>180</td>
<td>180</td>
<td>180</td>
</tr>
</tbody>
</table>

- **E** was a new school having almost doubled supply airflow rate (design value of 12 l/s per person, 340 l/s in total) and also other target values of the highest indoor climate class
- Schools **A** and **B** had CO₂- and CO₂& temperature controlled ventilation with 3 and 2 airflow steps respectively
- CAV systems in other schools
- **A** to **D** had a constant supply air temperature and in **E** and **F** supply air temperature was controlled according to exhaust air temperature
Room temperature & CO₂ measurements/
heating season

- One week in early spring, outdoor temperature between 9…12 °C
- Results from the school time only, from 8.00 to 15.00 on week-days
Air velocity results

- Air velocity measurements were done from the locations selected with the smoke test (i.e. identifying the locations with highest air movement)
- Maximum velocities from the occupied zone at three measured heights

<table>
<thead>
<tr>
<th>Meas. point</th>
<th>Air Velocity, m/s</th>
<th>Operative temperature, °C</th>
<th>Supply air temperature, °C</th>
<th>DT, room - supply air temperature,</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, perforated ducts, 138 L/s</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.25</td>
<td>0.06</td>
<td>0.13</td>
<td>24.7</td>
</tr>
<tr>
<td>6</td>
<td>0.03</td>
<td>0.13</td>
<td>0.20</td>
<td>24.9</td>
</tr>
<tr>
<td>9</td>
<td>0.18</td>
<td>0.29</td>
<td>0.08</td>
<td>24.6</td>
</tr>
<tr>
<td>Meas. point</td>
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<td></td>
<td>Measurement height</td>
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<td></td>
<td>0.1m</td>
<td>1.10m</td>
<td>1.80m</td>
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<tr>
<td>B, wall diffusers, 186 L/s</td>
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<tr>
<td>1</td>
<td>0.18</td>
<td><strong>0.43</strong></td>
<td>0.15</td>
<td>22.6</td>
</tr>
<tr>
<td>2</td>
<td><strong>0.30</strong></td>
<td>0.09</td>
<td>0.06</td>
<td>22.7</td>
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<td>Meas. point</td>
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<tr>
<td>C, duct diffusers, 136 L/s</td>
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<tr>
<td>1</td>
<td>0.10</td>
<td>0.07</td>
<td>0.16</td>
<td>22.6</td>
</tr>
<tr>
<td>Meas. point</td>
<td>Air Velocity, m/s</td>
<td>Operative temperature, °C</td>
<td>Supply air temperature, °C</td>
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<td>0.1m 1.10m 1.80m</td>
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<tr>
<td>D, ceiling diffusers, 168 L/s</td>
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<tr>
<td>4</td>
<td>0.03 0.05 0.14</td>
<td>21.0</td>
<td>19.4</td>
<td>1.6</td>
</tr>
<tr>
<td>7</td>
<td><strong>0.11</strong> 0.06 0.06</td>
<td>20.7</td>
<td>19.4</td>
<td>1.3</td>
</tr>
<tr>
<td>8</td>
<td>0.08 <strong>0.09</strong> 0.07</td>
<td>20.7</td>
<td>19.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Meas. point</td>
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<tr>
<td>E, duct diffusers 348 l/s</td>
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<tr>
<td>3</td>
<td>0.17</td>
<td>0.09</td>
<td>0.09</td>
<td>21.7</td>
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<tr>
<td>7</td>
<td>0.07</td>
<td>0.11</td>
<td>0.13</td>
<td>21.4</td>
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<tr>
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<td>F, displacement diffusers 180 l/s</td>
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<tr>
<td>4</td>
<td>0.28</td>
<td>-</td>
<td>-</td>
<td>3</td>
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</tbody>
</table>
Conclusions 1/2

• IEQ-problems in existing schools are typical (shown in many studies):
  – Ventilation rates
  – Temperature control
  – Air distribution
  – …

• Healthy, comfortable and productive IEQ can be achieved only through the performance based design:
  – Specify IEQ and EP target values/design values
  – Simulate temperatures with part- and full-load conditions
  – Check air distribution – reserve enough pressure for supply air device, all other ductwork can be low-pressure one

• Relevant standards and national guidelines can highly be recommended for the target values: EN15251, EN13779 and CR1752

• Solid evidence showing that mechanical ventilation systems are cost efficient, and provide good indoor climate and energy performance
Conclusions 2/2

- It was demonstrated that high airflow rates up to 12 L/s, pers, 6 L/s, m² were achieved without draft with cost-efficient solutions.
- Remarkable differences between air distribution schemes:
  - Duct and ceiling diffusers showed good performance with a maximum velocity less than 0.2 m/s.
  - Wall diffusers were clearly not suitable for classrooms due to high velocities up to 0.43 m/s.
  - Displacement ventilation was sensitive to supply air temperature.
- Measurements indicated room temperature control problems (poor temperature control of supply air and low airflow rates).
- Supply air flow rates up to 10 L/s per person with DCV and cool supply air down to 14–15 °C with free cooling was needed for room temperature control (no mechanical cooling in common classrooms).
- There do exist solutions for healthy and productive classroom ventilation and application of these should be lead to substantial increase in student performance.