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)
  - 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

• 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

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

The same system should serve all classrooms
Control in AC-system

In AC system:
- Room controller for cooling and room conditioning device
- Thermostat for heating and radiator
- CAV ventilation very often
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 is 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
Mediå School, Grong, Norway

Architects: Letnes Arkitekter A/S
• Typical hybrid ventilation system in Nordic countries
• 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
Fan assisted system in Ruusutorpppa 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
Poikkilaakso school, Helsinki, Finland

- 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 CO₂ sensors are located

![Diagram of ventilation system](image-url)
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
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)

- Unpleasant odors, spring/autumn
- Stuffy air, spring/autumn
- Draught, spring/autumn
- Inadequate ventilation, winter
- Inadequate ventilation, spring/autumn
- Draught, winter
- Stuffy air, winter
- Stuffy air, spring/autumn
- Unpleasant odors, winter
- Unpleasant odors, spring/autumn
Ventilation rates [l/s,pers;m²]

- Average value of all measurements: 3.5 [l/s,pers;m²]
- Natural ventilation: 1.6 [l/s,pers;m²]
- Mechanical exhaust: 2.3 [l/s,pers;m²]
- Mechanical supply and exhaust: 5.5 [l/s,pers;m²]

CO₂ concentrations [ppm]

- Average value of all measurements: 1061 [ppm]
- Natural ventilation: 1285 [ppm]
- Mechanical exhaust: 1181 [ppm]
- Mechanical supply and exhaust: 836 [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
Room temperature and CO₂ performance
(Kurnitski et al. 2008)

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

1. $y = 0.02x + 21.66$
   $R^2 = 0.01$

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

3. $y = 0.17x + 19.89$
   $R^2 = 0.36$

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

\[ y = 0.39x + 18.92 \]
\[ R^2 = 0.84 \]

\[ y = 0.23x + 20.96 \]
\[ R^2 = 0.79 \]
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

[Diagram showing number of persons over time for different classrooms with South and North locations]
Results, summer

- 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 CO$_2$ 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°CCh
- (excess of 2°C during 5 hours is 2*5=10°CCh)
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></td>
<td>Over 22 °C</td>
<td>Below 20 °C</td>
</tr>
<tr>
<td>Ventilation system and classroom orientation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Criterion, °Ch</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

**CAV**
- South classroom 300 L/s
  - 181 0 200 118
- South classroom 300 L/s, with solar protection glasses
  - 92 0 116 47
- North classroom 300 L/s, with low occupancy
  - 0 56 11 212

**CAV + heating coil in supply duct for each classroom**
- South classroom 300 L/s, with solar protection glasses
  - 96 0 114 70
- North classroom 300 L/s, with low occupancy
  - 0 0 11 106

**DCV 40-100%**
- South classroom 120-300 L/s, with solar protection glasses
  - 99 0 162 15
- North classroom 120-300 L/s, with low occupancy
  - 0 0 7 105

**DCV 40-100% + night ventilative cooling**
- South classroom 120-300 L/s, with solar protection glasses
  - 99 0 83 31
- North classroom 120-300 L/s, with low occupancy
  - 0 0 4 114
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)
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></td>
<td></td>
<td>348</td>
<td>340</td>
</tr>
<tr>
<td>F</td>
<td></td>
<td></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 & CO$_2$ 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, duct diffusers, 138 L/s</td>
<td></td>
<td></td>
<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>
<td>Air Velocity, m/s</td>
<td>Operative temperature, °C</td>
<td>Supply air temperature, °C</td>
<td>DT, room - supply air temperature,</td>
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</tr>
<tr>
<td></td>
<td>Measurement height</td>
<td>0.1m</td>
<td>1.10m</td>
<td>1.80m</td>
</tr>
<tr>
<td>B, wall diffusers, 186 L/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.18</td>
<td>0.43</td>
<td>0.15</td>
<td>22.6</td>
</tr>
<tr>
<td>2</td>
<td>0.30</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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<td>-------------</td>
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<tr>
<td>C, duct diffusers, 136 L/s</td>
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<td></td>
<td></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>
<td>DT, room supply air temperature,</td>
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<td>-------------</td>
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<td>--------------------------------</td>
</tr>
<tr>
<td>D, ceiling diffusers, 168 L/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.03</td>
<td>0.05</td>
<td>0.14</td>
<td>21.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.11</td>
<td>0.06</td>
<td>0.06</td>
<td>20.7</td>
</tr>
<tr>
<td>8</td>
<td>0.08</td>
<td>0.09</td>
<td>0.07</td>
<td>20.7</td>
</tr>
</tbody>
</table>
### Table: Measurement Data

<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></td>
<td>0.1m</td>
<td>1.10m</td>
<td>1.80m</td>
<td></td>
</tr>
<tr>
<td><strong>E, duct diffusers 348 l/s</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.17</td>
<td>0.09</td>
<td>0.09</td>
<td>21.7</td>
</tr>
<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>
<td><strong>E, duct diffusers 348 l/s</strong></td>
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<tr>
<td>7</td>
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<td>0.14</td>
<td>0.19</td>
<td>21.9</td>
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<td>Air Velocity, m/s</td>
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</tr>
<tr>
<td>F, displacement diffusers 180 l/s</td>
<td>0.28</td>
<td>-</td>
<td>-</td>
<td>3</td>
</tr>
</tbody>
</table>
Conclusions 1/2

- Typical IEQ-problems are shown in almost every school study:
  - Ventilation rates
  - Temperature control
  - Air distribution
  - ...

- Healthy, comfortable and productive IEQ can be achieved only through the objective based design:
  - Specify IEQ and EP target values/design values (set the targets first and when discuss the ventilation system type…)
  - 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
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