Ventilation strategies for good indoor air quality and energy efficiency

O. Seppänen
Helsinki University of Technology, Finland

Abstract
The requirements for good indoor air quality and energy efficiency have often been considered to conflict with each other, however, buildings with low energy consumption in Europe seem to have also a lower rate of building related health symptoms. This indicates the importance of proper design, installation and qualified, well trained operational personnel, who understands both the requirements for good indoor air quality and energy efficiency. Several strategies for ventilation are described in the paper by which at the same level of energy consumption, the indoor air quality is improved or at the same level of indoor air quality, the energy consumption is reduced. These include the following: source control and efficient removal of contaminants, proper location of fresh air intakes, cleaning of intake air, efficient air distribution in rooms with improved ventilation efficiency, heat recovery from exhaust air, control of ventilation rates by air quality, correct balancing of air flows, controlling of indoor climate locally, night time ventilative cooling.

1. Introduction
Ventilation has an important role in maintaining good indoor air quality. Ventilation air transfers efficiently the indoor pollutants from a building. If ventilation rates are reduced, energy is saved but at the same time indoor air quality deteriorates. Seppänen and Fisk (2004) and Fisk and Seppänen (2007) summarise the effect of ventilation in respect of health and productivity:

• Higher ventilation reduces the prevalence of air borne infectious diseases
• Ventilation rates below 10 l/s per person are associated with a significantly worse prevalence of one or more health or perceived air quality outcomes.
• Increases in ventilation rates above 10 l/s per person, up to approximately 20 l/s per person, are associated with a significant decrease in the prevalence of SBS symptoms or with improvements in perceived air quality.
• Improved ventilation can improve task performance and productivity.
• Ventilation rates below 0.5 ach are a health risk in Nordic residential buildings relative to natural ventilation, air conditioning (with or without humidification) is often associated with a statistically significant increase in the prevalence of one or more SBS symptoms.

One the other hand energy is used for ventilation. The share of heating ventilation air from the energy delivered for space conditioning of residential and service buildings is roughly 33%. Thus proper ventilation methods are important for the total energy efficiency of buildings. Good indoor air quality and energy efficiency are often seen as conflicting requirements. This is not at all a necessity. There are several ways to obtain significant savings in energy consumption in buildings and to improve indoor climate simultaneously. In this paper those methods are discussed.

2. Pollutant Concentrations and Ventilation

The basic steady-state equation (1) to calculate concentrations pollutants in indoor air is simple and relates the generation of pollutant, ventilation rate and concentration and outdoor air, other removal mechanisms than ventilation and ventilation efficiency.

\[ C_{h,i} = C_{h,o} + \frac{G_h}{Q_h} + \frac{1}{\lambda v} \]

where
\( Q_h \) = the airflow needed for selected air quality with respect to any contaminant in the air,
\( \lambda \) = the total rate of removal of the pollutant indoors by factors other than ventilation which includes deposition on surfaces, filtration, chemical reactions etc.
\( G_h \) = the generation of contaminant,
\( C_{h,i} \) = acceptable contaminant concentration in indoor air,
\( C_{h,o} \) = the contaminant concentration of intake air,
\( v \) = the ventilation efficiency, \( v = 1 \) for complete mixing to \( v = 2 \) for ideal piston flow.

Use of equation (1) in design means that the ventilation airflows in buildings are rationally selected and distributed to all rooms depending on the pollution loads. The problems, however, are in the application as:

• The acceptable concentration of various pollutants in indoor air is not known, especially for the mixtures of hundreds of the compounds found in the indoor air.
• The generation rate of pollutants indoors is not usually known.
• The contaminant concentration of intake air is not...
known in respect of all pollutants

• the concentration of contaminants in the supply air
  may be different from the outdoor air due to processes
  in the air handling system or structures through which
  the supply air is flowing

• rates of pollutant removal by processes other than ven-
 tilation are poorly known

• only limited amount of information is available on the
  ventilation efficiency of various air distribution systems

However, the equation (1) can be used to analyze sys-
tematically the factors affecting ventilation rates.

Energy use required for ventilation can be calculated
from the ventilation rate

\[ E = \sum (Q_{h,j} \rho (h_{i,j} - h_{o,j}) \Delta t + E_{e,j}) \]  (2)

Where

- \( h_{i,j} \): indoor enthalpy at during the time period \( \Delta t \)
- \( h_{o,j} \): outdoor enthalpy at during the time period \( \Delta t \)
- \( \Delta t \): time period
- \( Q_{h,j} \): outdoor air flow rate for ventilation
- \( E_{e,j} \): electrical energy used for moving the air with fans
- \( \rho \): density of air

3. SOURCE CONTROL AND EFFICIENT REMOVAL OF CONTAMINANTS

Most important principle in the design for good indoor
air quality is to try to avoid unnecessary pollutant gen-
eration and spread of pollutants in or between rooms
[reduce the term \( G_h \) in equation (1)]. To achieve this

• low pollution products and material should be used
  whenever possible

• escape of pollutants from processes to the room air
  should be prevented by sealing the processes as much
  as possible

• the processes causing pollution shall be equipped with
  local exhaust systems

• pollution generating equipament should be located in
  separate rooms whenever possible to minimise the
  spread of pollutants to other rooms

• the air balance (difference between supply and exhaust
  air flows) of the rooms should be so that air flows from
  less polluted rooms to more polluted rooms

• supply air jets should be directed so that they do not
  increase the spread of pollutants but decrease it.

The air balance principle of the ventilation means that
air always flows from room with higher air quality to
the rooms with lower air quality and higher pollution
generation. This means that clean air is supplied in the
cleaner rooms and exhausted from the polluted rooms,
and air is transferred from “clean” to “dirty” rooms.

In residential building this means that outdoor air is
supplied to bedrooms and living rooms and exhausted
from kitchens, bathrooms and toilets, etc.

In commercial buildings air is supplied to the occupied
zones and exhausted from rooms with pollution gener-
ation so that air balance is positive in the occupied rooms
and negative in rooms with higher pollution generation.

These principles are illustrated in Figure 1.

4. VENTILATION RATES AND POLLUTION LOAD

In the new CEN standard (EN 15251) the recommended
ventilation rates in non-residential buildings are derived
taking into account pollutant emission. The calculated
design ventilation rate is from two components (a) ven-
tilation for pollution from the occupancy and (b) ven-
tilation for the pollution from the building itself.

The ventilation for each category is the sum of these two
components as illustrated with the equation (3).

The ventilation rates for occupants (\( q_p \)) only are:

- Category A: 10 l/s, pers
- Category B: 7 l/s, pers
- Category C: 4 l/s, pers

The ventilation rates (\( q_B \)) for the building emissions are:

<table>
<thead>
<tr>
<th>Category</th>
<th>Low pollutating building</th>
<th>Non low-polluting building</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1,0 l/s, m²</td>
<td>2,0 l/s, m²</td>
</tr>
<tr>
<td>B</td>
<td>0,7 l/s, m²</td>
<td>1,4 l/s, m²</td>
</tr>
<tr>
<td>C</td>
<td>0,4 l/s, m²</td>
<td>0,8 l/s, m²</td>
</tr>
</tbody>
</table>
Total ventilation rate for a room is calculated from the following formula
\[ q_{\text{tot}} = n \cdot q_p + A \cdot q_B \]  
(3)

where
- \( q_{\text{tot}} \) = total ventilation rate of the room, l/s,
- \( n \) = design value for the number of the persons in the room,
- \( q_p \) = ventilation rate for occupancy per person, l/s, pers
- \( A \) = room floor area, m²
- \( q_B \) = ventilation rate for emissions from building, l/s, m²

EN 15251 gives also the additional ventilation rates when smoking is allowed. Smoking indoors should be banned due to increased need of ventilation and health effects of environmental tobacco smoke. Many technologies, however, are available to reduce the negative effects of smoking indoors (Skistad and Bronsema, 2004).

5. VENTILATION EFFICIENCY (\( \varepsilon_v \))

The air-flow pattern in a ventilated room is mainly divided into two different types, mixing (dilution) ventilation and displacement ventilation. In mixing ventilation the air is supplied in such a way that the room air is fully mixed and the contaminant concentration is the same in the whole room and concentration of pollutants diluted. In some cases the supply air is not mixed with the room air but flows directly to extract air opening (Figure 2). This short-circuiting reduces the effectiveness of the ventilation and should be avoided (Mundt et al., 2003). The opposite of the mixing flow pattern is the ideal piston flow (Figure 3) in which the air flow is laminar and the room air is not mixed at all with the supply air.

In displacement ventilation (Figure 4), a stratified flow is created using the buoyancy forces in the room. When the supply air temperature is a few degrees lower than room temperature, two zones are created in the room: a clear lower zone and polluted upper zone (Skistad et al., 2002). The air quality in the occupied zone is then generally better than for mixing ventilation. The ranges of typical ventilation effectiveness are given in Table 1.

<table>
<thead>
<tr>
<th>Flow pattern</th>
<th>Air change efficiency</th>
<th>Ventilation efficiency as in equation (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete mixing</td>
<td>50%</td>
<td>1</td>
</tr>
<tr>
<td>Piston flow</td>
<td>100%</td>
<td>2</td>
</tr>
<tr>
<td>Displacement flow</td>
<td>50-100%</td>
<td>1-2</td>
</tr>
<tr>
<td>Short circuiting flow</td>
<td>&lt; 50%</td>
<td>0-1</td>
</tr>
</tbody>
</table>

Figure 2  Mixing flow pattern. The upper diagram illustrates complete mixing when the concentration of contaminants is uniform in the room. The diagram below illustrates a partly short-circuiting flow pattern where part of the supply air flows directly to the exhaust opening and the concentration of contaminants generated in the room is higher than the concentration in exhaust duct – this should be avoided.

Figure 3  Laminar piston flow. This is used in special case such as operating theatres and other super clean rooms.

Figure 4 Displacement flow pattern. This creates two zones in a room – a lower and cleaner zone and an upper zone with higher concentration of pollutants.
6. CLEAN AIR FOR VENTILATION

6.1 Building protection

Buildings protect from outdoor air pollutants. A probabilistic exposure modelling exercise demonstrated that reducing the PM$_{2.5}$ infiltration into all buildings in the city of Helsinki to the level of the office buildings built after 1990, would reduce the population exposure to PM$_{2.5}$ from ambient origin as well as its adverse health effects by 27%, in fact almost as much as total elimination of all traffic sources from within the metropolitan area limits (Hänninen et al. 2005). Effective way to reduce outdoor pollution entering indoors is tight building envelope and effective filtering the air intake.

6.2 Location of outdoor intakes

The quality of outdoor varies around the building. The location of air intake close to pollutant sources, such as, traffic, loading decks, sewage vents etc should be avoided. Typically the outdoor air gets cleaner with increasing distance from the street level.

A recent analysis (Mendell et al. 2007) from 97 representative air-conditioned U.S. office buildings in the Building Assessment and Survey Evaluation (BASE) study showed that outdoor air intakes less than 60 m above ground were associated with significant increases in most symptoms: e.g., for upper respiratory symptoms, OR for intake heights 30 to 60 m, 0 to <30 m, and below ground were 2.7, 2.0, and 2.1.

6.3 Clean air handling system and equipment

The emission of pollutants may increase when the components and surfaces get dirty due to inferior maintenance. This hypothesis is supported by several field studies which have reported the association between the indoor air problems and cleanliness of HVAC-system. Crandall et al. (1996) reported that poor HVAC cleanliness was significantly related to elevated multiple respiratory symptoms with risk ratio of RR= 1.8, dirty filter with RR= 1.9, debris inside air intake with RR= 3.1, and dirty duct work with RR= 2.1. These all are indicators of sources of chemical pollutants in the HVAC-system.

A recent analysis (Mendell et al. 2007) from 97 representative air-conditioned U.S. office buildings in the Building Assessment and Survey Evaluation (BASE) study showed that humidification systems in poor condition were associated with significantly increased upper respiratory symptoms, eye symptoms, fatigue/difficulty concentrating, and skin symptoms, with OR= 1.5, 1.5, 1.7, and 1.6. Less frequent cleaning of cooling coils and drain pans was associated with significantly increased eye symptoms and headache, with OR=1.7 and 1.6. Symptoms may be due to microbial exposures from poorly maintained ventilation systems and to the greater levels of vehicular pollutants at air intakes nearer the ground.

The importance of the cleanliness of air handling systems has been already recognised in guidelines and standards in many countries (EN 13779, FiSIAQ 2001, Pasanen et al., 2007 and REHVA, 2007). A Finnish example of the cleanliness criteria of the duct system is given in the table 2 (FiSIAQ 2001).

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface density of oil in ducts $^{(1)}$</td>
<td>0.05 g/m$^2$</td>
</tr>
<tr>
<td>Surface density of oil in accessories, terminal units, and air and fire dampers $^{(1)}$</td>
<td>0.05 g/m$^2$</td>
</tr>
<tr>
<td>Parts manufactured by cutting, bending or jointing</td>
<td>0.3 g/m$^2$</td>
</tr>
<tr>
<td>Parts manufactured from deep-drawn sheet metal, processes requiring oil</td>
<td>$&lt;0.5$ fibers/m$^2$</td>
</tr>
<tr>
<td>Mineral fibers released into air flow (MMMF) $^{(2)}$</td>
<td>$10^3$ fibers/m$^2$</td>
</tr>
</tbody>
</table>

7. CONTROL OF VENTILATION BY AIR QUALITY

Air quality controlled ventilation (AQCV) is a ventilation system where air flows in the rooms are controlled according to the contaminant loads or concentrations (Figure 5), term $C_{i,j}$ in equation (1). The use of AQCV is based on temporarily varying contaminant sources, and actual needs of ventilation, when the system of constant airflow ventilation wastes energy, whereas a system with varying airflows saves energy but does not compromise indoor air quality. At present mainly CO$_2$-sensors are used for AQCV normal spaces due to cost and unreliability of other types of sensors. CO-sensors are used in special cases such as large garages.

Ventilation runs, typically, with constant outdoor air flows through all operational hours and the air flows are not changed with the change in the use of a room. Usually the ventilation loads of the interior spaces vary with time, and the ventilation rates should be adjusted to the loads. Practical experience shows that adapting the ventilation to the actual requirement can very often substantially reduce the energy use of a ventilation system. The simplest way to do this is to adapt the ventilation according to demand. This can be done by several ways (Table 3).
Figure 5 Principle of control of ventilation by air quality (air quality controlled ventilation – AQCV).

Table 3 Basic types of demand controlled ventilation (EN 13779)

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IDA – C1</td>
<td>No control: The system runs constantly.</td>
</tr>
<tr>
<td>IDA – C2</td>
<td>Manual control: The system runs according to a manually controlled switch.</td>
</tr>
<tr>
<td>IDA – C3</td>
<td>Time control: The system runs according to a given time schedule.</td>
</tr>
<tr>
<td>IDA – C4</td>
<td>Occupancy control: The system runs dependent on the presence (light switch, infrared sensors etc.)</td>
</tr>
<tr>
<td>IDA – C5</td>
<td>Presence control (number of people) The system runs dependent on the number of people in the space (Counting sensors etc).</td>
</tr>
<tr>
<td>IDA – C6</td>
<td>Direct control The system is controlled by sensors measuring indoor air parameters or adapted criteria (CO₂, mixed gas or VOC-sensors). The used parameters shall be adapted to the kind of activity in the space.</td>
</tr>
</tbody>
</table>

Contaminants originate from building and decoration materials, furniture, people and their activities, and intake air. From the AQCV point of view, the most important indoor air contaminants that are to be measured are carbon dioxide, emissions from building and decoration materials (VOC, volatile organic compounds), tobacco smoke, and from moisture. For AQCV, proper air quality sensors are needed. A room sensor can be one of the following: carbon dioxide, mixed-gas, attendance, combined CO₂/mixed-gas or combined CO₂/CO. A significant saving of energy has been achieved for air quality controlled system compared to the constant air flow system. Annual savings up to 50% have been reported (Table 4).

Table 4 Typical applications of demand controlled ventilation systems with respective energy savings in ventilation.

<table>
<thead>
<tr>
<th>Application</th>
<th>Savings, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Restaurants, canteens</td>
<td>20 – 50</td>
</tr>
<tr>
<td>Lecture halls</td>
<td>20 – 50</td>
</tr>
<tr>
<td>Open plan offices</td>
<td>40% of staff present on avg. 20 – 30</td>
</tr>
<tr>
<td></td>
<td>90% of staff present on avg. 3 – 5</td>
</tr>
<tr>
<td>Entrance halls, airport check-in areas</td>
<td>20 – 60</td>
</tr>
<tr>
<td>Exhibition and sports halls</td>
<td>40 – 70</td>
</tr>
<tr>
<td>Assembly halls, theatres, cinemas</td>
<td>20 – 60</td>
</tr>
</tbody>
</table>

8. BALANCING OF AIR FLOWS

An imbalance of the outdoor air flows leads to high energy use in the rooms with high outdoor rates, and deteriorated air quality in the rooms with low outdoor air flow rates. This is the case particularly in the ventilation systems without air circulation. By balancing the air flows the average air quality in a building can be improved and energy efficiency improved. Too low outdoor ventilation rates are possible in VAV systems with no minimum supply air flow value.

In the Helsinki office environment and health survey, ventilation rates were measured in 1,782 persons’ working rooms in 33 randomly selected buildings. The air flow was 17.2 L/s per person on the average. The variation of air flows between different buildings, and also within buildings, was considerable. The standard deviation of all of the air flows was 11.6 L/s per person (Teijonsalo et al. 1996). In ten buildings, the standard deviation of the air flows was higher than half of the mean value of the air flows, in which case the balancing of ventilation can be considered to be insufficient.

9. ENERGY EFFICIENT EQUIPMENT

9.1 Specific Power of Fans

Moving the air in and out in building requires energy in mechanically ventilated buildings, typically, this, however, is usually much smaller that the energy used to conditioning the air either in the air handling system or in the building. The use of electric energy of fans can be reduced by reducing the pressure drop in the system and by selecting high efficiency equipment. The specific fan power (4) is used to define the over all air moving efficiency of each fan.

\[
P_{SFP} = \frac{P}{q_v} = \frac{\Delta p}{\eta_{b,i}}
\]

Where

- \( P_{SFP} \) = the specific fan power in Wm⁻³s
- \( P \) = the input power of the motor for the fan, W
9.2 High efficiency equipment

The ventilation air can be used also for air conditioning. If air conditioning is used it high efficiency equipment should be selected. Table 5 shows the ranges of electric energy efficiency of chillers in classes A...G as in Eurovent Certification programme.

The selection of the best class A chiller instead of worst class F air cooled chiller will reduce the use of electricity by factor over 2.5.

Table 5 Eurovent classification of chillers

<table>
<thead>
<tr>
<th>Class</th>
<th>Air Cooled Condenser</th>
<th>Water Cooled Condenser</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>EER≥3.1</td>
<td>EER≥5.05</td>
</tr>
<tr>
<td>B</td>
<td>2,9≤ EER&lt;3.1</td>
<td>4,65≤ EER&lt;5,05</td>
</tr>
<tr>
<td>C</td>
<td>2,7≤ EER&lt;2,9</td>
<td>4,25≤ EER&lt;4,65</td>
</tr>
<tr>
<td>D</td>
<td>2,5≤ EER&lt;2,7</td>
<td>3,85≤ EER&lt;4,25</td>
</tr>
<tr>
<td>E</td>
<td>2,3≤ EER&lt;2,5</td>
<td>3,45≤ EER&lt;3,85</td>
</tr>
<tr>
<td>F</td>
<td>2,1≤ EER&lt;2,3</td>
<td>3,05≤ EER&lt;3,45</td>
</tr>
</tbody>
</table>

10. BENEFIT THE VARYING OUTDOOR AIR CONDITIONS

An example of the beneficial use of varying outdoor air conditions is night-time ventilative cooling. Its principle is based on the daily temperature swings during hot periods. A typical daily temperature swing is around 12 °C; however, it can be considerably smaller (e.g., on cloudy days) or higher with clear skies and a continental climate. The cool nighttime air can be used to cool the building during night. This cools the structure and furnishings, which become a heat sink during the day, thus, reducing the daytime temperatures. It can be applied both in natural and mechanical ventilation systems.

An example calculation showed (Wargocki and Seppänén 2006) that benefits from the reduced daytime temperature were many times higher than the electricity used to run the fans during day time when the improved performance at work due to lower day time temperatures were included in the analysis (Table 6).

Table 6. Cost of electricity and value of improved productivity due to night-time ventilative cooling. All values per occupant per day.

<table>
<thead>
<tr>
<th>Price of electricity, €/kWh</th>
<th>Use of electricity by fans for 8 hours of ventilative cooling, kWh</th>
<th>Cost of fan electricity, €</th>
<th>Productivity benefits, €</th>
<th>Benefits to cost ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>1.84</td>
<td>0.18</td>
<td>7.15</td>
<td>79</td>
</tr>
<tr>
<td>0.15</td>
<td>1.84</td>
<td>0.28</td>
<td>7.15</td>
<td>26</td>
</tr>
<tr>
<td>0.20</td>
<td>1.84</td>
<td>0.37</td>
<td>7.15</td>
<td>19</td>
</tr>
</tbody>
</table>

11. HEAT RECOVERY FROM EXHAUST AIR

Whenever heating of the supply air is needed, the installation of a heat recovery system should be considered. Exceptions are cases with high waste heat generation or special cases where the installation of a heat recovery system would not be economical, such as in situations with very short running time or existing plants with limited space. Typical use of the recovered heat is to heat the outdoor air for ventilation. The economy of heat recovery increases with the temperature difference between supply air and outdoor air, and with operation time of ventilation. Heat from exhaust air can also be used as a heat source in heat pump systems – with a heat pump the heat can be used also for other purposes like space heating or for heating domestic hot water.

Heat exchangers used for heat recovery can also be used for cooling the outdoor air for ventilation when the outdoor temperature is higher than the exhaust air temperature. Heat recovery increases the pressure drop in the system but the value of the recovered heat is usually much higher than the small increase in electricity use of the fan, however, the pressure loss should be kept as low as possible.

12. CONCLUSIONS

The requirements for good indoor air quality and energy efficiency have often been considered to conflict with each other. This is not necessarily true. Buildings with low energy consumption in Europe also seem to have lower rate of building related symptoms. This indicates the importance of qualified, well trained operational personnel who understand both the requirements for good indoor air quality and energy efficiency. Several strategies for ventilation have been described, with which at the same level of energy consumption, indoor air quality is improved, or at the same level of indoor air quality, energy consumption is reduced, or in best cases both objectives are achieved simultaneously.

REFERENCES


FiSIAQ (2001) Classification of Indoor Climate 2000 Espoo, Finland: Finnish Society of Indoor Air Quality and Climate (FiSIAQ), publication 5 E.


