Ventilation Strategies for Good Indoor Air Quality and Energy Efficiency

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Abstract

The requirements for good indoor air quality and energy efficiency have often been considered to be in conflict with each other. However, buildings with low energy consumption in Europe also seem to have a lower rate of building related health symptoms. This indicates the importance of proper design and installation as well as qualified, well trained operational personnel, who understand both the requirements for good indoor air quality and energy efficiency. Several strategies for ventilation are described in this paper. It is shown that, by selecting an appropriate strategy, the indoor air quality can be maintained or improved while reducing energy consumption. Aspects include: proper target and design values of indoor air quality and climate, source control, the efficient removal of contaminants, proper location of fresh air intakes, cleaning of intake air, efficient air distribution in rooms by means of improved ventilation efficiency, heat recovery from exhaust air, control of ventilation rates by air quality, correct balancing of airflows, controlling of indoor climate locally and using ventilation for night cooling.

Key words: review, air quality, task ventilation, heat recovery, energy efficiency, air intakes.

1. Introduction

Ventilation plays an important role in maintaining good indoor air quality by efficiently removing 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 higher 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 sick building syndrome (SBS) symptoms or with improvements in perceived air quality;
- Increased ventilation up to 17 L/s can improve task performance and productivity;
- Ventilation rates below 0.5 ac/h 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.

On 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 approximately 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 while simultaneously improving the indoor climate. In this paper various methods to achieve energy efficient ventilation are discussed.

2. Pollutant Concentration and Ventilation

The basic steady-state equation (Equation 1) for calculating the required ventilation rate for pollutant control is simple and relates the generation of pollutant, concentration differences of indoor and outdoor air, other removal mechanisms than ventilation and ventilation efficiency:

$$C_{h,i} = C_{h,o} + \frac{G_h}{Q_h + \lambda} \cdot \frac{1}{\varepsilon_v} \qquad (1)$$

where:

- Q_h = the airflow needed for selected air quality in respect to any contaminant in the air;
- λ = 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;
- ε_v = the ventilation efficiency, ($\varepsilon_v = 1$ for complete mixing to $\varepsilon_v = 2$ 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. There are, however, various problems associated with this approach. These include:

- The acceptable concentration of various pollutants in indoor air is not known, especially for mixtures of 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 with respect to 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;
- The rates of pollutant removal by processes other than ventilation are poorly known;
- Only a limited amount of information is available on the ventilation efficiency of various air distribution systems.

Nevertheless, Equation 1 can be used to systematically analyse the factors affecting ventilation rates.

Energy consumption related to ventilation can be calculated from Equation 2:

$$E = \sum (Q_{h,j}(h_{i,j} - h_{o,j})\Delta\tau_j + E_{e,j}) \qquad (2)$$

where:

- $h_{i,j}$ = indoor enthalpy over the time period $\Delta\tau_j$;
- $h_{o,j}$ = outdoor enthalpy over the time period $\Delta\tau_j$;
- $\Delta\tau_j$ = time period;
- $Q_{h,j}$ = outdoor airflow rate for ventilation;
- $E_{e,j}$ = electrical energy used for moving the air with fans.

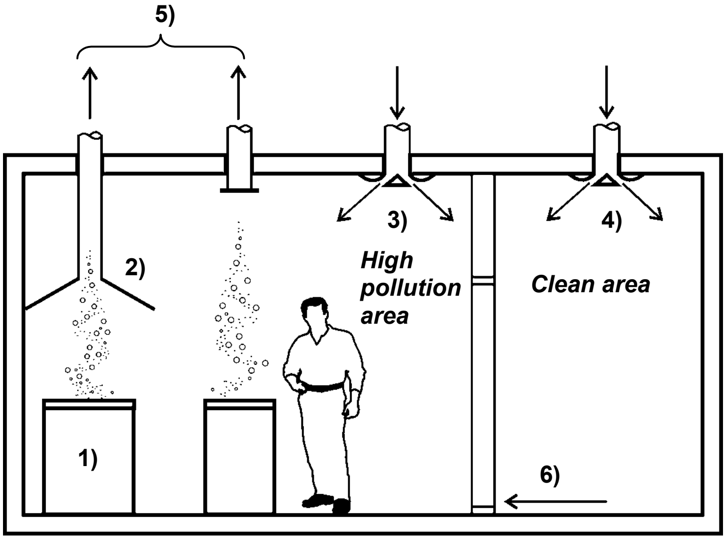
3. Source Control and Efficient Removal of Contaminants

The most important principle for the design of good indoor air quality is to avoid unnecessary pollutant generation (i.e. reducing the value of term G_h in Equation 1. This includes avoiding the spread of pollutants in or between rooms. To achieve this it is necessary to apply the following:

- Use low pollution products and materials whenever possible;
- Prevent the escape of pollutants from processes to room air by sealing the processes as much as possible;
- Equip processes causing pollution with local exhaust systems;
- Place pollution generating processes in separate rooms whenever possible to minimise the spread of pollutants to other rooms;
- Adjust ('balance') the airflow between supply and exhaust so that air flows from less polluted rooms to more polluted rooms;
- Adjust the direction of supply air jets so that they decrease rather than increase the spread of pollutants.

The air balance principle of ventilation means that air always flows from the room with higher air quality to rooms with lower air quality and/or higher pollution generation. This means that clean air is supplied to the cleaner rooms and exhausted from the polluted rooms (i.e. 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.



1) pollution generation processes are equipped with local exhaust;
2) exhaust air grilles and openings are located above the warm pollution generation sources;
3) air is supplied in the occupied zone in the rooms with high pollution generation to reduce exposure of the occupants to pollutants;
4) clean air is supplied to rooms with no specific pollution generation;
5) total exhaust airflow is larger than the supply air in the rooms with high pollution generation;
6) air is transferred from cleaner areas to more polluted areas through the openings in walls or doors

Figure 1. Air quality control principles for mechanical ventilation, (Vent Dis Course 2007).

In commercial buildings air is supplied to the occupied zones and exhausted from rooms with pollution generation so that air balance is positive in the occupied rooms and negative in rooms with higher pollution generation. This principle is illustrated in Figure 1.

4. Ventilation Rates and Pollution Load

In the new European standard (EN 15251) the recommended ventilation rates in non-residential buildings are derived taking into account pollutant emission. The design ventilation rate is calculated from two components; i.e. (a) ventilation for the pollution from occupancy and (b) ventilation for the pollution from the building itself. The total ventilation is the sum of these two components as illustrated in Equation 3.

Ventilation rates for occupants (q_p) only are:

Category A: 10 L/s per person
Category B: 7 L/s, per person
Category C: 4 L/s, per person

The ventilation rates (q_B) for building emissions are:

	Low polluting building	*Non low-polluting building*
Category A:	1.0 L/s.m^2	2.0 L/s.m^2
Category B:	0.7 L/s.m^2	1.4 L/s.m^2
Category C:	0.4 L/s.m^2	0.8 L/s.m^2

The total ventilation rate for a room is calculated from the following formula:

$$q_{tot} = n \cdot q_p + A \cdot q_B \qquad (3)$$

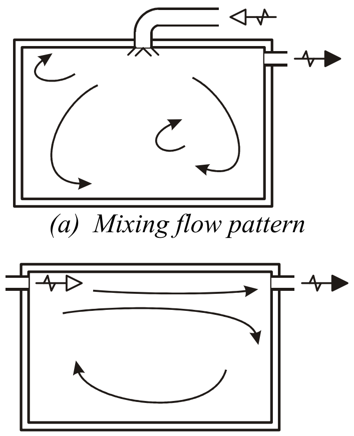
where:

q_{tot} = total ventilation rate of the room, L/s
n = design value for the number of persons in the room
q_p = ventilation rate for occupancy per person, L/s.person
A = room floor area, m^2
q_B = ventilation rate for emissions from the building, L/s.m^2

EN 15251 also specifies additional ventilation rates when smoking is allowed. However smoking indoors is increasingly being banned from public enclosed spaces throughout Europe as a consequence of the adverse health effects of environmental tobacco smoke. Various technologies have been introduced to reduce these negative effects of smoking indoors (Skistad and Bronsema 2004).

5. Ventilation Efficiency (ε_v)

Methods for ventilating rooms are primarily divided into two different approaches; these are mixing (dilution) ventilation and displacement ventilation. In the case of mixing ventilation the air is supplied such that the room air is fully mixed. Thus, contaminant concentration is evenly distributed throughout the whole room and the concentration of pollutants is diluted by the incoming ventilation air (Figure 2a). In some cases supply air may not mix with the room air but, instead, flow directly to the extract air opening (Figure 2b). This 'short-circuiting' reduces the effectiveness of ventilation and should be avoided (Mundt et al. 2003).



(a) Mixing flow pattern

(b) Short-circuiting flow pattern

(a) illustrates complete mixing with a uniform concentration of contaminants in the room.
(b) 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 the exhaust duct – this should be avoided.

Figure 2. Mixing and short circuiting flow pattern.

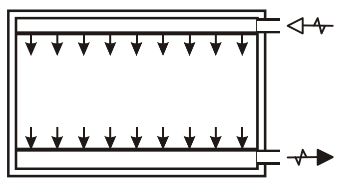


Figure 3. Laminar piston flow. This is used in special cases such as operating theatres and other super-clean rooms.

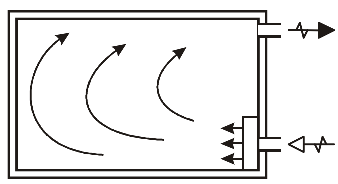


Figure 4. Displacement flow pattern. This creates two zones in a room – a lower and cleaner zone and an upper zone with a higher concentration of pollutants.

The alternative to mixing ventilation is the ideal 'piston' ('displacement') flow (Figure 3) in which airflow is laminar and the supply air does not mix with the room air. A practical example of this piston type displacement ventilation is illustrated in Figure 4, where 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 clean lower zone and a polluted upper zone (Skistad et al 2002). The air quality in the occupied zone is then generally better than for mixing ventilation. The degree of mixing and of pollutant removal in the occupied zone are described by the air change efficiency and ventilation effectiveness respectively. Typical values are presented in Table 1.

Table 1. Values of ventilation effectiveness for various flow patterns.

Flow pattern	*Air change efficiency*	*Ventilation effectiveness, ε_v as in Equation 1*
Complete mixing	50 %	1
Piston flow	100 %	2
Displacement flow	50-100%	1-2
Short circuiting flow	< 50%	0-1

6. Clean Air for Ventilation

6.1 Building Protection

Buildings offer protection 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 office buildings built after 1990 would reduce the population exposure to $PM_{2.5}$ from outside (ambient) sources, as well as its adverse health effects, by 27%. This benefit corresponds to

Table 2. The requirements of the cleanliness classification for ducts and accessories in a factory (FiSIAQ 2001).

Pollutant	*Criteria*
Surface density of oil in ducts	0.05 g/m^2
Surface density of oil in accessories, terminal units, and air and fire dampers;	
- Parts manufactured by cutting, bending or jointing	0.05 g/m^2
- Parts manufactured from deep-drawn sheet metal, processes requiring oil	0.3 g/m^2
Mineral fibres released into air flow (MMMF)	10^4 fibers/m^3
Amount of surface dust	<0.5 g/m^2

almost as much as would be achieved by the total elimination of all traffic sources from within the metropolitan area limits (Hänninen et al. 2005). An effective way to reduce outdoor pollution entering indoors is to ensure a tight building envelope and provide filtering of the intake air.

6.2 Location of Outdoor Intakes

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

A recent analysis (Mendell et al. 2006 and 2007) of ninety seven 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 health symptoms. For example, for upper respiratory symptoms, the Odds Ratios (OR) for intake heights 30 to 60 m, 0 to <30 m, and below ground were 2.7, 2.0, and 2.1 respectively.

6.3 Clean Air Handling System and Equipment

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

The BASE study (Mendell et al. 2006 and 2007) of 97 buildings (Section 6.2) also showed that humidification systems in poor condition were associated with significantly increased upper respiratory symptoms as well as eye symptoms, fatigue/difficulty concentrating and skin symptoms. These, respectively, gave Odds Ratios of 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 respectively. 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 already been recognised in the national 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 Table 2 (FiSIAQ 2001).

7. Control of Ventilation by Air Quality

Typically ventilation is operated at a constant airflow rate throughout operational hours, irrespective of variations in room use. Usually, however, the ventilation needs of the interior spaces vary with time, and therefore the ventilation rate should be adjusted to match such need. Air quality controlled ventilation (AQCV) is a method by which airflows in the rooms are controlled according to the contaminant loads or concentrations (Figure 5), term $C_{h,i}$ in Equation 1. In contrast to a constant airflow ventilation approach, which wastes energy when demand for ventilation is reduced, an AQCV system saves energy without compromising indoor air quality by responding to air quality needs.

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

Category	***Description***
IDA – C 1	*No control:* The system runs constantly.
IDA – C 2	*Manual control:* The system runs according to a manually controlled switch.
IDA – C 3	*Time control:* The system runs according to a given time schedule.
IDA – C4	*Occupancy control:* The system runs dependent on the presence of occupants (light switch, infrared sensors etc.)
IDA – C5	*Presence control (number of people):* The system runs dependent on the number of people in the space (Counting sensors etc).
IDA – C 6	*Direct control:* The system is controlled by sensors measuring indoor air parameters or adapted criteria (CO_2, mixed gas or VOC-sensors). The parameters used shall be adapted to the kind of activity in the space.

The simplest way to achieve AQCV is to adapt the ventilation according to demand (demand control). This can be achieved in several ways as summarised in Table 3.

Contaminants originate from the building, decoration materials, furniture, people, the activities of occupants and intake air. From the AQCV point of view, the most important indoor air contaminants to be measured are carbon dioxide, emissions from building and decoration materials (VOC, volatile organic compounds), tobacco smoke, and moisture. For AQCV, appropriate air quality sensors are needed. A room sensor can be one of the following: carbon dioxide, mixed-gas, attendance, combined CO_2/mixed-gas or combined CO_2/CO. At present mainly CO_2 sensors are used for AQCV in occupied spaces. Other types of sensors can be costly or unreliable. CO-sensors are used in special cases such as large garages. A typical control strategy is summarised in Figure 5.

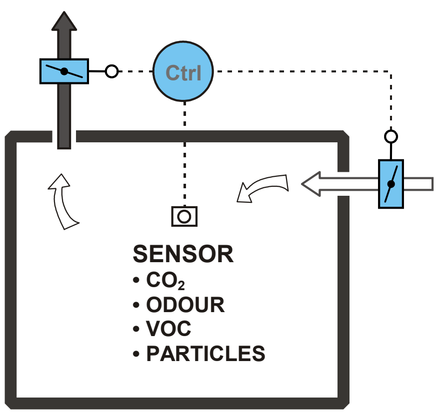


Figure 5. Principle of control of ventilation by air quality (air quality controlled ventilation – AQCV).

Practical experience shows that adapting the ventilation to the actual requirement can very often substantially reduce the energy use of a ventilation system. Annual savings up to 50% have been reported (Table 4).

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

Application	***Savings, %***
Restaurants, canteens	20 – 50
Lecture halls	20 – 50
Open plan offices	
- 40% of staff present on avg.	20 – 30
-90% of staff present on avg.	3 – 5
Entrance halls, airport check-in areas	20 – 60
Exhibition and sports halls	40 – 70
Assembly halls, theatres, cinemas	20 – 60

8. Balancing of Airflows

An imbalance of outdoor airflows leads to high energy use in the rooms with high outdoor rates, and poor air quality in the rooms with low outdoor airflow rates. This is particularly the case for ventilation systems without air circulation. By balancing the airflows the average air quality and energy efficiency can be improved simultaneously.

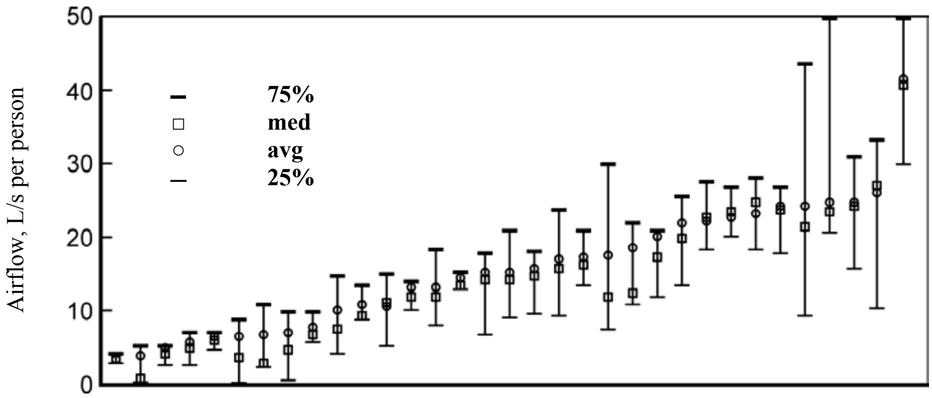


Figure 6. Range of outdoor airflows in 33 randomly selected mechanically ventilated office buildings in the Helsinki metropolitan area. Each vertical bar represents the range of airflow in an office building (Teijonsalo et al. 1996).

In a survey of health in the Helsinki office environment, ventilation rates were measured in the offices of 1782 people in 33 randomly selected buildings. The average airflow was 17.2 L/s per person. The variation in airflows between different buildings, and also within the same building, was considerable. The standard deviation of all of the airflows was 11.6 L/s per person (Teijonsalo et al. 1996). In ten buildings, the standard deviation of the airflows was higher than half of the mean value of the airflows. In these cases the balancing of ventilation can be considered to be insufficient (Figure 6).

9. Energy Efficient Equipment

9.1 Specific Power of Fans

Moving the air in and out of mechanically ventilated buildings requires electrical energy. Typically, this is usually much lower than the energy used to thermally condition the air. The use of electricity for fans can be reduced by decreasing the pressure drop in the system and by selecting high efficiency equipment. The specific fan power (Equation 4) is used to define the overall air-moving efficiency of each fan:

$$P_{SFP} = \frac{P}{q_v} = \frac{\Delta p}{\eta_{tot}} \qquad (4)$$

where:
P_{SFP} = the specific fan power in W/(m^3.s)
P = the input power of the motor for the fan, W
q_v = the nominal air flow through the fan in m^3/s
Δp = the total pressure difference across the fan, Pa
η_{tot} = the total efficiency of fan, motor and drive in the built-in situation.

9.2 High Efficiency Equipment

Ventilation air can be used also for air conditioning. If air conditioning is used, high efficiency equipment should be selected. Table 5 shows the ranges of electrical energy efficiency of chillers in classes A...G as defined by the Eurovent Certification programme. The selection of the best class A chiller instead of the worst class F air cooled chiller will reduce the use of electricity by a factor of over 2.5.

Table 5. Eurovent classification of chillers (http://www.euroventcertification.com/).

Class	*Air Cooled Condenser*	*Water Cooled Condenser*
A	EER≥ 3.1	EER≥ 5.05
B	2.9≤ EER< 3.1	4.65≤ EER<5.05
C	2.7 EER< 2.9	4.25≤ EER<4.65
D	2.5 EER< 2.7	3.85≤ EER<4.25
E	2.3 EER< 2.5	3.45≤ EER<3.85
F	2.1 EER< 2.3	3.05≤ EER<3.45

10. Benefiting from Diurnal Changes in Outdoor Air Conditions

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

An example calculation (Wargocki and Seppänen 2006) showed that, when taking performance at work into account, the benefits from reduced daytime temperature by running passive cooling were many times higher than the electricity used to operate the ventilation fans (Table 6).

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

Price of electricity, €/kWh	*Use of electricity by fans for 8 hours of ventilative cooling, kWh*	*Cost of fan electricity, €*	*Productivity benefits, €*	*Benefits to cost ratio*
0.05	1.84	0.09	7.15	79
0.10	1.84	0.18	7.15	40
0.15	1.84	0.28	7.15	26
0.20	1.84	0.37	7.15	19

11. Task Ventilation

Task ventilation is a method in which clean, air conditioned supply air is targeted directly at occupants. In this way, for example, working stations can be well ventilated while other areas (e.g. industrial halls) need not be as well controlled.

During the past few years an increasing amount of attention has been paid to air distribution systems that condition the immediate environments surrounding office workers and working stations. As with task lighting systems, the control of task ventilation can be partly or entirely decentralized placing it under the control of the occupants. Typically, the occupant has control over the airflow rate, speed and direction. In some cases the occupant also has control over the temperature of the supply air. A large majority of these systems incorporate a raised access floor through which under-floor air distribution is used to deliver conditioned air to the workstation through floor grilles. Alternatively, ducting may be incorporated into the workstation furniture and partitions. A comprehensive guide on task ambient systems has been written by Bauman and Arens (1996). The major advantages of task conditioning system are:

1. It offers occupants the opportunity to control their environment individually;
2. Task/ambient systems save heating, cooling and fan energy if properly designed and used;
3. Task/ambient systems have been reported to improve working efficiency.

Laboratory experiments reported by Palonen (1994) have shown that the potential energy savings of using task conditioning are significant. By integrating local cooling or heating to the workstation the operative temperature of the workstation can be approximately 4°C (7°F) higher or lower than the ambient temperature in a large space. This may result in significant energy savings on heating or cooling in industrial halls and shopping centres etc.

12. Heat Recovery from Exhaust Air

Whenever heating of 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 in existing plants with limited space. A typical use of recovered heat is in the pre-heating of incoming supply air. The economy of heat recovery increases with the temperature difference between supply air and outdoor air, and with the operational time of ventilation. Heat from exhaust air can also be used as a heat source in heat pump systems. This can then be used for other purposes such as space heating or the heating of domestic hot water.

Heat exchangers used for heat recovery can also be used for pre - cooling ventilation supply air when the outdoor temperature is higher than the exhaust air temperature.

Heat recovery increases the pressure losses in the system but the value of the recovered heat is usually much higher than the increase in electricity use of the fan. However, the pressure loss should be kept as low as possible.

Conclusions

The requirements for good indoor air quality and energy efficiency have often be considered to conflict with each other. This is not necessarily true. Buildings with low energy consumption in Europe also seem also to have lower rates of building related poor health 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. In the best cases reduced energy consumption and improved air quality can be achieved simultaneously. These strategies are summarized in Table 7.

Table 7. Summary of ventilation strategies for better indoor air quality and energy efficiency.

Strategy or technology	***Effect on investment cost***	***Effect on indoor air quality***	***Effects on energy and operation***
Win-win strategies that at the same time improve indoor air quality and reduce energy use			
Use low emission building products	No extra cost	Improved	Up to 50 % reduction in ventilation rates
Ban smoking indoors	No extra cost	Improved	Up to 50 % reduction in ventilation rates
Use high efficiency air distribution in rooms	No extra cost	Improved	Up to 50 % reduction in ventilation rates
Use free cooling	No extra cost	Improved	Minor increase in fan energy – no effect in naturally ventilated buildings
Particulate filtration of intake air	Minor extra cost	Significant improvement	Minor increase due to pressure drop in the filter
Balancing of air flows	Small cost due to balancing work	Improved in rooms with too low ventilation	May decrease or increase slightly
Keep air handling system clean with better maintenance	No extra cost	Improved supply air quality	Reduced energy use due to lower pressure drop
Win - strategies that improve indoor air quality and with same energy use			
Locate the fresh air intakes in the cleanest outdoor air location	No extra cost	Improved	Usually no effect
Control of specific pollution sources	Minor extra cost	Improved	Usually no effect
Local exhausts	Minor extra cost	Improved	Usually no effect
Win-strategies that reduce energy use with same level of indoor air quality			
Heat recovery from ventilation air	Increase due to equipment, space and ducting, decrease in heating and cooling capacity	Usually no effect	Slight increase in fan power Annual heat recovery up to 70 % in large systems up to 50 % in small
Demand controlled ventilation	Minor extra cost	May improve also air quality	Up to 50 % in large spaces
Task ventilation	Minor extra cost	May improve also air quality	Reduction in energy use

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