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Scientific basis for design of ventilation for health, productivity and good energy efficiency

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SUMMARY
The paper presents a summary of the effects of ventilation on human responses and of ventilation strategies that improve indoor environmental quality and reduce energy use.

KEYWORDS
Health, Productivity, Energy efficiency, Ventilation, Air-conditioning

INTRODUCTION

More than 40% of primary energy is used for buildings in EU countries and in the USA. Approximately 2/3 of this is used in residential buildings, and 1/3 in commercial buildings. The share of energy used for heating and ventilation is roughly two thirds of the energy delivered for buildings. About 10% of all primary energy is used for ventilation.

Great potential for energy conservation is seen in the building sector. Without proper design, energy saving measures may deteriorate indoor air environments. The need for heating and thermal control of indoor environments is well recognized. However, there are many misunderstandings relating to ventilation. Nevertheless, ventilation is important in efficiently expelling indoor pollutants from buildings and maintaining good air quality. If ventilation rates are reduced, energy is saved, but, at the same time, indoor air quality is deteriorated.

Deteriorated indoor air quality is commonly related to sick-building syndrome symptoms, respiratory illnesses, sick leave, reduced comfort and losses in productivity. Studies (Fisk and Rosenfeld, 1997; Seppänen and Palonen, 1998) have shown that, when all these effects are estimated on an economic basis, the cost of deteriorated indoor climates for society is high, even higher than the heating energy costs of the same buildings. The building-level calculations have shown that many measures that are taken to improve indoor air quality and climate are cost-effective when the potential savings resulting from an improved indoor environment are included in the calculations as benefits gained (e.g. Wargocki and Seppänen 2006). Potential benefits of indoor improvements include reduced medical care costs, working days gained due to reduced sick leave, better performance at work, lower turnover of employees, and lower cost of building maintenance due to fewer complaints about indoor air quality and climate.

The European Commission has estimated that the energy use of residential buildings can be reduced by 27%, and in commercial buildings by 30%, with cost-efficient measures. When selecting these measures, it is important to focus on those that do not deteriorate indoor air quality and cause harm to building occupants and building components. This paper

summarises scientific studies of the indoor environment in buildings, while focusing on ventilation in particular. It also presents several technologies developed to simultaneously improve indoor air quality and energy efficiency.
This paper focuses on studies reporting performance of ventilation in respect of human responses (health effects, performance or productivity, perceived air quality, comfort). In many studies, prevalence of sick-building syndrome symptoms has also been associated with characteristics of HVAC systems.

For cost-benefit analyses, it is not sufficient to have information demonstrating a statistically significant effect of IEQ on health or work performance; the size of that effect must be quantified. This can be achieved by relating ventilation rates to infectious diseases, office task performance, and learning. Qualitative associations were also used in developing ventilation strategies and technologies for better indoor air quality and energy efficiency. Based on findings that related ventilation to human responses, strategies for better performing ventilation systems were identified. In this paper, several strategies for ventilation are described.

EFFECTS OF VENTILATION RATES AND CHARACTERISTICS ON HUMAN RESPONSES

Ventilation in buildings is intended to remove pollutants or reduce their concentration and to control thermal conditions. Ventilation has complex effects on health, performance, perceived air quality, comfort, indoor air quality, dampness and airflows in buildings. It is known that sufficient ventilation is necessary to remove indoor-generated pollutants and humidity from indoor air or lessen their concentration to acceptable levels for occupant health and comfort, and to maintain building integrity. Reviews (e.g. Seppänen et al. 1999; Wargocki et al. 2002; Sundell and Levin, 2007) have shown that ventilation is associated with health but the exact dose-response relation cannot yet be established due to the large variability in conditions. As the limit values and source strengths are not known for all pollutants, the exact determination of required ventilation rates based on pollutant concentrations and associated risks is seldom possible. The selection of ventilation rates has also to be based on epidemiological research, laboratory and field experiments, odour perception, irritation, occupant preference, productivity and experience. The evidence suggests that better hygiene, commissioning, operation and maintenance of air-handling systems may be important for reducing the negative effects of HVAC systems.

Exposure to pollutants in indoor air and ventilation may cause a variety of effects. The severity of the effects covers a wide spectrum from perception of malodours to cancer. The effects may be acute or develop over a longer period of time. Effects related to ventilation and systems used for ventilation include the following:

- Ventilation rates below 10 L/s per person are associated with a significantly higher prevalence of one or more health outcomes or with worse perceived air quality in office environments (Seppänen and Fisk, 1999).
- Increases in ventilation rates above 10 L/s per person, up to approximately 20…25 L/s per person, are associated with a significant decrease in the prevalence of SBS symptoms or with improvements in perceived air quality in office environments (Seppänen and Fisk, 1999; Sundell and Levin, 2007).
- Improved ventilation can improve productivity in offices. Ventilation rates up to 17 L/s per person improve office task performance (Seppänen et al. 2006a).

- Ventilation rates below 0.5 ach (air change per hour) are a health risk in residential buildings (Wargocki et al. 2002; Sundell and Levin, 2007).
- Higher ventilation rates, up to 9 L/s per pupil, in schools improve the performance in school tasks (Wargocki and Wyon, 2006a, b).
- Ventilation and pollution sources influence perceived air quality. A relation between perceived indoor air quality and performance was developed in laboratory experiments with various pollution sources and ventilation rates. Performance in text typing was reduced 0.8% per each 10% increase in dissatisfaction with perceived air quality (Bako-Biro, 2004).
- Ventilation disperses airborne virus or bacteria that can cause infectious diseases or reduces their concentration. Thus, higher ventilation reduces the prevalence of airborne infectious diseases (Fisk et al. 2002; Li Y et al. 2007).
- Some microorganisms can grow in cooling coils and drip pans, air humidifiers and cooling towers and may result in symptoms of respiratory diseases such as legionnaire's disease and humidifier fever (Flannigan and Morey, 1996).
- Indoor humidity is affected by ventilation rates. Ventilation usually reduces indoor moisture levels. High humidity indoors is associated with an increased growth of microorganisms such as mould and bacteria (Institute of Medicine, 2004).
- High relative humidity, i.e. above approximately 45%, also increases indoor dust-mite levels. Low ventilation rates may therefore increase the prevalence or intensity of allergic and other types of symptoms (Flannigan and Morey, 1996).
- A tight building envelope and good filtering of outdoor air from particulate matter reduces significantly the exposure to harmful particulate matter and improves the health of occupants (Hänninen et al. 2005).
- The building envelope and mechanical filtering of outdoor air also protects occupants from harmful effects of ozone from outdoor origin, and the products of its reaction with indoor-generated pollutants (Apte et al. 2008).
- The prevalence of sick-building syndrome symptoms (SBS symptoms) has also been associated with characteristics of heating, ventilating and air conditioning systems (HVAC-systems). On average, the prevalence of SBS symptoms is higher in air-conditioned buildings than in naturally ventilated buildings (Mendell et al. 1996; Seppänen and Fisk, 2002;). The evidence suggests that better hygiene, commissioning, operation and maintenance of air-handling systems may be particularly important for reducing the negative effects of HVAC systems (Mendell and Smith, 1990; Mendell et al. 1996, 2006, 2007; Seppänen et al. 1999). Some potential problems with mechanical systems have been identified, such as:
    - sources close to ventilation air intake such as traffic, garbage, cooling towers, sewage vents etc.,
    - moisture and mould in the system (wet components – also drip pans of fan coils),
    - fibres released from the duct liners and sound dampers,
    - accumulated dust on surfaces of air-handling systems,
    - oil on new sheet-metal duct surfaces,
    - dirty or wet filters.
- An increased risk of developing lung cancer, heart attack, heart diseases and stroke has been linked to exposure to environmental tobacco smoke (ETS) and to radon decay products. Ventilation rates usually reduce the indoor concentrations of ETS and radon (Institute of Medicine, 2004).
- The strong and sufficient evidence of the association between ventilation, the control of airflow direction in buildings, and the transmission and spread of infectious diseases

supports the use of negatively pressurized isolation rooms for patients with these diseases in hospitals, in addition to the use of other engineering control methods (Li Y et al. 2007).

- Ventilation can be also used to control indoor temperature. Temperatures for thermal comfort are well established in a number of standards (e.g. EN 15251, EN 13779), but temperature also has many other effects:
    - Temperature has an effect on performance of office tasks. Too high or low temperatures deteriorate work performance. In routine-type work, the best temperature range seems to be between 20-24 °C, with an optimum of 22 °C (Seppänen et al. 2006b).
    - High indoor temperatures also increase the prevalence of SBS symptoms (Seppänen and Fisk, 2006), and deteriorate perceived indoor air quality.
    - High temperatures in classrooms deteriorate performance of schoolwork. Performance of school tasks was better in a temperature of 20 °C than 25 °C (Wargocki and Wyon, 2006a, b).
    - Low temperatures decrease the dexterity of hands and may reduce the performance of manual performance.
    - Low temperature also increases the sensitivity to air movement and draught risk.
- Ventilation also has an influence on room air velocities: high velocities can be used during the warm season to increase the cooling effect of the body; on the other hand, low velocities are beneficial during the heating season to reduce body heat loss. The criteria of air velocity are well established (e.g. EN 15251).

TECHNOLOGY FOR BETTER INDOOR ENVIRONMENT AND ENERGY EFFICIENCY

General principles

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 seem to often have a lower rate of building-related symptoms also (Bluyssen et al. 1996). This indicates the importance of proper design, installation and qualified well-trained operational personnel who understand both the requirements for good indoor air quality and energy efficiency.

Basic principles of the design for good IAQ and energy efficiency include:

- Use low-polluting building materials and processes (e.g. FiSIAQ, 2001).
- Control moisture to prevent dampness and mould problems.
- Prevent the escape of pollutants from processes – use local exhausts.
- Isolate the polluting process from other spaces.
- Balance the airflows so that the spread of polluted air is minimized.
- Supply clean fresh air to occupied zones.

Technologies for better IAQ and energy efficiency

Several strategies are available by which, at the same level of energy use, the indoor environmental quality is improved or, at the same level of indoor air quality, the energy use is reduced. Strategies that at the same time improve indoor environmental quality and reduce energy use include the following:

- Reduce the loads (need for) ventilation, heating, and cooling. Reduction of loads should always have a high priority in building design. This includes control of, and efficient removal of, contaminants by means of the following actions:
    - ban smoking indoors to reduce the need for ventilation and exposure to

    - environmental tobacco smoke,
    - use low-emission building products,
    - use low-emission consumer products,
    - avoid open flame combustion indoors (gas cooking etc.) to reduce release of nitrogen oxides to indoor air.
- Use efficient air distribution in rooms with improved ventilation efficiency (e.g. Mundt 2003); technologies such as displacement ventilation are available for this (e.g. Skistad, 2002).
- Use nighttime ventilative cooling and economiser when weather permits. Circulation of cool nighttime air in buildings reduces daytime temperatures significantly (e.g. Seppänen and Fisk 2005).
- Use economiser cycle in the air-handling system to increase ventilation rates and improve health, and reduce the need for mechanical cooling. Significant economic benefits can be gained (Fisk et al., 2005).
- Balance the supply and exhaust airflows for proper ventilation rates. Balancing will efficiently improve air quality in rooms with over ventilation and reduce energy use in such rooms.
- Keep the air-handling systems clean for better supply-air quality and lower pressure drops in ductwork and equipment – efficiency of fans is also better when impeller blades are clean.
- Adapt ventilation to the operation of the building. The usage and loads of rooms change during the lifetime of the buildings. The ventilation rates should be adjusted accordingly.
- Natural ventilation: use natural ventilation if climate and environment allows it. The climatic conditions may limit the use of natural ventilation - hybrid ventilation systems may be a solution. These would involve low-pressure mechanical systems to boost natural ventilation systems when needed.

Technologies for better energy efficiency

Strategies that reduce energy use with same level of indoor air quality:

- Select proper target and design values of indoor air quality and climate.
    - New standards such as EN 15251 allow lower ventilation rates when low-pollution building materials are used.
    - The set points of temperature should be adjusted to lower limit values of the range during the heating period and to upper limit values during the cooling period.
    - Unnecessary humidification and dehumidification should be avoided and, again, lower limit values (e.g. EN 15251) should be used during heating periods and upper limit values during dehumidification periods.
- Let recovered heat from exhausted ventilation air replace primary energy for heating, but avoid over heating of the supply air due to heat exchangers that are too efficient.
- Control ventilation rates by demand or by air-quality indicators. This can be achieved either by means of occupancy sensors or air-quality indicators. Most commonly used are CO_2 sensors that indicate the number of occupants in the space. Technology is most cost effective in large spaces with variable occupancy loads.
- Control indoor climate locally in large spaces and do not necessarily ventilate the whole space. Task ventilation may also improve comfort and productivity.
- Improve the energy of the system by using high-efficiency equipment and low pressure drop design. Performance indicators, such as specific fan power (SFP,

required electrical power in kW per ventilation airflow in m^3/s) integrate both equipment efficiency and design of air-handling systems.
- Improve exergy efficiency of energy use by using systems that can use energy sources with temperatures close to room temperature (use of low-temperature heating and high-temperature cooling, e.g. Babiak 2007).

Technologies for better IAQ

Strategies that improve indoor air quality and with same energy use

- Locate fresh-air intakes in the cleanest location of outdoor air far from pollutant sources such as loading decks, sewage vents etc.
- Use local exhausts to prevent spreading of pollutants to the occupied space and other rooms.
- Use good-quality particulate filters with low pressure drops in intake and supply air flow.
- Use tight air ducts and handling systems to avoid unnecessary escape of treated supply air. Criteria for air tightness are well established in standards (e.g. EN 13779),
- Keep the air-handling system clean (Pasanen, 2007).

CONCLUSIONS

Scientific evidence shows that ventilation is essential for good indoor environmental quality. Ventilation strategies are also important for the energy efficiency of buildings. The requirements for good indoor air quality and energy efficiency have often been considered to conflict with each other. However, several strategies and technologies presented in this paper show that better energy efficiency and indoor air quality can be achieved simultaneously. Buildings with low energy consumption in Europe also seem to have lower rates of building-related symptoms. This indicates the importance of qualified well-trained designers and operational personnel who understand both the requirements for good indoor air quality and energy efficiency. Several strategies for ventilation have been described: 1) at the same level of energy consumption, indoor air quality is improved, or 2) at the same level of indoor air quality, energy consumption is reduced, or 3) in best cases, both improvements are achieved simultaneously. In the future, it will be particularly important to better understand the effects, including sorption effects, of emissions from building materials and air-handling systems on air quality.

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Improving productivity and efficiency in agriculture is a priority concern for governments, policy makers, nongovernment organisations, relevant stakeholders and farming communities worldwide in order to meet the ever-increasing demand for food from a closing land frontier and degrading land base. Concern is also centred on sustaining agriculture to ensure future growth and supply of food. These concerns are particularly high for countries grappling with a low level of technical progress, subsistence farming, adverse production environment and changing climate. Energy efficiency measures can support good physical and mental health primarily by creating healthy indoor living environments with healthy air temperatures, humidity levels, noise levels, and improved air quality. The World Health Organization estimates that globally air pollution causes about 3 million premature deaths a year,1 making air pollution a significant environmental risk. Energy efficiency measures targeting indoor and outdoor air quality can have major impacts for global health. Recent evidence shows that chronic thermal discomfort and fuel poverty also have negative mental healt... Productivity improvement programs were mostly aimed at the worker level. Yet, as Peter F. Drucker, one of the most prolific writers in management, observed. The greatest opportunity for increasing productivity is surely to be found in knowledge, work itself, and especially in management. Effectiveness.Â Efficiency can be measured in terms of the ratio of output to inputs, utilization percentage of various resources, the unit cost of the product, cycle time or lead time, the extent of wastage etc. Effectiveness measures the total output produced â€" for example, total widgets produced in a day.Â In that case, worker â€˜Câ€™ is the best choice for the management. Because worker â€˜Câ€™ has the closet perfect balance of effectiveness and efficiency. Thus, making him the most productive of all workers.