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NEW PRINCIPLES FOR A FUTURE VENTILATION STANDARD

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Existing ventilation standards have serious shortcomings. They do not guarantee a good indoor air quality. New principles for a future ventilation standard are proposed. In contrast to existing standards, all pollution sources are acknowledged, i.e. both the occupants and the building, including furnishing, carpeting and ventilation system. The required ventilation is calculated based on the total indoor pollution load, the available outdoor air quality and the level of indoor air quality selected for design.

INTRODUCTION

Existing ventilation standards have serious shortcomings. They prescribe a certain quantity of outdoor air to be supplied per person in a space. Unfortunately, this does not guarantee good air quality. The same supply of air may provide acceptable air in some buildings, mediocre in many others and catastrophic air quality in a few buildings. This is well-documented in field studies in many countries.

There are three reasons why the present standards do not work. Most important is that they assume the occupants to be the major or exclusive pollutors. But recent studies have documented that the building itself, including furnishing, carpeting and ventilation system, usually is a more important polluter than the occupants (1,2,3). Another shortcoming is that the supplied air quantity is the same whether the outdoor air has a high or a low quality. A third shortcoming of many existing standards is that the indoor air quality aimed at is poorly defined.

The *thermal* design of buildings takes place in a much more rational way. The cooling load is determined by adding all heat sources, the outdoor design temperature and humidity are considered and the space is designed for thermal comfort, i.e. a certain operative temperature. If thermal design was as rudimentary as present ventilation standards, a constant cooling power would be prescribed per occupant independent of the outdoor temperature, all heat sources except the occupants would be ignored and nobody would care about the temperature in the space.

It is time that we upgraded the design of ventilation and indoor air quality to the same level of rationality that we have used for years in the thermal design of buildings. In the present paper such rational principles for a future ventilation standard are presented.

A future standard begins with a decision on the level of air quality aimed at in the ventilated space. A high, a standard or a minimum air quality may be selected. The available outdoor air quality is also considered. A high outdoor air quality requires a lower ventilation rate than a moderate outdoor air quality. The total pollution load is estimated based on all pollution sources. The required ventilation can then be calculated based on the selected indoor air quality, the outdoor air quality available and the total pollution load in the ventilated space.

AIMS AND SCOPE

This paper specifies the ventilation required to obtain a desired indoor air quality in a space. It applies to spaces for human occupancy in non-industrial buildings. Requirements to the thermal environment, i.e. air temperature, thermal radiation, air velocity are not discussed. They are specified in the international standard for thermal comfort, ISO 7730 (4).

INDOOR AIR QUALITY

The occupants in a space have two requirements to the air in a space. First the air should be perceived fresh and comfortable rather than stale, stuffy and irritating. Furthermore, the health risk of breathing the air should be negligible. There are large individual differences in the human requirements. Some persons are very sensitive and have high requirements to the air they are breathing. Other persons are rather insensitive and have low requirements to the air. The quality of the indoor air may be expressed as the extent to which human requirements are met. The air quality is high if there are few dissatisfied, while many dissatisfied persons means a low air quality. People may be dissatisfied because they perceive the air as stale, stuffy or irritating. Or they may be dissatisfied due to a possible health risk. The ventilation required to obtain a certain perceived air quality and a negligible health risk will be discussed separately.

PERCEIVED AIR QUALITY

Humans perceive the air by two senses. The olfactory sense is situated in the nasal cavity and is sensitive to several hundred thousand odorants in the air. The general chemical sense is situated all over the mucous membranes in the nose and the eyes and is sensitive to a similarly large number of irritants in the air. It is the combined response of these two senses that determines whether the air is perceived fresh and pleasant or stale, stuffy and irritating. Perceived air quality is expressed in decipol (5). One decipol is the perceived air quality in a space with a pollution strength of one olf, ventilated by 10 l/s of clean air, i.e. 1 decipol = 0.1 olf/(l/s). One olf is defined as the pollution from a standard person (5). Any pollution source can be expressed in olfs, i.e. the number of standard persons required to make the air as annoying as the actual pollution source. Fig. 1 shows the percentage of dissatisfied, i.e. those persons who perceive the air to be unacceptable just after entering a space, as a function of the ventilation rate per olf. Fig. 2 shows the corresponding relation between perceived air quality in decipol and the percentage of dissatisfied.

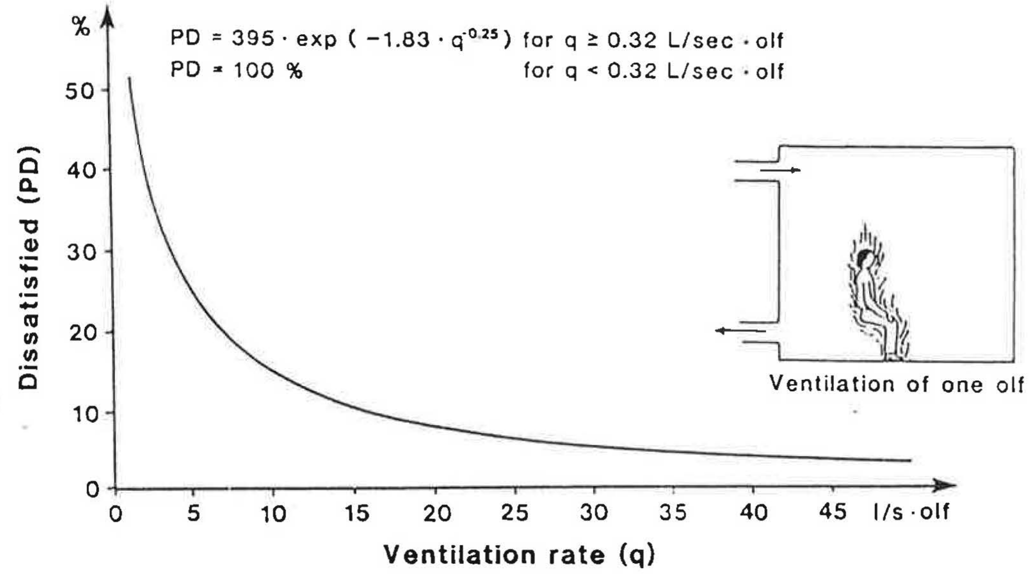

Figure 1. Dissatisfaction caused by one olf at different ventilation rates (5). The curve is based on studies where 168 European subjects judged air polluted by bioeffluents from more than one thousand sedentary men and women. Similar studies in North America (7) and Japan (6) show close agreement with the present European data.

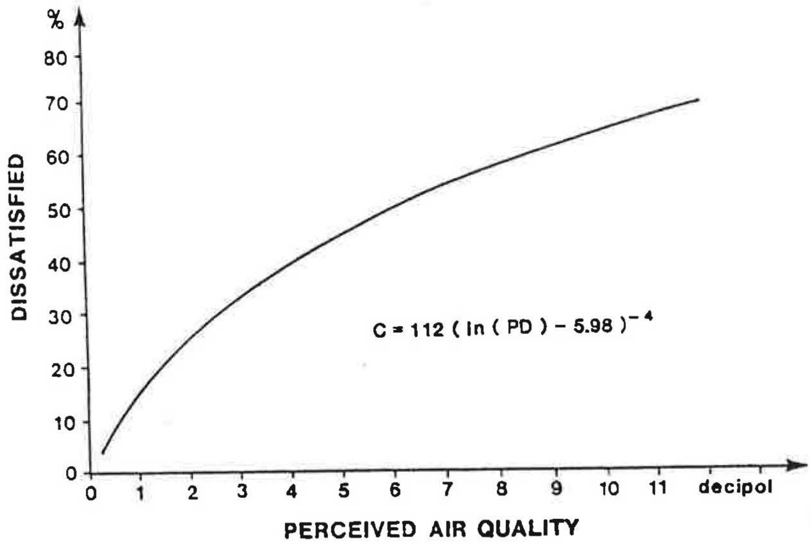

Figure 2. Perceived air quality in decipol as a function of the percentage of dissatisfied.

To determine the required ventilation it is essential to consider the level of indoor air quality to be desired. In some spaces it may be sufficient to provide a **minimum** air quality. In many spaces a **standard** air quality would be required, while in other spaces a **high** air quality may be desired. These three levels of perceived air quality are given in Table 1 as percent dissatisfied and in decipol. The selection of the desired level of air quality in a space depends mainly on economical considerations and on the application of the space.

Table 1. THREE LEVELS OF PERCEIVED INDOOR AIR QUALITY

	% dissatisfied	perceived air quality decipol	required ventilation rate* l/s · olf
High indoor air quality	10	0.6	16
Standard indoor air quality	20	1.4	7
Minimum indoor air quality	30	2.5	4

* Assuming clean outdoor air and a ventilation effectiveness of one

The perceived air quality in Table 1 refers to people's initial judgement when entering a space. The first impression is essential, i.e. it is important that the air is immediately perceived as acceptable. However, some adaptation does take place during the first 15 minutes of occupancy. Considerable adaptation takes place in air polluted by human bioeffluents, some adaptation occurs in tobacco smoke (at moderate levels), while little adaptation seems to take place in air polluted by building materials etc. (8).

HEALTH RISK

Exposure to pollutants in the air may provide a certain health risk. To limit this risk to an insignificant level, it would be useful to establish a list of maximum allowable concentrations for individual chemicals in the air.

For industrial premises Threshold Limit Values (TLV) exist. They apply to work places where chemicals are used routinely in the production process. In offices and similar work places there is no industrial justification for air pollution and lower limits should therefore be aimed at. This applies also to dwellings where people spend longer time than at the work place, and the occupants include more susceptible persons (e.g. children and the elderly). It has therefore been suggested (9) to use a certain fraction of the TLV values, but there is no agreement on the value of this fraction. The World Health Organization has recently published "Air Quality Guidelines for Europe" (10). In this publication the health effect of certain air pollutants has been evaluated and guideline values are given. They are elaborated for outdoor and indoor air quality and these limits may be used as a guideline. But it should be emphasized that at present no generally accepted comprehensive list of health limits exists, elaborated specially for indoor air in non-industrial buildings.

The metabolic processes of the occupants in a space require oxygen and produce carbon dioxide. The ventilation rate required to maintain oxygen and carbon dioxide at safe levels is very low, i.e. per sedentary occupant 0.3 l/s for oxygen and 2 l/s for carbon dioxide. In real buildings this is normally not a problem.

AIR POLLUTION SOURCES

The purpose of ventilation is to dilute the pollution emitted in a space. The pollution sources comprise the occupants and their possible smoking. Furthermore, materials in the building, including furnishing, carpets and the ventilation system may contribute significantly to the pollution. Some materials pollute a lot, some a little, but they all contribute to degrade the indoor air quality. Many sources emit hundreds or thousands of chemicals but usually in small quantities. The source strength can either be expressed by the olf unit which integrates the effect of the many chemicals as perceived by human beings. Or it can be expressed as the emission of individual gases from the sources. The source strength may also be given as the total emission of a group of chemicals, e.g. volatile organic compounds.

A pollution source strength is not always a constant. It may change with temperature, humidity, age and pollution level in the space.

OLF LOAD

The total olf load in a space is found by adding the olf values of the different pollution sources in the space. The pollution sources comprise the occupants and the building including furnishing, carpeting and ventilation system.

The occupants emit bioeffluents and some produce tobacco smoke. A standard sedentary person produces 1 olf, while an average smoker produces 6 olf (7). Table 2 lists the olf load from occupants at different activities with no smoking and with different percentages of smokers among the occupants. Table 3 lists examples of occupancy per m^2 floor in typical spaces.

The source strength of the building may be found by adding the olf values of all materials present. But information on olf per m^2 is available for only a few materials at present. A more feasible approach how is to estimate the olf load per m^2 floor caused by the building, including furnishing, carpeting and ventilation system. Such data have been measured in some existing buildings (1,2,3). Table 4 comprises data from the measured olf loads in different types of existing buildings. The olf load caused by the building is often high and varies widely from building to building. It is essential that new buildings be designed as low olf-olf buildings. This requires a systematic selection of low-polluting materials for the building including furnishing, carpets and ventilation system. Many existing buildings need to be redecorated to reduce the olf load.

Table 2. olf load caused by the occupants

SEDENTARY, 1-1.2 met*	olf/occupant
0% smokers	1
20% smokers**	2
40% smokers**	3
100% smokers**	6
PHYSICAL EXERCISE	
Low level, 3 met	4
Medium level, 6 met	10
High level (athletes), 10 met	20

* 1 met is the metabolic rate of a resting sedentary person (1 met = 58W/m^2 skin)

** average smoking rate around 1 g tobacco/hour per smoker, i.e. typically around 1.2 cigarettes/hour per smoker in Europe and 2 cigarettes/hour in North America

Table 3. Examples of occupancy in spaces

	occupants/(m^2 floor)
Offices	0.07
Conference rooms	0.5
Assembly halls, theatres, auditoria	1.5
Schools (class rooms)	0.5
Dwellings	0.05

Table 4. olf load caused by the building, including furnishing, carpets and ventilation system

	olf load olf/(m^2 floor)	
EXISTING BUILDINGS	mean	range
Offices*	0.3	0.02-0.95
Schools (class rooms)**	0.3	0.12-0.54
Assembly halls***	0.5	0.13-1.32
LOW-OLF BUILDINGS	0.05-0.1	

* Data for 24 mechanically ventilated office buildings (1,2)

** Data for 6 mechanically ventilated schools (3)

*** Data for 5 mechanically ventilated assembly halls (1)

It is recommended to calculate the total olf load in a space by simple addition of the olf values of the individual pollution sources in a space. This has been shown to provide a reasonable first approximate method of combining many pollution sources (11,12). But simple addition is not a prerequisite for the present method. Future studies may show that some materials, when occurring in the same space, provide a stronger or weaker total source strength than predicted by simple addition of the individual olf values.

CHEMICAL LOAD

The source strength of a material may also be expressed as the emission rate of individual chemicals in $\mu g/m^2 \cdot s$. The total load in the space of each individual chemical can then be estimated by addition of the sources and expressed in $\mu g/s$. Unfortunately little information is available on the emission rate from the many materials used in practice. And it may be rather impractical to account for the source strength of each of the hundreds or thousands of chemicals occurring in indoor air. But in some cases where an individual gas is suspected, an estimate of the total load of that particular chemical in a space may be possible.

OUTDOOR AIR QUALITY

The required ventilation depends also on the quality of the outdoor air. If the outdoor air has a high quality, less ventilation is required than if the outdoor air has a low quality. Table 5 lists characteristic levels of outdoor perceived air quality.

The World Health Organization has published "Air Quality Guidelines for Europe" (10), where guideline values for certain substances in the outdoor air are given. If the outdoor air quality is poor it may be necessary to clean the air before it is suitable for ventilation.

Table 5. Typical outdoor levels of perceived air quality

	decipol
In mountains, at sea	0
In towns, high air quality	< 0.1
In towns, medium air quality	0.2
In towns, low air quality	> 0.5

VENTILATION EFFECTIVENESS

The air quality may not be the same throughout a ventilated space. What really counts for the occupants is the air quality in the breathing zone. Such an inhomogeneity of the air quality in a space has an impact on the ventilation requirement. This is expressed by the ventilation effectiveness (ϵ_v) defined as the relation between the pollution concentration in the return air (C_e) and in the breathing zone (C_i)

$$\epsilon_v = \frac{C_e}{C_i}$$

The ventilation effectiveness depends on the air distribution and the location of the pollution sources in the space. If there is complete mixing of air and pollutants, the ventilation effectiveness is one. If the air quality in the breathing zone is better than in the exhaust, the ventilation effectiveness is higher than one and less ventilation is required. If the air in the breathing zone is poorer than in the exhaust air, the ventilation effectiveness is lower than one and more ventilation is required. The effectiveness depends on the ventilation principle for the air distribution and on the location of the pollution sources in the space (13). For properly designed systems the ventilation effectiveness is often around 1 for mixing ventilation and around 1.2-1.4 for displacement ventilation.

REQUIRED VENTILATION

The required ventilation rate to obtain the perceived air quality desired indoors is calculated from this equation (14):

$$Q_c = 10 \frac{G}{C_i - C_o} \cdot \frac{1}{\epsilon_v} \qquad [1]$$

where

Q_c = ventilation rate required for comfort (l/s)

G = total pollution load (olf)

C_i = perceived indoor air quality, desired (decipol)

C_o = perceived outdoor air quality (decipol)

ϵ_v = ventilation effectiveness

Similarly, the ventilation required to control the air quality from a health point of view may be calculated. The ventilation required to maintain the most critical chemical below the allowable concentration may be calculated by this equation:

$$Q_h = \frac{G}{C_i - C_o} \cdot \frac{1}{\epsilon_v} \qquad [2]$$

where

Q_h = ventilation rate required for health (l/s)

G = total pollution load (μg/s)

C_i = allowable concentration (μg/l)

C_o = outdoor concentration (μg/l)

ϵ_v = ventilation effectiveness

The ventilation rates required to control comfort and health are calculated separately from Eqs. [1] and [2] and the highest value is used for design. Eqs. [1] and [2] apply to steady-state conditions. Adsorption and desorption of air pollutants at surfaces in the space may prolong significantly the period it takes to obtain steady-state air quality.

PROCEDURE TO DETERMINE THE REQUIRED VENTILATION

The following procedure should be followed to determine the ventilation requirement in a building. First a decision should be taken on the desired indoor air quality in the ventilated space. Table 1 offers three levels of air quality corresponding to 10, 20 or 30% dissatisfied. Then the perceived outdoor air quality should be estimated (Table 5).

The next step is to estimate the strength of the pollution sources in the building, i.e. to estimate the olf load. The olf load per occupant is given in Table 2, depending on physical activity and the tobacco smoking behaviour of the occupants. Examples of occupancy, i.e. the number of people per m^2 floor is given for different spaces in Table 3. The pollution caused by the building including furnishing, carpets and ventilation system can be estimated from Table 4. The total olf load is found by adding the loads from the occupants and the building.

It is necessary to estimate the ventilation effectiveness depending on the principle of ventilation used in the space.

The ventilation required to handle the total olf load and obtain the desired perceived indoor air quality is found from Eq. [1].

An analogous calculation of the ventilation required to avoid health problems may be found from Eq. [2]. The highest of the two ventilation rates is then used for design.

For several reasons it may still be difficult to use Eq. [2] in practice. First the emission rates from the pollution sources (the chemical load) are usually not available. Furthermore there is not yet any generally accepted list of allowable indoor concentrations of chemicals for non-industrial buildings. Field studies in many buildings indicate however, that for spaces ventilated for comfort, the concentration of chemicals will usually be very low, typically several orders of magnitude lower than the TLV values. Still, for special cases, there may occur pollution sources of concern from the point of view of health. It is recommended to avoid or control such sources and apply low-polluting materials in the building.

EXAMPLES

New office building, situated in a town with high outdoor air quality C_o = 0 decipol (Table 5). Standard indoor air quality is desired, i.e. C_i = 1.4 decipol (Table 1). No smoking, i.e. 1 olf/occupant (Table 2). The occupancy is 0.07 occupants/(m^2 floor) (Table 3). Systematic use of low olf materials in the building, i.e. 0.1 olf/(m^2 floor) (Table 2). Displacement ventilation is applied with an estimated ventilation effectiveness of 1.3.

Occupants $1 \cdot 0.07$ =	0.07 olf/(m^2 floor)
Building	0.1 olf/(m^2 floor)
Total olf load	0.17 olf/(m^2 floor)

Required ventilation rate $Q_c = 10 \cdot \frac{0.17}{1.4\text{-}0} \cdot \frac{1}{1.3} = \underline{0.9\ l/s\ (m^2\ floor)}$

Existing office building situated in town with medium outdoor air quality C_o = 0.2 decipol (Table 5). Minimum indoor air quality is desired, i.e. C_i = 2.5 decipol (Table 1). Smoking is allowed and 40% are estimated to be smokers, i.e. 3 olf/occupant (Table 2). The occupancy is 0.07 occupants/(m^2 floor) (Table 3). Standard materials are used in the building, i.e. 0.3 olf/(m^2 floor) (Table 4). Displacement ventilation is applied with an estimated ventilation effectiveness of 1.3.

Occupants	3 · 0.07 =	0.2 olf/(m^2 floor)
Building		0.3 olf/(m^2 floor)
Total olf load		0.5 olf/(m^2 floor)

$$\text{Required ventilation rate } Q_c = 10 \cdot \frac{0.5}{2.5-0.2} \cdot \frac{1}{1.3} = \underline{1.7 \text{ l/s (m}^2 \text{ floor)}}$$

New school situated in town with high outdoor air quality C_o = 0 decipol (Table 5). Minimum indoor air quality is desired, i.e. C_i = 2.5 decipol (Table 1). No smoking, i.e. 1 olf/occupant. The occupancy is 0.5 occupants/(m^2 floor). Systematic use of low olf materials in the building, i.e. 0.1 olf/(m^2 floor) (Table 4). Ventilation effectiveness is 1.0.

Occupants	1 · 0.5 =	0.5 olf/(m^2 floor)
Building		0.1 olf/(m^2 floor)
Total olf load		0.6 olf/(m^2 floor)

$$\text{Required ventilation rate } Q_c = 10 \cdot \frac{0.6}{2.5-0} \cdot \frac{1}{1.0} = \underline{2.4 \text{ l/s (m}^2 \text{ floor)}}$$

CONCLUSIONS

- New principles for a future ventilation standard are presented.
- The desired indoor air quality should be selected among three suggested levels: minimum, standard and high quality.
- The outdoor air quality available for ventilation should be estimated.
- The total indoor pollution load comprising both occupants and building, including furnishing, carpets and ventilation system should be estimated.
- The required ventilation may be calculated based on the desired indoor air quality, the available outdoor air quality and the total indoor pollution load.
- The new method for ventilation design is analogous with the rational method for thermal design of buildings, used for years.

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