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EFFICIENT VENTILATION FOR HUMAN COMFORT

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ABSTRACT

The purpose of ventilation is usually to improve the indoor air quality for the occupants. To do this in an efficient way, it is essential that detailed information on human comfort requirements are available. Human comfort in a ventilated space depends on the perceived air quality, on the general thermal sensation of the occupants and on the risk of draft. Each of these aspects are reviewed separately based on new European Guidelines for Ventilation Requirements in Buildings and a modified ISO standard on thermal comfort. The perceived air quality is expressed in decipol or percentage of dissatisfied occupants. The general thermal sensation is expressed by the PMV/PPD indices. The perception of draft is expressed by the new model of draft risk. Indoor air quality is mediocre and causes complaints in many buildings. The reason for this is often hidden pollution sources in the building, hitherto ignored in previous ventilation standards. To determine the required ventilation, a new method is used in the European Guidelines. The new Guidelines acknowledge <u>all</u> pollution sources in the building, expressed in olfs. The method is based on the desired air quality in the space, the available quality of the outdoor air, the ventilation effectiveness and on the total pollution load in the space.

Keywords: Ventilation, Indoor Air Quality, Comfort, Draft, PMV.

INTRODUCTION

Spaces for human occupancy are ventilated or air conditioned for two reasons: (i) to provide a good air quality in the breathing zone of the space; (ii) to provide a comfortable temperature field in the occupied zone of the space. It is the challenge of the engineer to design a system which meets these two requirements without causing any significant risk of draft for the occupants.

The thermal capacity of the system should be designed to provide the required temperature level in the space. Well-known methods for the thermal design are available. The system should also be designed to supply the outdoor air required to obtain a desired level of air quality in the space. The European Guidelines for Ventilation of Buildings (CEC 1992), just published, prescribes a new method to calculate the required ventilation. The method is presented in the present paper. But although the right level of temperature and air quality is provided, there may be large differences from place to place in the occupied zone. This non-uniformity is caused by the air distribution system and the location of heat and pollution sources. Ways of expressing the non-uniformity of the thermal environment, of the air quality and of the draft risk in the occupied zone are also described in the paper.

INDOOR AIR QUALITY AND VENTILATION

Ventilation is supply of air to a space to improve the indoor air quality. The idea is to dilute pollutants emitted in the space to a desired, acceptable level. Since Pettenkofer (1858) and Yaglou (1936) ventilation standards have assumed that the occupants are the dominating or exclusive polluters. Unfortunately, compliance with the existing standards have not prevented widespread complaints on indoor air quality in many buildings. Recent studies have identified that materials in the building often are more important polluters than the occupants and contribute significantly to the complaints (Fanger et al. 1988, Pejtersen et al. 1990, Thorstensen et al. 1990). In the present paper a new method of determining the required ventilation is prescribed. This method is used in the new European Ventilation Guidelines (CEC 1992). An essential point is that all pollution sources are considered. This means, that use of low-polluting materials in a building is rewarded by a low required ventilation, while the use of high-polluting materials is penalised by a high required ventilation.

In contrast to existing standards this paper does not just prescribe a given quantity of outdoor air to be supplied to a space. It begins with a decision on the level of air quality aimed at in the ventilated space. A high, a standard or a more modest air quality may be desired. The available quality of the outdoor air is also considered. A high outdoor air quality requires a lower ventilation rate than a moderate outdoor air quality. The required ventilation can then be calculated based on the total pollution load, the desired indoor air quality, the outdoor air quality available and the ventilation effectiveness of the ventilated space. The occupants in a space have two requirements to the air they are breathing 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. In the European Guidelines (CEC

1992) the ventilation rate required for comfort and health are calculated separately and the highest value is used for design. But usually the ventilation rate required for comfort is much higher than required from the point of view of health. The ventilation required for comfort, i.e. to obtain a certain perceived air quality, is discussed in this paper.

PERCEIVED AIR QUALITY AND VENTILATION

Man perceives 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 (Fanger 1988a). One decipol is the perceived air quality in a space with a sensory pollution source 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. Any pollution source can be expressed in olfs, i.e. the number of standard persons required to make the air equally 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.

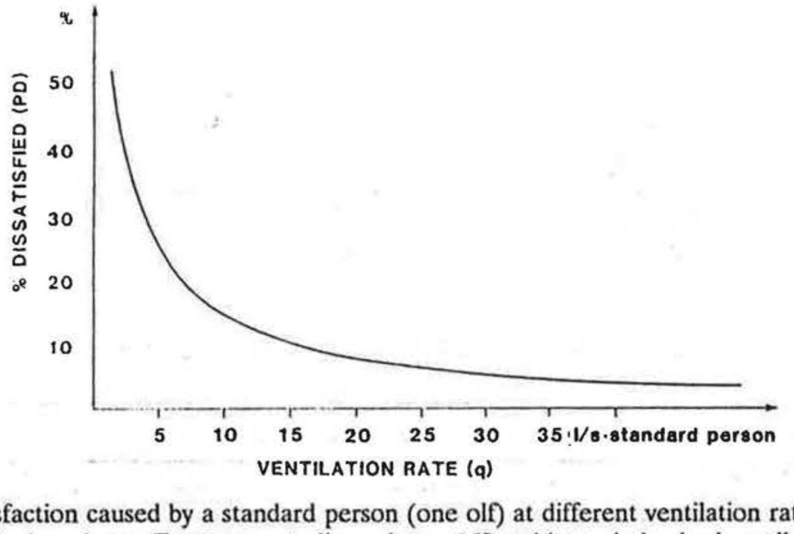

Fig. 1 Dissatisfaction caused by a standard person (one olf) at different ventilation rates. The curve is based on European studies where 168 subjects judged air polluted by bioeffluents from more than one thousand sedentary men and women (Fanger 1988a). Similar studies in North America (Cain et al. 1983) and Japan (Iwashita et al. 1990) by other research groups show close agreement with the present European data. The curve is given by these equations:

$$PD = 395 \cdot \exp(-1{,}83 \cdot q^{0.25}) \quad \text{for } q \geq 0.32 \text{ l/s} \cdot \text{olf}$$
$$PD = 100 \quad \text{for } q < 0.32 \text{ l/s} \cdot \text{olf}$$

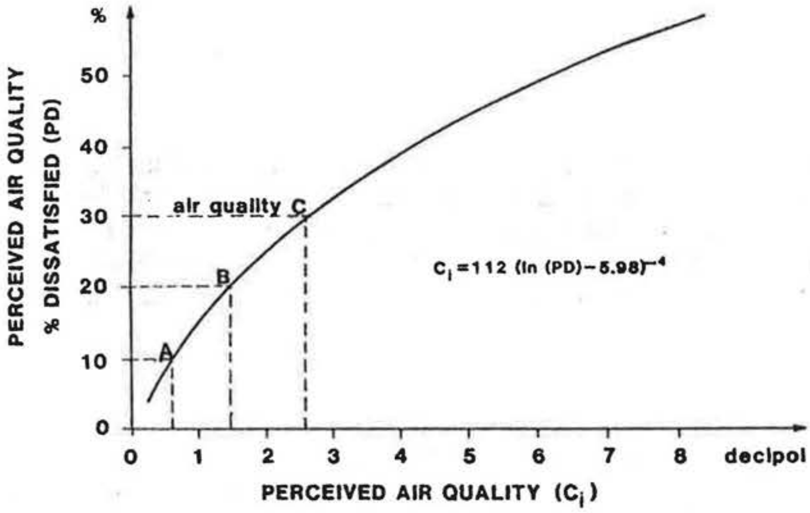

Fig. 2 The relation between perceived air quality expressed by the percentage of dissatisfied and expressed in decipol. The three indoor air quality levels, categories A, B and C are shown.

To determine the required ventilation it is essential to consider what level of indoor air quality is desired. In some spaces it may be sufficient to provide a modest air quality (category C). In many spaces a standard air quality (category B) would be required, while in other spaces a high air quality (category A) may be desired. These three levels of comfort are given in Table 1 and shown in Fig. 2 as percent dissatisfied and in decipol. The decision on the desired level of air quality in a space depends mainly on economic considerations and on the application of the space.

Table 1. Three levels of perceived indoor air quality (examples)

Quality level (category)	Perceived air quality		Required ventilation rate* l/s· olf
	% dissatisfied	decipol	
A	10	0.6	16
B	20	1.4	7
C	30	2.5	4

* The ventilation rates given are examples referring to clean outdoor air and a ventilation effectiveness of one.

Table 2. Pollution load caused by the occupants

	Sensory pollution load olf/occupant	Carbon dioxide l/(h· occupant)	Carbon monoxide [2] l/(h· occupant)	Water vapour [3] g/(h· occupant)
Sedentary, 1-1.2 met [1]				
0% smokers	1	19		50
20% smokers [4]	2	19	$11 \cdot 10^{-3}$	50
40% smokers [4]	3	19	$21 \cdot 10^{-3}$	50
100% smokers [4]	6	19	$53 \cdot 10^{-3}$	50
Physical excercise				
Low level, 3 met	4	50		200
Medium level, 6 met	10	100		430
High level (athletes), 10 met	20	170		750
Children				
Kindergarten, 3-6 years, 2.7 met	1.2	18		90
School, 14-16 years, 1-1.2 met	1.3	19		50

[1] 1 met is the metabolic rate of a resting sedentary person (1 met = $58 W/m^2$ skin area), i.e. approx. 100 W for an average person)
[2] from tobacco smoking
[3] applies for persons close to thermal neutrality
[4] average smoking rate 1.2 cigarettes/hour per smoker, emission rate 44 ml CO/cigarette

Table 3. Pollution load caused by the building, including furnishing, carpets and ventilation system

	Sensory pollution load olf/(m^2 floor)		Chemical pollution load TVOC $\mu g/s \cdot (m^2$ floor)	
	Mean	Range	Mean	Range
Existing buildings				
Offices [1]	0.3	0.02-0.95	- [6]	
Schools (class rooms) [2]	0.3	0.12-0.54	- [6]	
Kindergartens [3]	0.4	0.20-0.74	- [6]	
Assembly halls [4]	0.5	0.13-1.32	- [6]	
Dwellings [5]			0.2	0.1-0.3
Low-polluting buildings (target values)		0.05-0.1	- [6]	

[1] Data for 24 mechanically ventilated office buildings
[2] Data for 6 mechanically ventilated schools
[3] Data for 9 mechanically ventilated kindergartens
[4] Data for 5 mechanically ventilated assembly halls
[5] Data for 3 naturally ventilated dwellings
[6] Data not yet available

The perceived air quality in Table 1 refers to peoples' initial judgement when entering a space. The first impression is essential, i.e. it is important that the air immediately is perceived acceptable. However, some adaptation do 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 usually takes place in air polluted by building materials etc. (Gunnarsen 1990).

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. A sensory pollution source can be expressed by the olf unit which integrates the effect of the many chemicals as perceived by human beings.

SENSORY POLLUTION LOAD

The total sensory pollution load on the air in a space is found by adding the individual loads 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. Table 2 lists the sensory pollution load from occupants at different activities with no smoking and with different percentages of smokers among the occupants.

The pollution load from the building may be found by adding the individual loads of all materials present. But information on olf per m^2 is only available for few individual materials yet. A more feasible approach at this present time is to estimate the sensory pollution load per m^2 floor caused by the building, including furnishing, carpeting and ventilation system. Table 3 comprises data from the measured sensory pollution loads in different types of existing buildings. The sensory polltuion 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 pollution 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 sensory pollution load.

It is recommended to calculate the total pollution load in a space by simple addition of the loads of the individual pollution sources in a space. This has been shown to provide a reasonable first approximate method of combining many pollution sources (Bluyssen and Fanger 1991). 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 sources.

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 lower quality. Table 4 lists characteristic levels of outdoor air quality.

The World Health Organization has published "Air Quality Guidelines for Europe" (WHO 1987), where guideline values for certain individual substances in the outdoor air are given. If the outdoor air quality is poor, it may be required to clean the air before it is suitable for ventilation.

Table 4. Outdoor levels of air quality*

	Perceived air quality decipol	Air pollutants			
		Carbon dioxide mg/m³	Carbon monoxide mg/m³	Nitrogen dioxide µg/m³	Sulfur dioxide µg/m³
At sea	0	680	0-0.2	2	1
In towns, good air quality	< 0.1	700	1-2	5-20	5-20
In towns, poor air quality	> 0.5	700-800	4-6	50-80	50-100

* The values for the perceived air quality are typical daily average values. The values for the four air pollutants are annual average concentrations.

REQUIRED VENTILATION

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

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

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

The ventilation effectiveness is the relation between the air pollution concentration in the return air and in the breathing zone. It is important to select an air distribution system which provides a high ventilation effectiveness. The location of the pollution sources in the space as well as the air distribution system influence the ventilation effectiveness.

Equation [1] applies 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.

NON-UNIFORMITY OF AIR QUALITY

The required ventilation has been calculated to provide a certain air quality in the breathing zone. Still there may be large differences inside the space depending upon the selected air distribution system and the location of the pollution sources. The non-uniformity of the perceived air quality may be calculated and expressed by drawing iso-decipol curves at the breathing level inside the occupied zone.

THERMAL ENVIRONMENT

The thermal sensation of the occupants in a ventilated space may be predicted by the PMV index (Fanger 1970). The Predicted Mean Vote is a function of the clothing and activity of the ocupants and of the thermal parameters: air temperature, mean radiant temperature, air velocity and humidity. The activity and clothing may be estimated according to the application of the space and the season. The PMV may then be calculated throughout the occupied zone. The PPD (Predicted Percentage of Dissatisfied) is a function of PMV and may also be calculated. The thermal non-uniformity in the occupied zone may be expressed by iso-PMV or iso-PPD curves. The international standard (ISO 1984) recommends as a comfort limit that PMV be within ±0.5. This corresponds to less than 10% dissatisfied.

RISK OF DRAFT

Draft is an unwanted local cooling of the human body due to air movement. In ventilated spaces it is one of the most common causes of complaint. There are large individual differences in the sensitivity to draft. Some people are extremely sensitive while others are rather insensitive to air movement. The risk of draft may be expressed as the percentage of people predicted to be dissatisfied due to air movement. The risk of draft may be calculated by the model of draft risk (Fanger et al. 1988) shown in Fig. 3. The risk of draft depends on the air temperature, the mean velocity and the turbulence intensity. The risk of draft may be predicted by the model for any point in the occupied zone and the average risk may be estimated. Iso-draft-risk curves may also be drawn in the occupied zone. The comfort limit used for design may be a draft risk less than 15, 20 or 25%.

MODEL OF DRAFT RISK

$$PD = (34 - t_a)(v - 0.05)^{0.62}(0.37\ \bar{v}\ Tu + 3.14)$$

for $\bar{v} < 0.05$ m/s insert $\bar{v} = 0.05$ m/s, for $PD > 100\%$ use $PD = 100\%$

where PD = Percentage Dissatisfied people due to draft (%)
t_a = air temperature (°C)
$\bar{v}$ = mean air velocity (m/s)
Tu = turbulence intensity (%)

Fig. 3 The model of draft risk predicts the percent of dissatisfied people caused by draft as a function of air temperature, mean air velocity and turbulence intensity (= standard deviation divided by mean velocity). The model applies for sedentary persons.

CONCLUSIONS

- Human comfort in a ventilated space depends on the perceived air quality, on the general thermal sensation and on the risk of draft.

- The new European Guidelines for Ventilation Reqirements presents a novel method of designing for indoor air quality, rather than for air quantity.

- The new method calculates the ventilation required to obtain a desired indoor air quality, acknowledging <u>all</u> pollution sources in the space, the available outdoor air quality and the ventilation effectiveness.

- The non-uniformity of the perceived air quality may be expressed by iso-decipol curves in the breathing zone of the space.

- The non-uniformity of the thermal field may be expressed by iso-PMV or iso-PPD curves in the occupied zone.

- The average draft risk may be predicted in a space and iso-draft-risk curves be drawn in the occupied zone.

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