A COMFORT EQUATION FOR INDOOR AIR QUALITY AND VENTILATION

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Abstract

A comfort equation for indoor air quality and ventilation is introduced. The equation is based on the new units, olf and decipol, for perceived air quality. The comfort equation prescribes the ventilation required to obtain a given perceived air quality (in decipol) in a space with a given pollution load (in olfs). In contrast to ventilation standards during a century the comfort equation acknowledges all pollution sources, not just human bioeffluents and smoking. The equation prescribes more ventilation than present standards, or a reduction of the hidden olfs occurring in many existing buildings. The comfort equation establishes a rational basis for future ventilation standards.

Introduction

Many people are bothered by indoor air and feel relieved when they come outdoors. This dissatisfaction has been documented in hundreds of detailed field studies in offices, schools, dwellings, and other non-industrial buildings in Europe, North America, and Japan (1-11). The complaints comprise the perception of stale and stuffy air, irritation of mucous membranes, headache, lethargy etc. These symptoms are usually called the sick building syndrome (12).

The symptoms are not confined to a few special buildings, for they occur in nearly all indoor spaces. There are, however, wide variations in the percentage of occupants who are bothered.

In some buildings there are obvious reasons for the poor air quality. The air supply may for instance be lower than designed. But the frustrating fact is that most of the buildings studied in different parts of the world complied with existing ventilation standards. Nevertheless 20, 40 or 60% of the occupants typically found the air unacceptable.

The purpose of a ventilation standard is to provide acceptable air for the occupants. If this is not achieved there must be something wrong with the existing standards. The basis of these is still the philosophy of Pettenkofer (13) who founded modern hygiene more than a century ago, and the classical studies of Yaglou at Harvard in the 1930's (14). Their experiments on human bioeffluents have had a fundamental influence on ventilation standards in this century. In offices, assembly halls and other similar non-industrial spaces it has been assumed implicitly that man was the dominating or exclusive polluter. Required ventilation was therefore specified per occupant. The standards have assumed that rooms and ventilation systems were absolutely clean and did not contribute to pollution of the air.

Recently Fanger et al. (15) have identified severe pollution sources in spaces and ventilation systems by studying unoccupied office buildings. The introduction of the olf-unit (16) made it possible to quantify and compare different types of pollution sources. On an average, human bioeffluents were found to comprise as little as 13% of the pollution sources. Materials in spaces and ventilation systems, ignored for a century as pollution sources in standards, were the major cause of the rather poor air quality observed in the 15 office buildings investigated. These hidden olfs are believed to be the main reason for the sick building syndrome.

In the present paper a comfort equation for air quality is presented which considers all pollution sources present. It is based on the new units, olf and decipol, which integrate the pollutants in the air in the same way as they are perceived by human beings. The idea is to express all pollution sources in olfs. For a total pollution load in a space it is then possible to calculate the required ventilation to obtain a desired air quality.

Initially the new units, olf and decipol, will be discussed. Olf is a unit which quantifies the source strength of air pollution, while decipol is a unit quantifying the perceived air pollution. Humans perceive the air by their olfactory and chemical sense, being sensitive to odorants and irritants in the air.

The olf unit

One olf (from Latin "olfactus" = olfactory sense) is the emission rate of air pollutants (bioeffluents) from a standard person (Fig. 1). Any other pollution source is expressed by the number of standard persons (olfs) required to cause the same dissatisfaction as the actual pollution source (Fig. 2). The olf is thus a relative unit similar to the clo unit for insulation of clothing or the met unit for metabolic rate.

A human being was chosen as the reference because this has been considered the main pollution source in ventilation standards for a century.

The most comprehensive information on bioeffluents is given in Fig. 3, which shows the definition curve for one olf (16). The curve shows how air polluted by one standard person (one olf) is perceived at different ventilation rates. The figure identifies the percentage of dissatisfied, i.e. those who perceive the air as unacceptable just after entering the room. The curve is based on bioeffluents from more than one thousand subjects judged by 168 men and women (16,22). Table 1 lists olf values for different human pollution sources (17). As the olf concept is so new (16) only few values exist at present but measurement of olf values for typical building materials and other pollution sources are currently being collected.

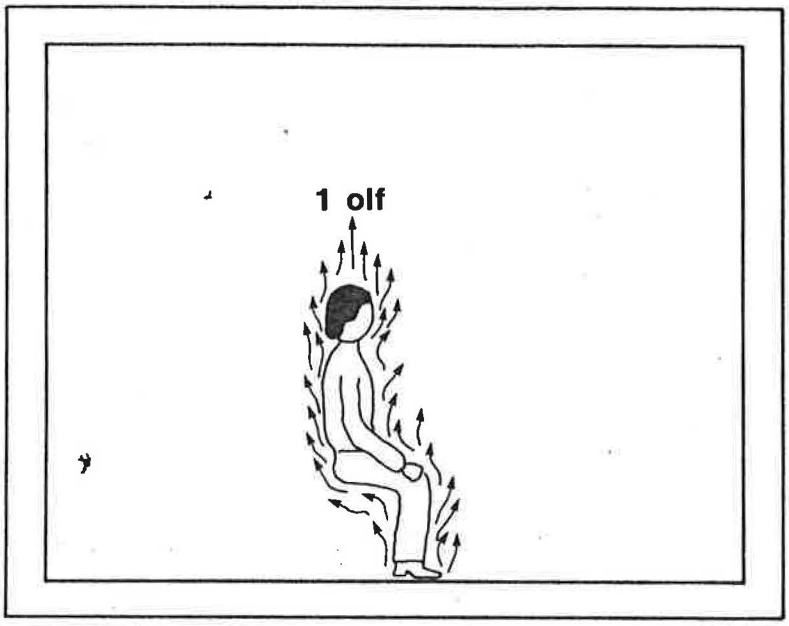

Fig. 1. One olf is the air pollution from one standard person, i.e. from an average adult working in an office or a similar non-industrial workplace, sedentary and in thermal comfort with a hygienic standard equivalent to 0.7 bath/day.

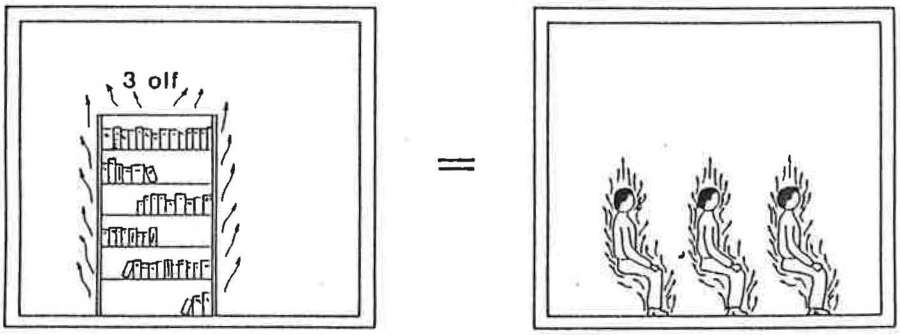

Fig. 2. A pollution source has a strength of 3 olf, if the pollution from 3 standard persons causes the same dissatisfaction as the source.

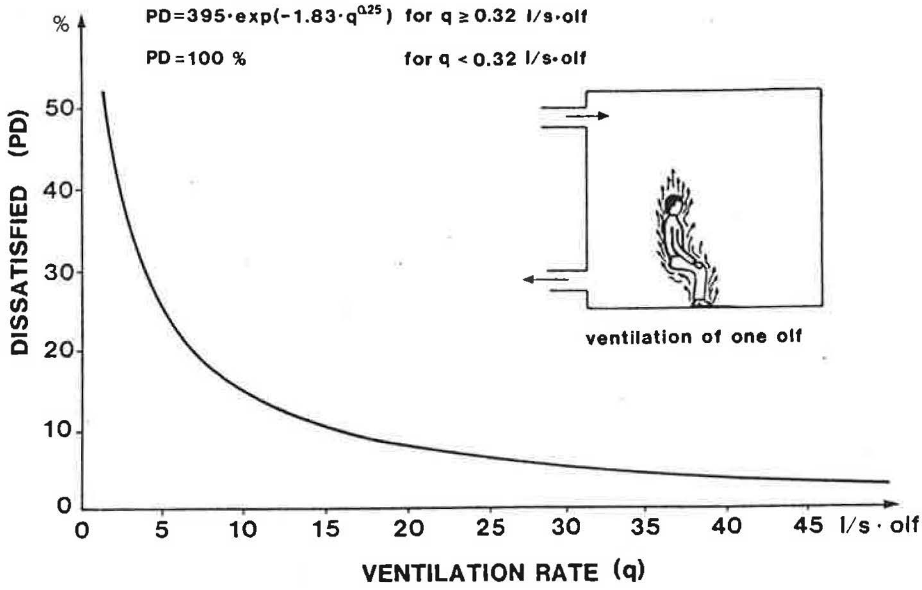

Fig. 3. Dissatisfaction caused by one olf at different ventilation rates. The dissatisfied are the persons who find the air unacceptable, when entering the space. The curve is based on bioeffluents from more than one thousand persons, judged by 168 subjects (16,22).

Table 1. Olf-values for human pollution sources (17)

Sedentary person, 1 met	1 olf
Active person, 4 met	5 olf
Active person, 6 met	11 olf
Smoker, when smoking	25 olf
Smoker, average	6 olf

The decipol unit

The concentration of air pollution depends on the pollution source and the dilution caused by the ventilation. The perceived air pollution is defined as that concentration of human bioeffluents that would cause the same dissatisfaction as the actual air pollution (16). One decipol (pol from Latin "pollutio" = pollution) is the pollution caused by one standard person (one olf) ventilated by 10 l/s of unpolluted air (Fig. 4). That is,

$$1 \text{ decipol} = 0.1 \text{ olf}/(\text{l/s})$$

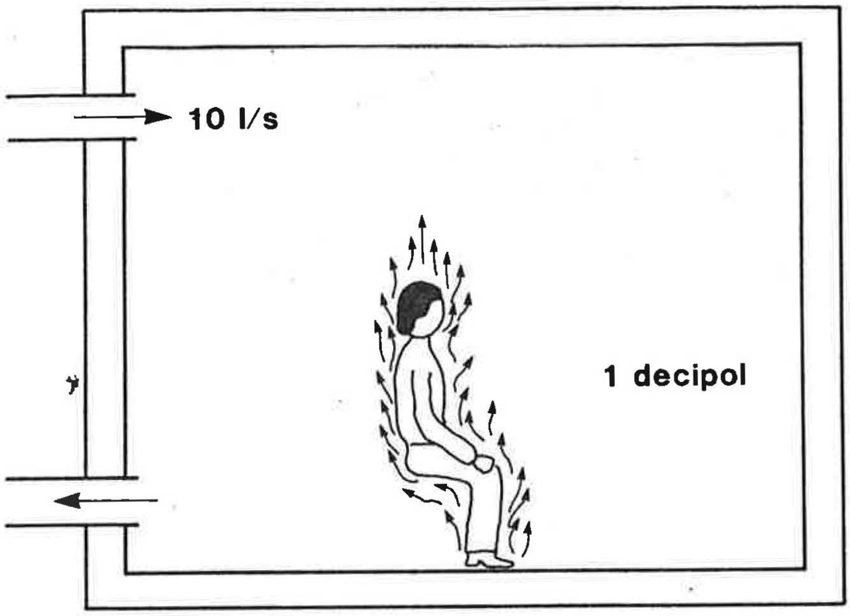

Fig. 4. One decipol is the perceived air pollution in a space with a pollution source of one olf ventilated by 10 l/s of unpolluted air. Steady-state conditions and complete mixing are assumed.

Fig. 5 shows the percentage of dissatisfied as a function of the perceived air pollution in decipol. Fig. 5 is derived from the same data as Fig. 3.

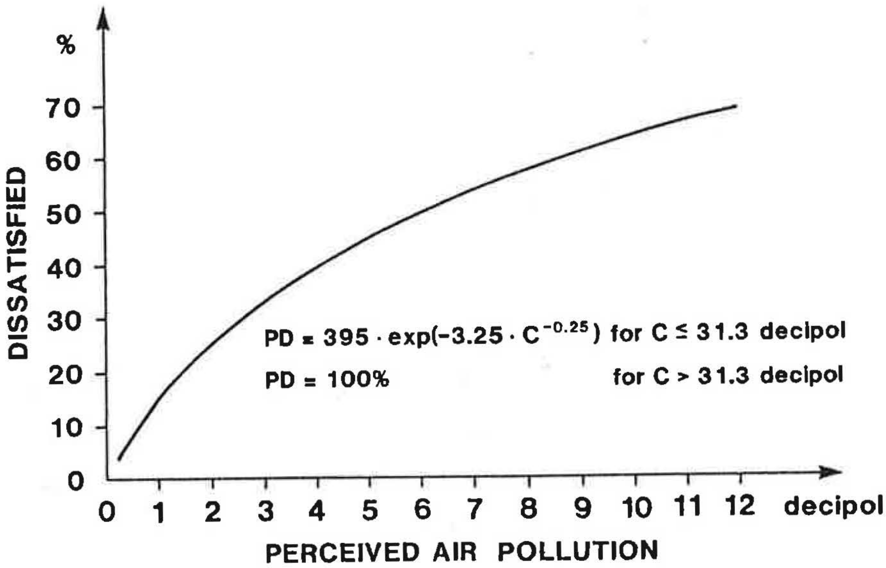

Fig. 5. Percentage of dissatisfied as a function of the perceived air pollution in decipol.

In many well ventilated buildings with low pollution sources the perceived air pollution is below one decipol or 15% dissatisfied ("healthy buildings"). Spaces with low ventilation and high pollution sources may easily have a perceived air pollution around 10 decipol or 60% dissatisfied. Air qualities around 0.1 decipol or 1% dissatisfied are common outdoors but are hard to establish in indoor environments. Fig. 6 shows the decipol scale and indicates typical levels of perceived air quality.

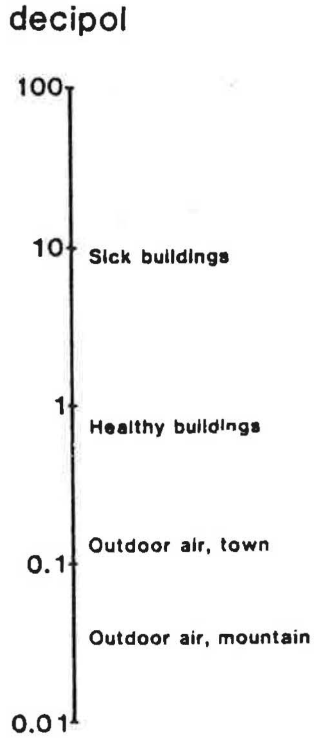

Fig. 6. The decipol scale for perceived air pollution with typical examples shown.

Analogy to light and noise units

The two new units for air quality, olf and decipol, correspond to analogous units for light and noise.

As listed in Fig. 7, olf corresponds to lumen for light. Lumen is the unit for light emitted from a source. Only electromagnetic radiation sensitive to the human eye is considered, i.e. with wave lengths between 380 and 720 nm. Within this range the impact of the different wave lengths is weighted according to the sensitivity of the eye.

For noise the source strength is given by the sound power measured in watt. Only power sensitive to the human ear is considered, i.e. with frequencies between 20 and 20.000 Hz.

The olf unit integrates the emitted pollutants according to their impact on the human nose and the perceived annoyance.

	Light	Noise	Air Pollution
Source Strength	lumen	watt	olf
Perceived Level	lux	decibel (A)	decipol

Fig. 7. Comparison between the new units for air pollution and analogous units for light and noise.

The decipol expresses the air pollution perceived by the nose as the lux expresses the light perceived by the eye and the decibel(A) expresses the sound perceived by the ear. Both lux and decibel express the perceived level independent of the annoyance. A given dB(A) may for example be caused by traffic or by chamber music. Here we have a deviation in relation to decipol; it was found more useful to define the decipol by the annoyance rather than by the perceived level or intensity. A certain decipol level expresses a constant annoyance,i.e. a constant percentage of dissatisfied, independent of the type of air pollution.

In the beginning, light and noise could only be measured using man as a meter. Later, instruments were developed with built-in information about the sensitivity of the eye and the ear depending on the wave length. Similarly, we can at the moment measure olf and decipol only by using man as a meter. This means using a panel of judges. It will, however, be a challenge in the future to develop an instrument which can measure the perceived air pollution - a decipol meter.

Health risk

It should be emphasized that the decipol level expresses the perception of the air by humans, not whether the pollution is a health risk. Any such risk should be considered separately. Still, our senses - with a few exceptions - are also influenced by harmful pollutants. Our senses have an important warning function against dangers in the environment. The perceived air pollution in decipol may therefore in many cases also provide a first estimate of a possible health risk.

Comfort equation for indoor air quality and ventilation

Utilizing the olf and decipol units makes it possible to establish a pollution balance for the air in a space (see Fig. 8). The following equation expresses that the pollution emitted from the pollution sources in the space is taken up by the outdoor air supplied to the space

$$C_i = C_o + 10 \frac{G}{Q} \qquad (1)$$

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where C_i = perceived air pollution in the space (decipol)

C_o = perceived air pollution outdoors (decipol)

G = pollution source strength in the space and the corresponding ventilation system (olf)

Q = outdoor air supply = ventilation rate (l/s)

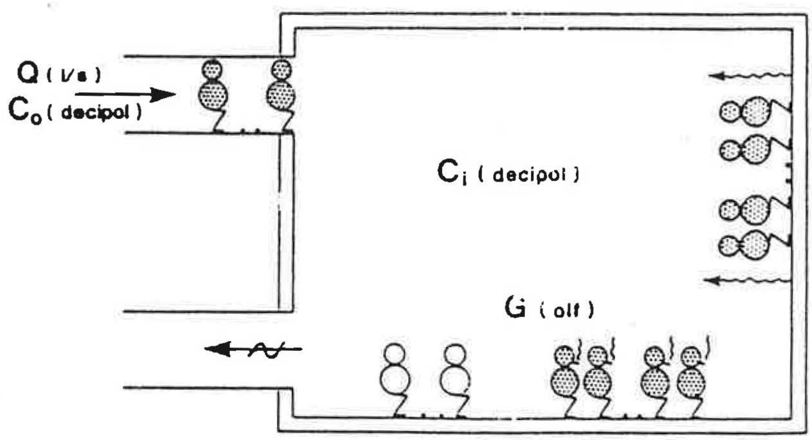

Fig. 8. A space with total pollution sources G and perceived air quality C_i, ventilated by a flow of outdoor air Q with the air quality C_o.

For design purposes it is usually the required ventilation that needs to be determined and eq. (1) is therefore re-arranged, while C_i is expressed by the percentage of dissatisfied, PD (Fig. 5)

$$Q = 10 \frac{G}{C_i - C_o}$$

$$C_i = 112(\ln(PD) - 5.98)^{-4} \quad (2)$$

Eq. (2) is the new comfort equation for indoor air quality and ventilation. For any desired perceived indoor air quality, i.e. percentage of dissatisfied, the comfort equation determines the ventilation required to handle the total pollution source strength in the space. The perceived outdoor air pollution is also included in the model and should be estimated to determine the required ventilation.

The comfort equation may also be used to predict the air quality in a space (in decipol or percentage of dissatisfied) when the pollution source strength and the ventilation rate are known. The comfort equation may furthermore be used to determine the source strength in olfs in a space experimentally, by measuring the outdoor air supply and by a judgment of the air quality indoors and outdoors by a panel (15).

The comfort equation applies for steady-state conditions and complete mixing of the air in the space. A corresponding equation for transient conditions and any ventilation efficiency can easily be set up.

A basic idea in ventilation standards since Pettenkofer (13) and Yaglou (14) has been that people should perceive the air quality acceptable from the first moment they enter a space. It was essential that the first impression of the air was good. It was felt rather unrealistic to tell people not to worry about their first negative impression of the air quality, but to wait some time until they became adapted to the pollution, for the air would then be more acceptable. The present comfort equation honors the idea concerning the first impression. The equation is based on a judgement of air quality just after entrance to a space.

Future ventilation standards

The comfort equation for indoor air quality may be used as a rational basis for future ventilation standards. It acknowledges for the first time all pollution sources, not just human bioeffluents and smoking, and it quantifies for the first time the quality of indoor and outdoor air as perceived by human beings.

The first step in a ventilation standard is to determine the desired air quality in the space to be ventilated. This is already done in the present ASHRAE ventilation standard (18) which specifies that the air quality should be acceptable to 80% of the occupants. This corresponds to 20% dissatisfied or 1.4 decipol. But a future standard may very well specify different air qualities for spaces with different applications.

The next step is to estimate the quality of the outdoor air available for ventilation of the space. In many cases the perceived outdoor air pollution is negligible compared to the indoor level. Table 2 lists some measured and estimated orders of magnitude of perceived outdoor air pollution, but further data should be collected for typical locations and different heights above the ground. If the outdoor pollution is severe it may be necessary to clean the outdoor air before it is suitable for ventilation.

Table 2. Perceived outdoor air pollution

	decipol
During smog episodes	> 1
In cities with moderate air pollution (15)	∿ 0.05-0.3
In mountains or at sea	∿ 0.01

The present estimates of pollution loads in olf/m^2 are analogous to rough estimates of heating or cooling loads in buildings expressed in W/m^2. A more detailed analysis of the thermal load requires information on the insulation of the various building components etc. Similarly, a more detailed analysis of pollution sources in a space will require information on olf-values of single materials in spaces and of components in ventilation systems. Such an olf-catalogue does not exist yet, but will be useful for future design and selection of materials.

Table 3 comprises also an estimate of the total pollution load in office buildings. For an average of existing office buildings with 40% smokers the total pollution load from occupants, smoking, materials and ventilation system is 0.7 olf/m^2. In low-olf office buildings with no smoking the total load is only 0.2 olf/m^2.

Ventilation requirements for office buildings may now be determined by the new comfort equation. To obtain an indoor air quality of 1.4 decipol (20% dissatisfied) a ventilation rate of 5 l/s m^2 is required for average existing office buildings (Table 4). This is three times higher than prescribed by any existing ventilation standard (Table 4). Such an increase in ventilation is <u>not</u> recommended, but rather the obvious alternative, i.e., to reduce the unnecessary hidden olfs. This will at the same time improve indoor air quality, decrease required ventilation and energy consumption, and diminish the risk of draught.

Table 4. Ventilation requirements in office buildings*

		l/s m^2
Comfort equation (Indoor air quality = 1.4 decipol)		
	Existing buildings (0.7 olf/m^2) smoking	5
	Low-olf buildings (0.2 olf/m^2) non-smoking	1.4
ASHRAE Standard 62-81 (18)		
	smoking	1.7
	non-smoking	0.25
Nordic Guidelines, NKB (20)		
	smoking	1.0
	non-smoking	0.4
DIN 1946 Standard, large offices (21)		
	smoking	1.9
	non-smoking	1.4

*Assuming 0.1 person/m^2 and negligible outdoor air pollution

In low-olf buildings the ventilation requirement is 1.4 $l/s\ m^2$ (Table 4). This ventilation rate is of the same order of magnitude as prescribed by some of the standards. The key to obtaining an acceptable indoor air quality at a reasonable ventilation rate is thus to control the olf-load in the building at a low level. The design, development and maintenance of low-olf buildings is a fascinating challenge for the future. It is an obvious way of improving indoor air quality, and a promising method to prevent sick buildings.

Conclusions

- A comfort equation for indoor air quality and ventilation is introduced based on the new units, olf and decipol.
- The comfort equation prescribes the ventilation required to obtain a given perceived air quality (in decipol) in a space with a given pollution load (in olfs).
- The comfort equation acknowledges for the first time all pollution sources, not just human bioeffluents and smoking, and it quantifies for the first time the quality of indoor and outdoor air as perceived by human beings.
- The equation prescribes more ventilation than present standards, or a reduction of the hidden olfs occurring in many existing buildings.
- The comfort equation establishes a rational basis for future ventilation standards.

Acknowledgements

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