N/S.

#3456

IAQ 89: The Human Equation: Health and Comfort,
April 17-20, 1989, San Diego

THE NEW COMFORT EQUATION FOR INDOOR AIR QUALITY

By P.O. Fanger, D.Sc., ASHRAE Fellow
Laboratory of Heating and Air Conditioning
Technical University of Denmark

ABSTRACT

For more than a century, ventilation standards have been based on Pettenkofer's and Yaglou's classical theory that the human being is the dominant polluter in non-industrial buildings. Unfortunately, the existing standards do not prevent serious complaints concerning air quality in many buildings. A new philosophy of ventilation is introduced acknowledging all pollution sources (materials, furniture, systems, etc.) in addition to bioeffluents and smoking caused by humans. This is accomplished by the olf and the decipol, the new units for perceived air quality. The units are used in a new comfort equation for indoor air quality. The comfort equation prescribes the ventilation required to obtain a given air quality (in decipol) in a space with a given pollution load (in olfs). The equation prescribes more ventilation than present standards or a reduction of the hidden olfs that ruin the air in many existing buildings. The comfort equation establishes a rational basis for future ventilation standards.

INTRODUCTION

The quality of indoor air is frequently unacceptable. Many people are bothered by the air they breathe and feel relieved when they get 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. The complaints include the perception of stale and stuffy air, irritation of mucous membranes, headache, lethargy, etc. These complaints are sometimes called the sick building syndrome (WHO 1983).

The complaints are not confined to a few special buildings, for they occur in most 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 less than designed. But the frustrating fact is that most of the buildings studied in different parts of the world complied with existing ventilation standards and concentrations of measured contaminants were several orders of magnitude below any conceivable limit. Nevertheless, typically 20%, 40%, or 60% of the occupants 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. Their basis is still the philosophy of Pettenkofer (1858), who founded modern hygiene, and the classical studies of Yaglou et al. in 1936. 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 predominant or exclusive polluter. Required ventilation was therefore specified per occupant. Some recent standards do refer to other pollution sources or single pollutants. But, for practical applications, they still assume that rooms and ventilation systems are absolutely clean and do not contribute to pollution of the air.

Recently Fanger et al. (1988) have identified severe pollution sources in spaces and ventilation systems by studying both occupied and unoccupied office buildings. The introduction of the olf unit (Fanger 1988) made it possible to quantify and compare different types of pollution sources. On 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 many of 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 new philosophy of ventilation is introduced considering <u>all</u> pollution sources present. This philosophy is quantified in a new comfort equation for indoor air quality. The equation is based on the olf and the decipol, the new units which integrate the pollutants in the air in the same way as they are perceived by human beings (Fanger 1988). 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 ventilation required to obtain a desired air quality.

Comfort Equation for Indoor Air Quality

The use of the olf and decipol units makes it possible to establish a pollution balance for the air in a space (see Figure 1). 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.

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

<u>where</u>

C_i = perceived air quality in the space (decipol)

C_o = perceived air quality outdoors (decipol)

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

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

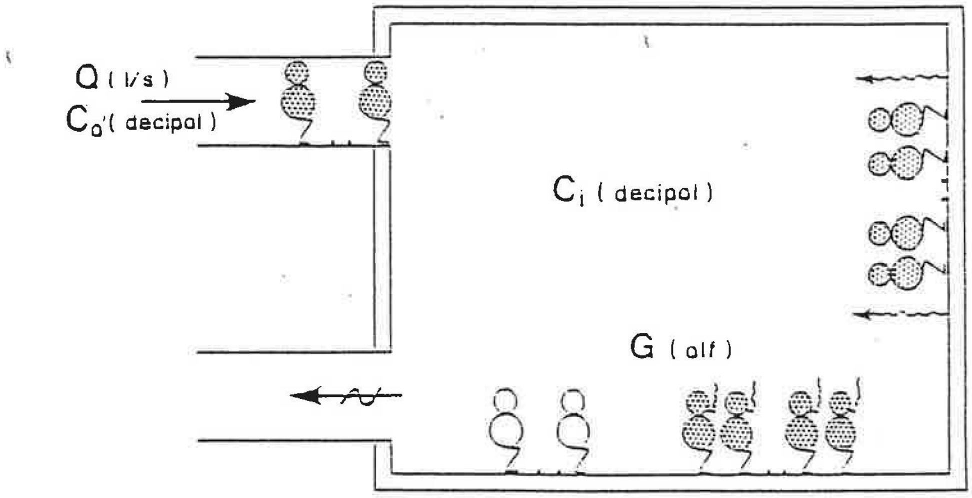

Fig. 1. A space with total pollution sources G and perceived air quality C_i, ventilated by a flow of outdoor air with the air quality C_o.

For design purposes it is usually the required ventilation that needs to be determined and Equation 1 is therefore rearranged in Figure 2. The relation between indoor air quality in decipol and percentage of dissatisfied is also given in Figure 2 (Fanger 1988).

COMFORT EQUATION FOR INDOOR AIR QUALITY

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

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

where Q = ventilation rate (l/s)
G = total pollution sources (olf)
C_i = perceived indoor air quality (decipol)
C_o = perceived outdoor air quality (decipol)
PD = percent dissatisfied (%)

Fig. 2. The comfort equation for indoor air quality.

The model in Figure 2 is the new comfort equation for indoor air quality. 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 quality is 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 experimentally the source strength in olfs in a space by measuring the outdoor air supply and by a judgment of the air quality indoors and outdoors by a panel (Fanger et al. 1988).

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 and Yaglou 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 to be rather unrealistic telling people to disregard their first negative impression of the air quality and instead to wait some time until they became adapted to the pollution, as the air would be more acceptable then. The present comfort equation honors the idea concerning the first impression. The equation is based on a judgment of air quality just after entering a space.

It is essential to underline that the comfort equation predicts how the air is perceived. Some contaminants like radon and carbon monoxide are not perceived but may still present a health risk. Such contaminants should be considered separately.

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 (ASHRAE 1989), 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 1 lists some measured and estimated orders of magnitude of perceived outdoor air quality, 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 1. Perceived Outdoor Air Quality

	decipol
During smog episodes	> 1
In cities with moderate air pollution (Fanger et al. 1988)	0.05-0.3
On mountains or at sea	0.01

The third step requires an estimation of all the pollution sources in the space and the corresponding ventilation system. The total olf load in the space should be calculated. Table 2 shows, as an example, estimated olf loads in offices per m^2 floor area. There is a contribution from the bioeffluents of the occupants. That is straightforward, i.e., 1 olf per person according to the olf definition. With 0.1 persons per m^2, the bioeffluents contribute 0.1 olf per m^2 floor area. If smoking is permitted, there is an additional contribution, estimated on the basis of studies by Cain et al. (1983). For 40% smokers, which is a typical figure in Europe, this corresponds to an additional 0.2 olf/m^2. In North America less than 30% of occupants smoke, but each one smokes a larger number of cigarettes. So the average source strength of smoking is also around 0.2 olf/m^2 in North America.

The estimated pollution loads from materials plus the ventilation system are based on a field study by Fanger et al. (1988) in 15 randomly selected office buildings in Copenhagen. They found extensive pollution sources in the unoccupied buildings. The average pollution load was 0.4 olf/m^2, with a range of 0.1 to 0.9 olf/m^2. The pollution originated from all types of building materials, furniture, carpets, books, office machines, etc., and a major contribution came from the ventilation systems. As a first rough estimate of pollution sources from materials and ventilation systems in existing office buildings it is proposed to use the figure 0.4 olf/m^2.

For future design of office buildings it is recommended that strict control be kept of all materials used, that ventilation systems be designed with a low olf value when new, and that a rigorous maintenance scheme be prescribed to keep it low during its lifetime. In this way it is estimated that low-olf office buildings can be constructed with a pollution load around 0.1 olf/m^2 from materials and the ventilation system. This corresponds to the best buildings found in the Copenhagen study. Further field studies on olf values of a wide range of unoccupied, existing, and future buildings in different parts of the world are recommended.

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 of ventilation systems. Such an olf catalogue does not yet exist, but will be useful for future design and selection of materials.

Table 2 also gives 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 systems is 0.7 olf/m^2. In low-olf office buildings with no smoking, the total load is only 0.2 olf/m^2.

Table 2. Estimated olf Loads in Offices per m^2 Floor Area

Pollution sources	olf/m^2
Occupants (one person per 10 m^2)	
Bioeffluents	0.1
Additional load from 20% smokers	0.1
40% smokers	0.2
60% smokers	0.3
Materials and ventilation system	
Average in existing buildings	0.4
Low-olf buildings	0.1
Total load in office buildings	
Average in existing buildings, 40% smokers	0.7
Low-olf buildings, non-smoking	0.2

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 3). This is three times higher than prescribed by any existing ventilation standard (Table 3). 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 draft.

Table 3. 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 62-89 (ASHRAE 1989)	0.8
Nordic Guidelines, NKB (NKB 1981)	
smoking	1.0
non-smoking	0.4
DIN 1946 Standard, large offices (DIN 1983)	
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 3). 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 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 of preventing sick buildings.

CONCLUSIONS

- A new philosophy of ventilation is introduced. The philosophy is quantified in a new comfort equation for indoor air quality based on the new units olf and decipol.
- The comfort equation prescribes the ventilation required to obtain a desired 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 ruining the air quality in many existing buildings.
- The comfort equation establishes a rational basis for future ventilation standards.

REFERENCES

ASHRAE. 1989. ASHRAE Standard 62-89, "Ventilation for acceptable indoor air quality." Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Cain, W.S., Leaderer, B.P., Isseroff, R., Berglund, L.G., Huey, R.J., Lipsitt, E.D., and Perlman, D., 1983. "Ventilation requirements in buildings: control of occupancy odor and tobacco smoke odor". Atmos. Environ., Vol. 17, No. 6.

DIN. 1983. 1946 Teil 2: Raumlufttechnik gesundheitsheitstechnische Anforderungen (VDI-Lüftungsregeln). Berlin: Deutsche Institut für Normung.

Fanger, P.O., 1988. "Introduction of the olf- and the decipol-unit to quantify air pollution perceived by humans indoors and outdoors". Energy and Buildings, Vol. 12, pp.1-6.

Fanger, P.O., Lauridsen, J., Bluyssen, P., and Clausen,G., 1988. " Air pollution sources in offices and assembly halls, quantified by the olf unit". Energy and Buildings, Vol. 12, 1988, pp.7-19.

NKB. 1981. Report No. 41: indoor climate. Stockholm.

Pettenkofer, M.S., 1858 "Über den Luftwechsel in Wohngebäuden". Munich: Cottasche Buchhandlung.

WHO 1983. "Indoor air pollutants: exposure and health effects". EURO Reports and Studies 78, pp.23-26.

Yaglou, C.P., Riley, E.C., and Coggins, D.I., "Ventilation Requirements". ASHVE Transactions, Vol. 42, pp. 133-162.