Introduction of the olf and the decipol Units to Quantify Air Pollution Perceived by Humans Indoors and Outdoors

P. O. FANGER

Laboratory of Heating and Air Conditioning, Technical University of Denmark, DK-2800 Lyngby (Denmark)

(Received August 17, 1987; accepted October 23, 1987)

SUMMARY

Two new units, the olf and the decipol, are introduced to quantify air pollution sources and air pollution perceived by humans indoors and outdoors. The olf is introduced to quantify pollution sources. One olf is the emission rate of air pollutants (bioeffluents) from a standard person. Any other pollution source is quantified by the number of standard persons (olfs) required to cause the same dissatisfaction as the actual pollution source. The olf unit is analogous to lumen and watt for light and noise sources. The decipol is introduced to quantify the concentration of air pollution as perceived by humans. The perceived air pollution is that concentration of human bioeffluents that would cause the same dissatisfaction as the actual air pollution. One decipol is the pollution caused by one standard person (one olf), ventilated by 10 l/s of unpolluted air. The decipol unit is analogous to lux and decibel(A) for light and noise. The percentage of dissatisfied as a function of the perceived air pollution in decipols is presented here, based on bioeffluents from more than one thousand occupants, judged by 168 subjects. A method for measurement of pollution sources and perceived air pollution is described. The new units provide a rational basis for the identification of pollution sources, for the calculation of ventilation requirements and for the prediction and measurement of air quality indoors and outdoors.

INTRODUCTION

In this paper two new units will be introduced, which make it possible to quantify air pollution sources and air pollution as perceived by humans in the indoor and the outdoor environment. This quantification provides a rational basis for identification and removal of pollution sources, for calculation of ventilation requirements and for establishing future ventilation standards in buildings. This has important, potential implications for the consumption of energy in buildings and for the prediction and measurement of air quality both indoors and outdoors.

For more than a century the quality of air has been judged by its chemical composition. In industrial environments, hygienists have established threshold limit values for single chemical compounds, where the chemicals in question are usually a result of the production process. The basis for the threshold limit values has been the relation between a dose of the chemical and the response of the workers. A limit has then been established below which the health risk was acceptable. These limits have generally been placed at relatively high levels, where it was quite easy to measure the chemical with standard instrumentation.

In non-industrial buildings (e.g., offices, schools or dwellings), the same hygienic/chemical principle has not been very successful. In such buildings there are often complaints about the indoor air quality, sometimes described as the 'sick building syndrome'. The syndrome comprises the sensation of stuffy, stale and unacceptable air, irritation of mucous membranes, headache, malaise, etc. The syndrome occurs in many buildings but with large variations in intensity. In some buildings only a few sensitive persons may complain, while in other buildings 20%, 40% or 60% of persons may suffer. Often there is no single chemical in the indoor air that can explain the complaints, but thousands of compounds may be present in concentrations several orders of magnitude lower than in

0378-7788/88/$3.50 © Elsevier Sequoia/Printed in The Netherlands

industrial premises. Since the concentrations are so low, they are difficult to measure by ordinary chemical analysis. Even if we were able to make a complete chemical analysis, there are only minimal data available on the effects on human beings of the single compounds in such small concentrations. Furthermore, if we assumed that such information on each single compound was available, we would still not know how to deal with the many thousands of compounds when they occur together. We would not know their combined impact on the human perception of air quality.

The conclusion is that the traditional hygienic/chemical method at this stage is usually insufficient to define or rate the quality of air as perceived by human beings.

THE olf UNIT

A next logical step is to admit that the human senses are usually superior to chemical analysis of the air. The senses involved are the olfactory, sensitive to odorous compounds, and the chemical, sensitive to irritating compounds in the air. Both senses are situated in the mucous membrane of the nose. These senses determine whether the air feels fresh or stuffy, whether it irritates or not, whether it feels good or bad, whether the air can be judged acceptable or unacceptable. A natural alternative to chemical analysis is therefore to use man as a meter to quantify air pollution.

The idea is to express any pollution source by a comparable known reference source. The new unit is called one 'olf', from the latin word *olfactus* (olfaction), although both the olfactory and the chemical sense are involved in the definition of the unit. *One olf is the emission rate of air pollutants (bioeffluents) from a standard person.* Any other pollution source is then expressed by the equivalent source strength, defined as the number of standard persons (olfs) required to cause the same dissatisfaction as the actual pollution source. The olf is thus a relative unit similar to the met unit for metabolic rate or the clo unit for insulation of clothing, both introduced by Gagge *et al.* [1].

Air pollution from a human being was chosen as the reference to define the new olf unit for two reasons. The first reason is that bioeffluents emitted from a person to the air are quite well known to everyone, based upon daily experience. The second reason is that more complete data are already available on the dissatisfaction caused by human bioeffluents than by any other type of pollutant. For more than one hundred years, human beings have been assumed in ventilation standards to be the major pollution source in non-industrial buildings. Human bioeffluents were studied extensively already by Pettenkofer in the 19th century [2] and later by Yaglou in the 1930s [3].

The most recent data on human bioeffluents were collected in two experimental auditoria in Denmark [4, 5]. In two studies, bioeffluents were emitted from a total of more than one thousand sedentary men and women in thermal neutrality. The air quality was judged by 168 men and women just after entering the space. They were asked to imagine that they should enter this space frequently during their daily work. They were then asked whether they would judge the air quality to be acceptable or not. Occupants and judges were adult students or white-collar workers between the ages of 18 and 30 years. The occupants were sedentary (1 met) with an average skin area of 1.8 m^2, and their hygienic standard corresponded to 0.7 bath/day and changing underwear every day. Eighty percent of them used deodorant. The age of the bioeffluents when judged was, on average, approximately 20 minutes. The standard person referred to in the definition of one olf is the average sedentary occupant participating in these studies [4, 5].

The original data [4, 5], which compare well with similar North American studies [6], were re-analysed and a minor correction was made considering a recent identification of pollution sources of 17 olfs from materials in the experimental auditoria. The corrected curve is depicted in Fig. 1, showing the percentage of dissatisfied judges as a function of the ventilation rate per olf during steady state conditions. This basic curve defines the dissatisfaction caused by one standard person (one olf) being ventilated by unpolluted air at different rates. The dissatisfied are those judges who found the air quality unacceptable.

The formula for the curve in Fig. 1 is:

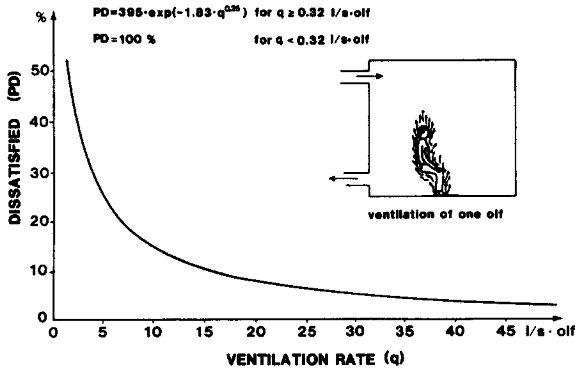

Fig. 1. The curve defines the percentage of dissatisfied judges caused by one standard person (one olf), when ventilated by unpolluted outdoor air at different ventilation rates. A standard person is the average of more than one thousand sedentary, adult experimental subjects in thermal comfort. The air quality was assessed by 168 judges just after entering the experimental space.

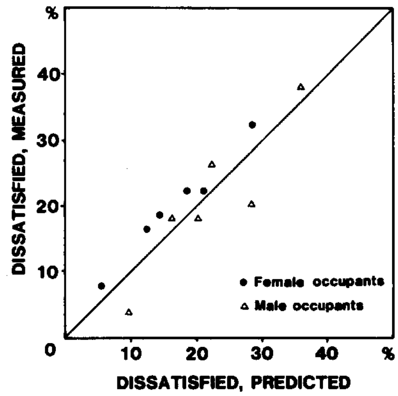

Fig. 2. Comparison between measured percentage of dissatisfied and percentage of dissatisfied predicted by eqn. (1). The correlation coefficient is 0.89 (R^2 = 0.79). In the studies with male [4] and female [5] occupants, the air quality was assessed by panels of male and female judges. In the female study each point represents 203 votes, in the male study 59 votes.

$$PD = 395 \exp(-1.83 q^{0.25}) \quad \text{for } q \geq 0.32 \text{ l/s olf}$$
$$PD = 100\% \quad \text{for } q < 0.32 \text{ l/s olf} \qquad (1)$$

where PD is the percentage of dissatisfied and q is the steady-state ventilation rate per olf (l/s olf).

The percentage dissatisfied decreases first steeply and then slowly with increased ventilation. It is obvious that some people are extremely sensitive and require a high ventilation rate to make them feel that the air is acceptable. On the other hand, the curve shows that others are rather tolerant, judging even extremely low ventilation rates as acceptable.

Figure 2 shows the percentage of dissatisfied predicted by eqn. (1) as a function of the actually measured percentages of dissatisfied in the experimental studies [4, 5].

THE decipol UNIT

The concentration of air pollution depends on the pollution source and the dilution caused by the ventilation rate (indoors) or the wind (outdoors). The perceived air pollution is defined as that concentration of human bioeffluents that would cause the same dissatisfaction as the actual air pollution concentration. The perceived air pollution is measured in the new unit 'pol' from the latin word *pollutio* (pollution). One pol is the air pollution caused by one standard person (one olf) ventilated by 1 l/s of unpolluted air. This means

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

To obtain more convenient numbers it is suggested that the perceived air pollution be expressed by one tenth of the pol unit:

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

One decipol is thus the pollution caused by one standard person (one olf) ventilated by 10 l/s of unpolluted air.

Calculated from Fig. 1, the percentage of dissatisfied as a function of the perceived air pollution is depicted in Fig. 3.

The formula for the curve in Fig. 3 is:

$$PD = 395 \exp(-3.25 C^{-0.25}) \quad \text{for } C \leq 31.3 \text{ decipol}$$
$$PD = 100\% \quad \text{for } C > 31.3 \text{ decipol} \qquad (2)$$

where

PD = percentage of dissatisfied (%)
C = perceived air pollution (decipol)

In many well-ventilated buildings with low pollution sources, the perceived air pollution is below one decipol or 15% dissatisfied. Spaces with low ventilation and high pollution sources may have a perceived air pollution above 10 decipol or 60% dissatisfied. Air qualities around 0.1 decipol or 1% dissatisfied are hard to establish in indoor environments.

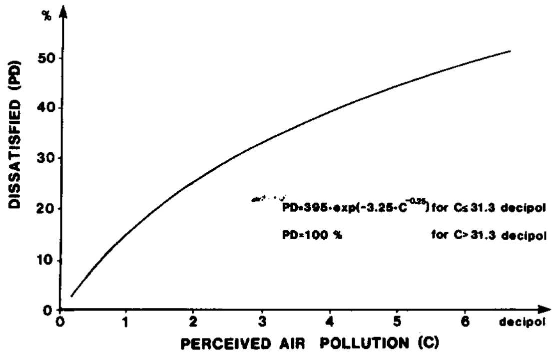

Fig. 3. The curve defines the relation between the percentage of dissatisfied judges and the perceived air pollution in decipols.

The use of perceived air pollution to quantify air quality is not restricted to buildings, automobiles, airplanes or other indoor environments. It may just as suitably be used to quantify outdoor air pollution. Power stations, industrial plants, automobiles and other outdoor pollution sources may be quantified in olf units, and the perceived air pollution in decipols may be predicted throughout a city under specified meteorological conditions. Models used for predicting the distribution of single pollutants (e.g., SO_2, NO_x) from pollution sources [7] may be used to predict the perceived air pollution in decipols throughout an urban area.

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 Table 1, olf corresponds to lumen for light. Lumen is the unit for the light emitted from a source. The only electromagnetic radiation which counts is that to which the human eye is sensitive, i.e., radiation with wavelengths between 380 and 720 nm. Within this range the impact of the different wavelengths is weighted according to the sensitivity of the eye.

TABLE 1

Analogy between the new units for air pollution and existing units for light and noise

	Light	Noise	Air pollution
Source strength	lumen	watt	olf
Perceived level	lux	decibel(A)	decipol

For noise, the source strength is given by the sound power measured in watts. The only power which counts is that to which the human ear is sensitive, i.e., with frequencies between 20 and 20 000 Hz. But they count equally much, i.e., the varying sensitivity of the human ear to different frequencies is normally not taken into account when specifying the source strength. This is in contrast to the olf unit that integrates the emitted pollutants according to their impact on the human nose and the perceived annoyance.

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 quantity or intensity, whether annoying or not. A given dB(A) may, for example, be caused by traffic or by chamber music. In contrast to this, it was found more useful that the decipol should define the annoyance. A certain decipol level expresses a constant annoyance, a constant percentage of dissatisfied, independent of the type of air pollution.

In the beginning, light and sound could only be measured using man as a meter. Later, instruments were developed taking into account the sensitivity of the human senses. At the moment we can only measure olf and decipol using man as a meter. It will 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 how the air is perceived by humans, not the possible health risk. Any such effect should be considered separately. Still, harmful pollutants, with a few exceptions, also have a sensuous impact on man. Our senses have an important warning function against dangers in the environment. The decipol level may therefore in many cases even provide a reasonable first estimate of a possible health risk. There are exceptions such as radon, which is not perceived, but provides a risk for lung cancer. This is analogous to ultraviolet light, which does not contribute to the lux level since it is not perceived by the eye but nevertheless provides a risk for skin cancer.

MEASUREMENT OF POLLUTION SOURCES

The measurement of the olf value of a pollution source requires a panel of subjects and a measurement of the supply of outdoor air to the space. The use of panels of human subjects is common in several other fields, where the human senses are superior to chemical analysis, e.g., in food science. The panel should judge the acceptability of the indoor air in the same way as was described in the above-mentioned experiments with human bioeffluents [4, 5]. They may also judge the outdoor air. The perceived air pollution in decipols can then be found indoors and outdoors from Fig. 3. As a calibration, an additional judgment of human bioeffluents from a large group of sedentary persons during standard conditions would be useful. If the selected panel of subjects happens to be significantly more or less sensitive to air pollution than the large panel defining Fig. 1, then all the judgments of the panel should be adjusted up or down.

The judgment should take place immediately after the panel enters the space. This gives the first impression of the air quality, which has been used as a criterion in ventilation standards. The judgment of the bioeffluents defining the olf (Fig. 1) was also based on the first impression. With time, some adaptation of the human senses may take place. The panel should therefore, before each judgment, be exposed to air with low pollution for some minutes (outdoor air or air in a well-ventilated space).

During steady-state conditions, the emission rate from all pollution sources in the space and the ventilation system, if any, may then be calculated from

$$C_{\text{outdoor}} + \frac{G}{Q} = C_{\text{indoor}} \qquad (3)$$

where

C_{outdoor} = the perceived air pollution outdoors (pol)
C_{indoor} = the perceived air pollution indoors (pol)
G = the equivalent strength of all pollution sources in space and ventilation system (olf)
Q = the rate of supply of outdoor air (l/s)

Pollution sources in the space may be separated from sources in the ventilation system by turning off the ventilation system and asking the panel to make a second judgment. Q is then the infiltration of outdoor air, which should be measured. Fanger *et al.* [8] used this method to quantify pollution sources in 20 offices and assembly halls in Copenhagen.

A certain pollution source in a space may be measured by introducing the source to the space or removing it and asking the panel to make a judgment during steady state conditions before and after the change.

When two sources emitting pollutants of the same nature occur in the same space, it is obvious that their olf values can be added. Even if the pollution sources are of a different nature, it is assumed that the combined effect of both sources in one space can be found by simple addition of the olf values. However, further research on this topic is recommended.

The pollution from many building materials, carpets, etc., may most conveniently be quantified as olf per surface area (olf/m^2). Furniture, office machines, etc., may be quantified as olf per piece.

The olf value of outdoor pollution sources, e.g., a chimney, may be estimated by exposing a panel to a diluted, known part of the total flow of smoke in the chimney. For combustion of oil, gasoline, kerosene, gas, coal, wood, etc., the pollution source may be quantified as olf per watt of fuel burned.

Comprehensive systematic studies of pollution sources could most easily take place in climate chambers where the chambers and the air-conditioning system have a low olf value and where the air supply can easily be controlled and measured.

CONCLUSIONS

Two new units, the olf and the decipol, are introduced to quantify air pollution sources and air pollution as perceived by humans indoors and outdoors.

The olf is introduced to quantify air pollution sources. One olf is the emission rate of air pollutants (bioeffluents) from a standard person. Any other pollution source may be quantified by the number of standard persons (olf) required to cause the same dissatisfaction as the actual pollution source (Fig. 1). The olf is analogous to lumen for light sources and watt for noise sources.

The decipol is introduced to quantify air pollution perceived by humans. One decipol is the pollution caused by one standard person (one olf) ventilated by 10 l/s of unpolluted air (1 decipol = 0.1 olf/(l/s)). The decipol is analogous to lux for light and decibel (A) for noise.

A method for measurement of pollution sources and perceived air pollution is presented.

REFERENCES

1 A. P. Gagge, A. C. Burton and H. C. Bazett, A practical system of units for the description of the heat exchange of man with his environment, *Science, 94* (1941) 428 - 430.
2 M. V. Pettenkofer, *Über den Luftwechsel in Wohngebäuden*, München, 1858.
3 C. P. Yaglou, E. C. Riley and D. I. Coggins, Ventilation requirements, *ASHVE Trans., 42* (1936) 133 - 162.
4 P. O. Fanger and B. Berg-Munch, Ventilation and body odor, *Proc. An Engineering Foundation Conference on Management of Atmospheres in Tightly Enclosed Spaces, Atlanta,* ASHRAE, 1983, pp. 45 - 50.
5 B. Berg-Munch, G. Clausen and P. O. Fanger, Ventilation requirements for the control of body odor in spaces occupied by women, *Environ. Int., 12* (1986) 195 - 199.
6 W. S. Cain *et al.*, Ventilation requirements in buildings — I. Control of occupancy odor and tobacco smoke odor, *Atmos. Environ., 17* (6) (1983) 1183 - 1197.
7 D. B. Turner, A diffusion model for an urban area, *J. Appl. Meteor., 3* (1964) 83 - 91.
8 P. O. Fanger, J. Lauridsen, P. Bluyssen and G. Clausen, Air pollution sources in offices and assembly halls, quantified by the olf unit, *Energy Build., 12* (1988) 7 - 19.