

ENERGY EFFICIENT DOMESTIC VENTILATION SYSTEMS FOR ACHIEVING  
ACCEPTABLE INDOOR AIR QUALITY

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VENTILATION RATES IN RELATION TO EMISSION OF GASES AND VAPOURS  
FROM BUILDING MATERIALS.

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## 1. SYNOPSIS

Mathematical models for formaldehyde concentrations of each of three normal rooms in a single family house is used to estimate ventilation rates needed to maintain the formaldehyde concentration below the Danish recommended indoor standard (0.15 mg/m<sup>3</sup>). It appears that in an initial period after the house was finished a ventilation rate more than 10 times the recommended Scandinavian maximum value (0.5 air change per hour) was needed to keep the concentration below the indoor standard.

Neither an indoor standard nor an elaborated mathematical model exists for gases and vapours of solvent type in the indoor air. A rough estimate, however, does not eliminate the possibility that the same high ventilation rates may be needed for these compounds if complaints from occupants are to be avoided in the first period after a house is finished.

In consequence it is proposed that ventilation standards are set not only for the initial period but for the following period where emissions are in a more steady state. In the initial period the occupants should be advised to ventilate as much and as often as they feel necessary and new houses should for such purpose be constructed with extra permanent or temporary ventilation facilities.

## 2. INTRODUCTION

For several years both moderate and severe complaints about indoor climate have been registered among occupants of modern buildings. Malfunctioning ventilation and climate systems are in many cases found to be the main reason for the complaints. Some complaints are, however, reported from rooms where these and other technical reasons for complaints can be excluded.

The symptoms described by the occupants of these rooms are often similar to those resulting from exposure to low concentrations of irritating gases and vapours, and the symptoms are often found in new buildings built of - or older buildings renovated with modern types of construction materials with unknown effects on the indoor climate. If the complaints are related to exposure to low concentrations of gases and vapours originating from such materials their impact could increase by the general effort to decrease domestic energy consumption by reduction of ventilation rates and by the introduction into house building and house renovation of huge volumes of new types of construction and installation materials.

Excessive formaldehyde emission from e.g. particle board has been found to be the reason for some of these complaints (1). Formaldehyde concentrations are, however, in many cases so low that this compound cannot be the cause for complaints. Therefore measurements to survey the occurrence of other organic gases and vapours in indoor environments were performed. The occurrence of gases and vapours of the solvent type in indoor air was demonstrated by measurements of their concentrations in 7 new houses and 39 older dwellings (3,4). The emissions of the same compounds from 42 common building materials were later measured in our laboratory (5).

Based on our measurements mathematical models were developed for the concentrations of both formaldehyde originating from particle boards (6) and organic gases and vapours of solvent type from normal building materials (5). In this paper these models will be used to illustrate the relation between calculated equilibrium concentrations of gases and vapours in normal rooms and the ventilation rate of the room. Further the results will be discussed in relation to proposed minimum ventilation rates.

### 3. THE MATHEMATICAL MODELS

#### 3.1 Formaldehyde

The mathematical model for the equilibrium concentration of formaldehyde emitted from Urea-Formaldehyde glued particle boards was first established in 1975 as a result of investigations of the performance of a set of 14 particle boards in a climate chamber (1). The general mathematical form was found to be:

$$C = \frac{(RT + S)(aH + b)}{1 + \frac{n \cdot c}{\alpha}}$$

where C (mg/m<sup>3</sup>) is the equilibrium concentration of formaldehyde in the air around a particle board, and T, H, n, and  $\alpha$  are respectively air temperature (°C), air humidity (g H<sub>2</sub>O/kg dry air), n ventilation rate (h<sup>-1</sup>) and  $\alpha$  amount of particle board per volume room air (m<sup>2</sup>/m<sup>3</sup>). The constants R, S, a, b and c describes the emission properties of the board under investigation.

The model was further developed for formaldehyde concentrations expected in actual rooms where different particle boards have been used (6). This model was tested in three rooms in a new single family house. The house was constructed according to normal Danish building tradition with urea formaldehyde glued particle boards coated with a formaldehyde absorbing paint. The emission of formaldehyde from all boards used for the three rooms was found according to a standard procedure (7) based on measure-

ments of the equilibrium concentration of formaldehyde around a 0.25 m<sup>2</sup> sample of the particle board under investigation in a stainless steel box (225 l). The box is ventilated 0.25 times per hour by fresh air (45% RH) and is kept at 23°C.

Each of the three rooms in the house was described with individual models for the air concentrations of formaldehyde and the calculated formaldehyde concentrations were found to agree within 15% with those measured in the rooms immediately after the house had been finished (6).

### 3.2 Organic Gases and Vapours

The mathematical model for the equilibrium concentration of organic gases and vapours is not so detailed as that for formaldehyde. The reason is that the influence of indoor climate parameters on the emission rates is unknown. In the establishing of the mathematical model for organic gases and vapours it was therefore assumed (5) that the emission rate is constant and independent of the indoor climate.

By this simple mathematical model the equilibrium concentration of any indoor air pollutant emitted from building materials used in a room or the total concentration of all such pollutants is estimated. According to the model the total concentration  $C$  mg/m<sup>3</sup> in a room volume  $V$  m<sup>3</sup> (ventilated  $n$  times per hour) can be calculated through

$$C = \frac{1}{V \cdot n} \sum_{i,j} E_{ij} \cdot A_i$$

where  $E_{ij}$  is the emission rate (mg h<sup>-1</sup>m<sup>-2</sup>) of compound (j) from material (i) and  $A_i$  is the amount of material (i) used in the room (m<sup>2</sup>).

The validity of this model was investigated by calculation of expected total concentration of organic gases and vapours in three model rooms constructed from materials with known emission of 52 different organic compounds (5). The range of the calculated concentrations was from 1.6 to 23.5 mg/m<sup>3</sup>. Measurements in similar rooms in seven single family houses showed concentrations ranging from 0.48 to 18.7 mg/m<sup>3</sup>. In comparing these results it should be remembered that the model deals with equilibrium concentrations which very seldom occurs in homes etc., and that no corrections were made for differences in indoor climate and in room construction between investigated rooms in real houses and the model rooms used for the calculations.

4. THE INFLUENCE OF VENTILATION ON INDOOR AIR POLLUTION

The mathematical models described above for formaldehyde and for total concentrations of organic gases and vapours of solvent type have been used to illustrate the relation between ventilation rate and equilibrium concentrations of formaldehyde in the three actual rooms in the single family house described in (6), and the total concentration of organic gases and vapours in the three model rooms described in (5).

Formaldehyde: According to the model each room of the single family house was described with its own mathematical model. Each model had the same mathematical form

$$C = \frac{(R \cdot T - 0.764) \cdot (0.143 \cdot H + 0.048)}{1 + \frac{n \cdot 0.304}{\alpha}} \text{ mg/m}^3$$

where R is a constant representing the emission rate of formaldehyde in each room and  $\alpha$  is the amount of particle board  $\text{m}^2/\text{m}^3$ . The temperature ( $^{\circ}\text{C}$ ), the humidity (g/kg) and the ventilation rate ( $\text{h}^{-1}$ ) is designated T, H and n respectively. Values for these variables are given in table 1.

These models were used to calculate expected formaldehyde concentrations in the rooms under standard indoor climate concentrations  $23.0^{\circ}\text{C}$ . and 7.8 g water per kg dry air (45% RH).

Table 1: The mathematical model for equilibrium concentration of formaldehyde in three rooms. The general mathematical form is:

$$C = \frac{(RT - 0.764) (0.143 \cdot H + 0.048)}{1 + \frac{n \cdot 0.304}{\alpha}}$$

where C = Equilibrium concentration of formaldehyde in the room air  $\text{mg}/\text{m}^3$ .  
 R = Emission constant.  
 T = Air temperature  $^{\circ}\text{C}$ .  
 H = Air humidity g/kg  
 $\alpha$  =  $\text{m}^2$  particle board/ $\text{m}^3$  room volume.  
 n = Ventilation  $\text{h}^{-1}$ .

Room	TOC	H g/kg	n $\text{h}^{-1}$	$\text{m}^2/\text{m}^3$	R	C $\text{mg}/\text{m}^3$
I	23.4	5.7	1.4	2.30	0.0431	0.26
II	21.6	5.3	0.6	1.92	0.0494	0.27
III	23.0	5.3	2.3	2.33	0.0427	0.25

Fig. (1) shows the calculated relations between formaldehyde concentrations in the three rooms and the ventilation rate of the room. The dotted part of the figure indicates a region in which

the present model has been found invalid (1).

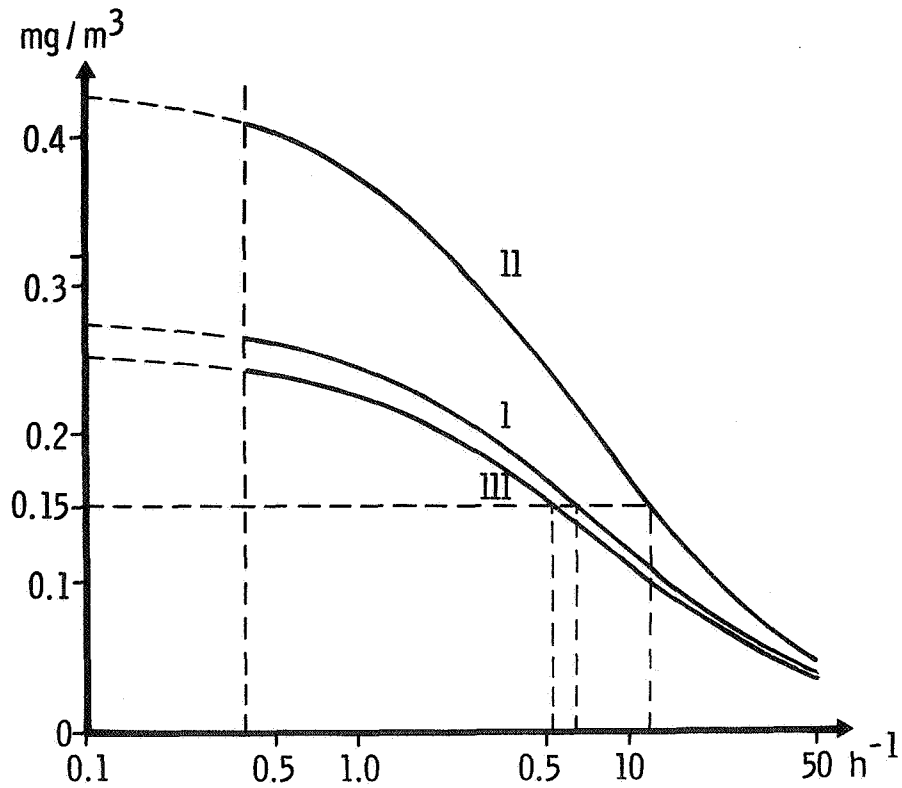


Fig. (1): The influence of ventilation rate ( $\text{h}^{-1}$ ) on the equilibrium concentration of formaldehyde in three rooms containing about  $2 \text{ m}^2/\text{m}^3$  particle boards per  $\text{m}^3$  room volume.

Solvent gases and vapours: The influence of indoor climate parameters on the emission rate of organic gases from normal building materials is unknown. A detailed model as that described for formaldehyde has therefore not yet been established for other pollutants or building materials. If, however, as a first approximation the emission rate of any compound is assumed to be constant and independent of temperature, humidity and ventilation rate the equilibrium concentration of organic gases and vapours in the three model rooms described in (5) can be calculated. Fig. (2) shows for the three rooms the relation between ventilation rate and total concentration of 52 different compounds emitted from the building materials used for the rooms.

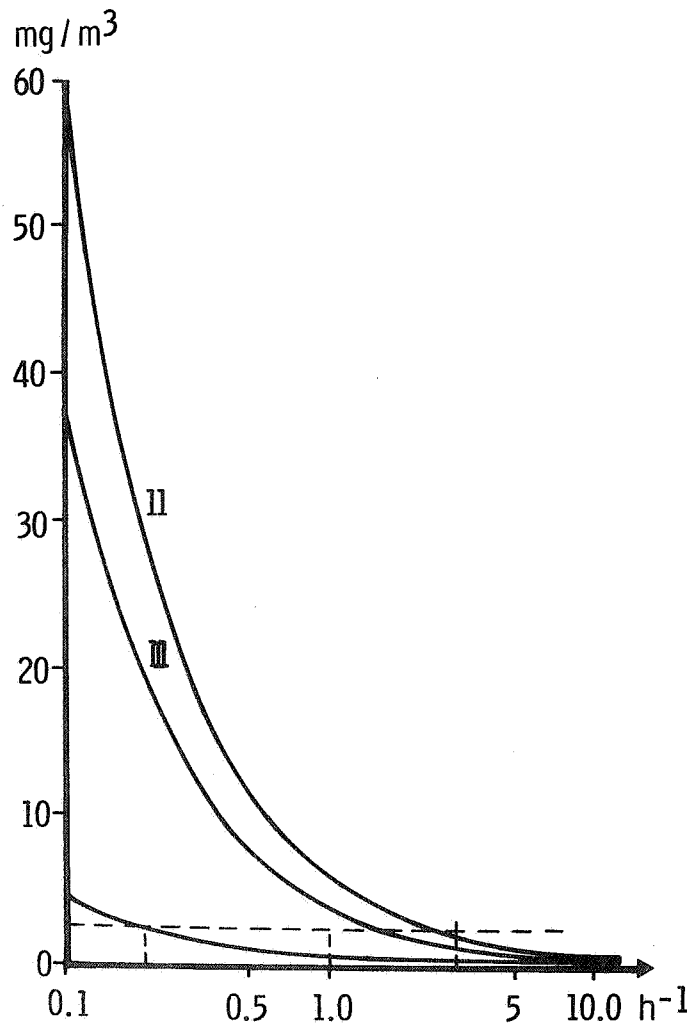


Fig. (2): The relation between total equilibrium concentration  $\text{mg/m}^3$  of 52 organic compounds of solvent type in three model rooms.

## 5. DISCUSSION

For the first weeks after the finishing of a normal Danish house the model indicates that formaldehyde concentrations below the recommended Danish indoor air standard for formaldehyde ( $0.15 \text{ mg/m}^3$ ) is achieved only with ventilation rates higher than  $6.4$ ,  $11.9$  and  $5.2 \text{ h}^{-1}$  for room I, II and III respectively (see fig. 1). These figures are an order of magnituder higher than the proposed Scandinavian ventilation standard of  $0.5 \text{ h}^{-1}$  (8) for normal homes and they demonstrate further that efforts to decrease this initial formaldehyde concentration to below  $0.15 \text{ mg/m}^3$  by increasing the ventilation are unrealistic.



Repeated measurements in the three rooms in the following 14 weeks showed a marked decrease in concentrations. This decrease occurred despite the fact that the rooms in the meantime were inhabited by occupants who through furniture etc. introduced an unknown amount of potential sources for formaldehyde in the rooms. After 14 weeks the measured formaldehyde concentrations in all rooms were below  $0.15 \text{ mg/m}^3$ . This decrease in concentrations took place with unchanged ventilation as shown in table 1. A further decrease of the concentrations can be expected as the house grows older and in the long range a ventilation of 0.5 per hour may be sufficient to keep the concentration of formaldehyde below  $0.15 \text{ mg/m}^3$ .

The discrepancy between recommended maximum formaldehyde concentration, proposed ventilation rate and the extended use of particle boards therefore seems to be restricted to a relatively short initial period after the house was finished.

For this initial period the model predicts the maximal acceptable amount of particle board in the rooms to be about  $0.2 \text{ m}^2$  per  $\text{m}^3$  room volume if the concentration is not to exceed  $0.15 \text{ mg/m}^3$  at a ventilation rate of 0.5 per hour. This amount of particle board corresponds to that normally introduced by the occupants through furniture etc. Urea-Formaldehyde glued particle boards of the type investigated here therefore can not be used in homes at all if recommended norms for ventilation rates and formaldehyde concentrations must be maintained in the initial period of a new house. The model on the other hand indicates that ventilation rates up to 10 exchanges per hour are needed in this period if about  $2 \text{ m}^2/\text{m}^3$  of normal particle boards treated with a formaldehyde stopping coating are used.

Indoor air standards only exist for formaldehyde. In a general recommendation of ASHRAE (2) maximal acceptable indoor air concentrations of any indoor pollutant is set to one tenth of its maximal allowable concentration in industrial environments. This recommendation is, however, not generally accepted.

The average MAC-value for those of the 52 compounds mentioned above for which such MAC-value exists is about  $600 \text{ mg/m}^3$ . From fig. (2) follows that with normal occurring ventilation rates 1/10 of this value ( $60 \text{ mg/m}^3$ ) will not be exceeded in the 3 model rooms. The use of an average threshold value is, however, not toxicologically justified.

A more safe estimate of the low limit may be obtained by using the lowest MAC-value for the 52 compounds. This is  $20 \text{ mg/m}^3$  and in two of the three model rooms the expected concentrations do exceed 1/10 of this value ( $2 \text{ mg/m}^3$ ) if the ventilation rate is below 0.5 air change per hour.

In evaluating the results it should be kept in mind that no adequate indoor standard exists for the 52 compounds nor exists an elaborated mathematical model.

The results, however, which are rough estimates do not eliminate the possibility that these compounds may reach such concentrations in the initial period that ventilation rates higher than 0.5 air-changes per hour are needed if complaints from occupants are to be avoided.

## 6. CONCLUSION

The investigations show that for formaldehyde and possibly for other indoor airpollutants like solvent vapours 0.5 airchanges per hour may not be sufficient to maintain airconcentrations at an acceptable level in an initial period after the completion of a house. In consequence it is proposed that ventilation standards are set not for this initial period but only for the period of normal use of the house where emissions have decreased and reached a more steady state. In the initial period occupants should be advised to ventilate as much and as often they feel necessary.

## 7. REFERENCES

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