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COMPARISON OF NATURAL AND MECHANICAL VENTILATION PERFORMANCE IN SIMILAR HOUSES.

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ABSTRACT

The ventilation performance in 59 terraced houses of similar construction was investigated using a passive tracer gas technique. Some thirty houses were ventilated through the original natural ventilation, while eight were equipped with an additional bathroom fan and 20 were retrofitted with a mechanical supply and exhaust ventilation system. All measurements were made simultaneously in March.

The ventilation performance was computed using both single-zone and two-zone approaches. Using the two-zone approach specific information about the bedroom ventilation (direct in-flow of air, purging flow rate and air exchange with the rest of the dwelling) could be obtained.
A comparison between naturally and mechanically ventilated houses shows that those with mechanical ventilation on average show a considerably higher ventilation rate.

KEYWORDS

Tracer gas, Natural ventilation, Mechanical ventilation, Residential buildings, Survey

INTRODUCTION

In northern countries, people spend 90% or more of their time in buildings. A variety of unavoidable sources contribute to the accumulation of contaminants in the indoor air which we breathe. The only way of keeping the contamination level under control is by ventilation. Proper ventilation of buildings is therefore the key-stone for a healthy environment. The importance of good ventilation has been emphasised periodically during the past two centuries - the attention often arising due to the appearance of public health problems. This periodical interest has also been reflected in varying national standards and regulations for building ventilation.

The last such incident occurred in the early 1980´s with the appearance of Sick Building Syndrome (SBS). However, while SBS essentially involves reversible symptoms i.e. such which disappear when absent from the "sick" building, a new serious public health problem has slowly manifested itself. In many countries, especially industrialised countries with a high standard of living, there appears to be a severe increase in the incidence of hypersensitivity and allergic diseases, especially among young people. Such diseases are generally not reversible but will be permanent.

The connection between the appearance of allergic diseases and the quality of the indoor environment is presently the subject of intensive research.

At the same time, there is a renewed interest in ventilating buildings "naturally" i.e. without using fans. A crucial question here is, whether modern building techniques and natural ventilation constitute a good combination. A Swedish study (ELIB) (Stymne *et al.* 1994a) shows that the naturally ventilated part of the Swedish dwelling stock on average has a considerably poorer ventilation than the part which is mechanically ventilated. Naturally ventilated dwellings, generally do not fulfil the legal ventilation requirements for new dwellings. Finnish (Ruotsalainen *et al.* 1992) and Danish (Bergsøe 1991) studies show similar results.

One reason for naturally ventilated buildings not fulfilling the ventilation requirements in the Nordic climate is obvious. In order to save energy, the buildings have to be well insulated and reasonably airtight, with well defined openings for letting ambient air in. Cold draughts through the openings during cold weather conditions is often a nuisance which may lead to permanent sealing of such openings.

But how much of the ventilation is due to the building construction and ventilation system and how much depends on the habits of and measures taken by people utilising the building? This question is not so easy to answer with help of investigations already performed.

The present paper reports the details of a measurement of ventilation in a sample of 59 terraced houses (out of 250) which were built at the same time (1968-1970) and with essentially similar construction. The work is part of an investigation of how mechanical ventilation affects air humidity, house dust mite allergen and volatile organic compounds (Emenius *et al.* 1998). Originally all houses were naturally ventilated, but 22 of the sampled houses were retrofitted with balanced mechanical ventilation systems. Eight of them had been retrofitted with some other ventilation measure, like an extra bathroom fan, airing windows etc.

This study gives a unique opportunity to investigate the importance of mechanical ventilation means and user habits in a study which is large enough to draw some statistical conclusions.

DESCRIPTION OF THE BUILDINGS.

The buildings consist of flat-roofed single-storey terraced houses. As illustrated in figure 1 there are two sizes of dwellings, type I (125 m^2) and type II (108 m^2). The houses are attached to each other with building space, originally intended to be used as garage and storeroom. However, in some of the houses part or whole of this space has been converted to serve as dwelling space. There are two types of building foundations, one equipped with a sub-floor space (crawl space), the other consisting of a massive concrete slab without sub-floor space. Both types are represented in the investigation.

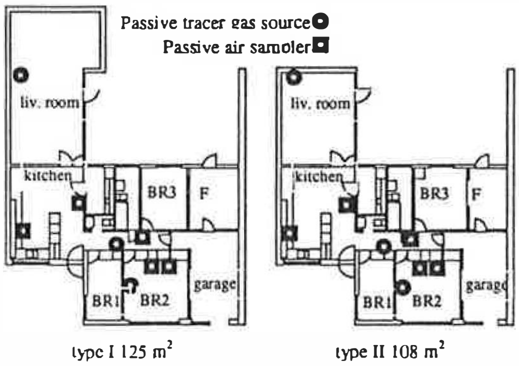


Figure 1. *Plans over the two types of dwellings investigated. The deployment of tracer gas sources and samplers is similar in all investigated dwellings. However, the bedroom equipment may be either in BR1, BR2 or BR3.*

LAYOUT OF THE EXPERIMENT.

A passive tracer gas technique (described under a separate heading) was used to investigate the ventilation performance. The experimental layout was similar to the one used in a study of the indoor climate in the Swedish housing stock - the ELIB study (Stymne *et al.* 1994a) and a study of the ventilation in 344 Norwegian dwellings (Øie *et al.* 1998).

Passive tracer gas sources were positioned in the dwellings as indicated in figure 1. Two different types of tracer gas were used. One type (type A) was positioned in a bedroom, usually in the room denoted with BR2 in figure 1 (42 cases), but also in room BR3 (13 cases) and in room BR1 (3 cases) and in one case in room F. The other type of tracer gas (type B) was used to tag the air in the rest of the dwelling. Two equal sources were used, always located in the same positions as indicated in figure 1 - one in the living room and one in the corridor outside the bedrooms.

Five passive air samplers were distributed in the dwellings as indicated in figure 1. Two of them were located side by side in the bedroom equipped with tracer gas source A. The other three were distributed in the dwellings, always located in the same positions as indicated in figure 1. The strategy for positioning these samplers was to locate them so that they will sample air which is as characteristic as possible for air leaving the dwelling. Therefore, one of them was positioned close to the exhaust hood in the kitchen, the second one outside the door to the laundry room and the third outside the door to the bathroom.

The deployment of the measurement equipment was performed by trained personnel during two consecutive days (9-10 March). In addition to the passive tracer gas equipment, the houses were equipped with temperature and air humidity sensors. After 14 days the houses were visited again and all equipment taken down. The passive samplers were capped and sent by mail to the laboratory for analysis and evaluation. All houses were therefore investigated during approximately the same weather conditions.

DESCRIPTION OF THE PASSIVE TRACER GAS TECHNIQUE.

The passive tracer gas technique has been described in detail in other publications (e.g. Stymne *et al.* 1994a). Only a short description will therefore be given here.

Miniature passive tracer gas sources emitting perfluorocarbon tracer gas (PFT) with a constant rate through a capillary tube are distributed in the space to be investigated. The steady state concentration of tracer gas in the air will be directly proportional to the emission rate and inversely proportional to the ventilation rate. The concentration is measured using passive samplers, consisting of glass tubes filled with an active carbon adsorbent, into which the tracer gas diffuses and is trapped in the adsorbent. The sampler tubes are exposed during an extended time (in the present case 14 days).

The amount of tracer gas trapped in the samplers is analysed in the laboratory using a gas chromatograph equipped with an electron capture detector. The ventilation rate is computed from the analysed tracer amount, the known emission rate of tracer gas, the air sampling rate and the sampling time.

By using two different types of tracer gas in different zones, interzonal air exchange can also be determined.

CALCULATION TECHNIQUE.

The calculation technique used is described in detail by Stymne *et al.* (1994a).

In the single-zone approach the ventilation rate is calculated from

$$Q = \frac{m}{C} \qquad (1)$$

where

Q is the total ventilation rate,
m is the tracer gas emission rate and
C is the average tracer concentration in air leaving the zone.

In the two zone-approach the flow matrix **Q** is calculated from:

$$\mathbf{Q} = \begin{bmatrix} \frac{C_{1A}}{m_A} & \frac{C_{1B}}{m_B} \\ \frac{C_{2A}}{m_A} & \frac{C_{2B}}{m_B} \end{bmatrix}^{-1} = \begin{bmatrix} q_{11} & -q_{12} \\ -q_{21} & q_{22} \end{bmatrix} \qquad (2)$$

where

C_{1A} is the average concentration of tracer gas A in zone 1 etc.

m_A and m_B are the emission rates of tracer gas A in zone 1 and tracer gas B in zone 2 respectively.
q_{12} is the air flow rate from zone 2 to zone 1 and q_{21} is the flow rate from zone 1 to zone 2.
$(q_{11} - q_{12})$ is the direct inflow of outside air into zone 1 and $(q_{22} - q_{21})$ is the corresponding flow into zone 2.

The total air flow rate is computed from the sum of all matrix elements.

Sometimes due to bad mixing within a zone, the two zone approach fails and yields negative values of some air flows. In these cases the total ventilation flow has been calculated as a weighted average of two one-zone calculations as described by Stymne *et al.*(1994a).

RESULTS

The determined total ventilation air change rates (ACH) in the houses are displayed in figure 2 in the form of a distribution plot, which resembles a statistical distribution function. The naturally ventilated houses (29 cases) and the mechanically ventilated houses (22 cases) are treated in separate groups. The 8 cases with modified systems are not included in this figure. The ACH-values are normally calculated with the 2-zone approach. However, in some cases a weighted value of two one-zone calculations has been used as described in the "calculation" section.
From figure 2 it is clear that the houses with mechanical ventilation have on average a considerably higher ventilation rate (mean 0.62 [h^{-1}], standard deviation 0.20 [h^{-1}]) than the naturally ventilated houses (mean 0.32 [h^{-1}], standard deviation 0.16 [h^{-1}]).

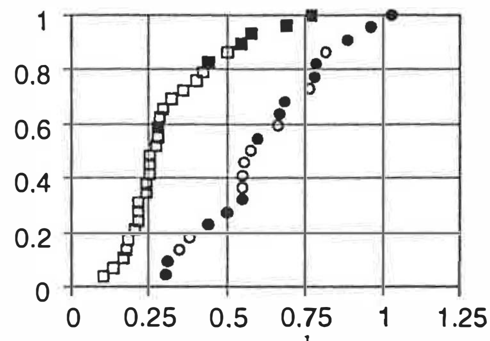


Figure 2. *Distribution of measured ACH in naturally ventilated houses (rectangles) and mechanically ventilated houses (circles). (i.e. fraction of houses having ACH less than a given value). Filled symbols represent houses with crawl space.*

90% of the naturally ventilated houses do not fulfil the requirement of 0.5 ACH, while this is the case only for 25 % of the mechanically ventilated houses.

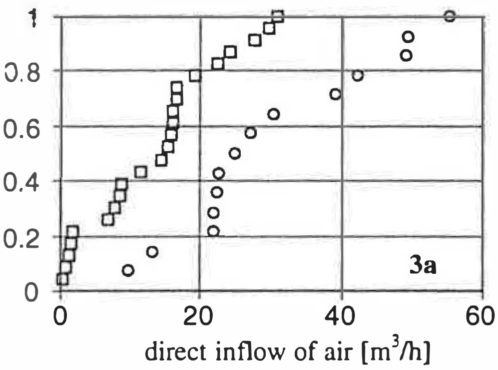


Figure 3a. *The distribution of direct inflow of outside air into the investigated bedrooms in naturally ventilated houses (rectangles) and mechanically ventilated houses (circles). Negative values of direct inflow are excluded from the plot.*

In figure 3a the calculated direct inflow of outside air to the investigated bedrooms is displayed. This part of the total air flow rate is calculated with the 2-zone approach. It should be observed that the 2-zone calculation sometimes yields inconsistent negative values for this flow, due to the great sensitivity of such calculations to bad mixing of the tracer gas, especially when the interzonal air exchange is large. Negative values are excluded from the diagram.

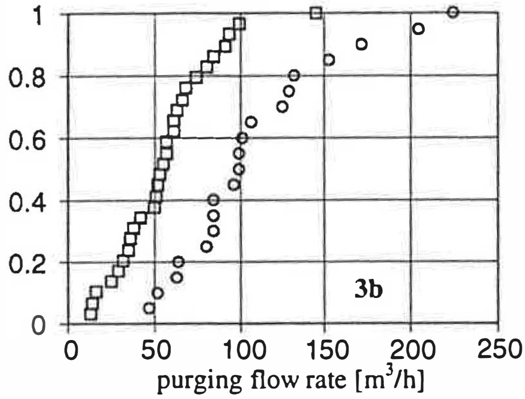


Figure 3b. *The distribution of purging flow rate into the investigated bedrooms in naturally ventilated houses (rectangles) and mechanically ventilated houses (circles).*

In figure 3b the calculated purging flow rates in the investigated bedrooms are displayed. The purging flow rate is the air flow rate available in the bedroom for removal of contaminants emitted in that room. The purging flow depends not only on the rate of outside air flowing directly into the bedroom, but a considerable part of the air flowing into the rest of the dwelling is also available for purging the bedroom, especially when the door is open

The rate of air exchange between the dwelling and the bedroom can be considerable. In figure 4 this air exchange is displayed. The large range of variation is noteworthy, as is the relatively small difference between naturally and mechanically ventilated dwellings.

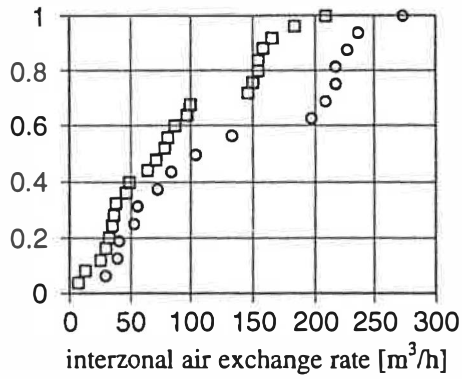


Figure 4. *Distribution of interzonal air exchange between the rest of the dwelling and the investigated bedroom in naturally ventilated houses (rectangles) and mechanically ventilated houses (circles).*

DISCUSSION

Despite the fact that all investigated houses are very similar in construction and ventilation system and that they were all investigated during the same period of time, the ventilation varies considerably both within the group of naturally ventilated houses and within the group of mechanically ventilated houses. In the naturally ventilated houses the air change rate varies from 0.1 [h^{-1}] to 0.75 [h^{-1}], while it varies between 0.3 [h^{-1}] and 1.0 [h^{-1}] in the mechanically ventilated houses. As discussed later, this large variation cannot be due to measurement uncertainties, but must be real. The reason must be different occupational habits, different system maintenance and different measures taken affecting the air supply rate.

The large variation and the approximate values of average ventilation rate as well as the large difference between natural and mechanical ventilation obtained in this study is consistent with the result obtained in the much larger ELIB study (Stymne *et al.* 1994a) including approximately 1300 dwellings. It is therefore quite possible that user habits are the main reason for the large variation in ventilation rate even on a national level and that the type of building or the weather conditions during measurement are of secondary importance. It is also doubtless the case that mechanical systems radically increase the chance of adequate ventilation, though several naturally ventilated houses show better ventilation than many mechanically ventilated houses in this study.

The ventilation in the naturally ventilated houses is definitely not satisfactory on average, while many of the mechanically ventilated houses may be considered overventilated, at least compared to present standards.

The ventilation of bedrooms is of special interest, since they are normally the rooms in which people, especially small children, spend the majority of their time. The exposure to mite allergen is also strongly connected to the humidity and ventilation of bedrooms. In Sweden, codes require a bedroom ventilation of minimum 4 litres per second and person (14 m^3/h,p). It is however not clear from the regulations, if this minimum ventilation requirement refers to ambient air supplied directly to the bedroom, or if it is sufficient that an equivalent amount of air is transferred through the doorway. A common interpretation is that this amount of air shall be supplied even with a closed door.

The two-zone approach in this study allows the estimatation of both the rate of directly supplied outdoor air and the "purging flow rate" in the bedrooms. However, it should be observed that the estimates are time averages, i.e. values averaged over day and night during a 2 week period. Night time conditions are not explicitely dealt with and may therefore be appreciably worse than the ones reported here.

The estimated average direct air flows into the bedrooms in the naturally ventilated houses (fig. 3a) show that 14 m^3/h is not fullfilled in one third of the cases, while 28 m^3/h (required for two persons) is only fullfilled in 3 (out of 23) cases. 4 cases show essentially no direct inflow of air into the bedroom. In the mechanically ventilated houses essentially all fulfil 14 m^3/h and approximately half of them also 28 m^3/h.

The purging flow rate is the flow rate of air, which is available for diluting contaminants released in a room. Therefore this flow rate not only includes the outside air directly transferred to a room, but also incorporates the diluting power of air transferred from other spaces connected to the room, for example through the doorway. Figure 3b shows that the purging flow rate of 14 m^3/h level is fulfilled in all bedrooms and the 28 m^3/h level is fulfilled in all mechanically ventilated houses and in 90% of those ventilated naturally.

The two-zone approach also allows computation of the air exchange between the bedroom and the rest of the dwelling. Such air exchange takes place through the doorway and is principally driven by temperature differences between the different spaces. The part of the purging flow not eminating from direct inflow of air, is mediated by such air exchange. As expected this air exchange between the bedroom and the rest of the dwelling is not much influenced by the type of ventilation. As shown in figure 4, the exchange rate varies widely between a few cubic metres per hour up to 300 m^3/h, but the distribution does not significantly depend on whether the ventilation is natural or mechanical.

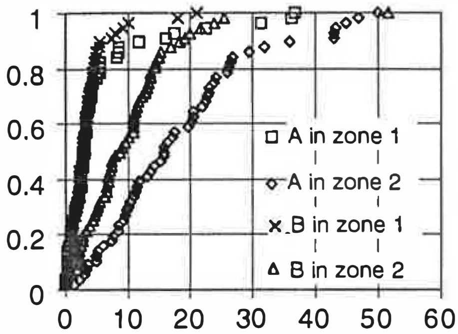
Quality of the measurements and calculations

The determination of ventilation parameters using the passive tracer gas technique suffers from uncertainties depending both on experimental error sources and on theoretical approximations.

The theoretical approximations involved concern the necessary assumption of uniform air mixing within zones, in order to interprete the result within the one-zone or two-zone approach. However, the most recent development of the passive tracer gas technique - the homogeneous emission technique (Stymne and Boman 1994b) -

allows multi-zone treatment and is therefore less sensitive to this approximation.

In the present case, zone 2 is large, covering the main part of the dwelling. The air mixing can therefore not be expected to be uniform throughout this zone. In zone 2, two tracer gas sources (type B) and three samplers are distributed. The variation of tracer concentration can be taken as a measure of the extent of mixing. In figure 5 the distribution of relative standard deviations from the mean (in %) are displayed.



relative standard deviation %

Figure 5. *The distribution of relative standard deviation of tracer concentration from the mean in the two zones. The bedroom is denoted as* zone 1 *and the rest of the dwelling as* zone 2. *Tracer type A is distributed in* zone 1 *while tracer type B is distributed in* zone 2.

In zone 1 the calculation is based on two samplers, while it is based on three samplers in zone 2. The median relative standard deviation is 3% in zone 1 (bedroom), while in zone 2 (the rest of the dwelling) it is approximately 9% for tracer B and 16% for tracer A. Except for a limited number of cases, the mixing is therefore good enough not to introduce unreasonable errors in the two-zone calculations. It should be pointed out however that the calculation of the direct inflow of air into the two zones is extremely sensitive to non-uniform mixing. The calculations of total air flow rate, the purging flow rate and the interzonal air flows are however not so sensitive and the estimated relative errors in these values are of the same order as the relative standard deviation of tracer mixing as illustrated in fig. 5.

Apart from the uncertainties introduced through the non-uniform mixing, uncertainty is also introduced due to the tracer gas technique itself, which is composed of analysis errors, calibration errors and variations in sampling rate of the passive samplers and emission rates of the tracer gas sources. All such errors have been analysed in earlier work (Stymne *et al.* 1994a) and shown to contribute approximately 11% uncertainty to the result. It is therefore believed that for most of the investigated houses the total relative uncertainty of the calculated values for the total ventilation flow rate, the purging flow rate and the interzonal air flows are within 20%, while the direct inflow to the bedroom may be associated with some larger uncertainty.

CONCLUSIONS

The experimental investigation of ventilation in 59 similar terraced houses using a passive tracer gas technique showed that ventilation varies widely from house to house even though the buildings are similar and the weather conditions are the same. This holds true both for the naturally ventilated houses and for those ventilated mechanically. However on average the ventilation rate in the mechanically ventilated houses is considerably larger than in those ventilated naturally. Only a few of the 29 naturally ventilated houses fulfil the 0.5 ACH requirement, while the greater part of the mechanically ventilated houses do fulfil it. The large variations in ventilation rate must be explained by widely different occupant behaviour and various measures taken, which affect the air supply rate.

The low and mostly insufficient natural ventilation is probably due to the small stack effect created in these single-storey houses without attic space, in combination with airtight modern building techniques. It seems necessary to equip such houses with mechanical ventilation.

The direct inflow of ventilation air into the bedrooms varies considerably and is very low indeed in some bedrooms in the naturally ventilated houses, while in most mechanically ventilated houses it easily fulfils the standard of 4 l/s for one bed. The purging flow rate in the bedrooms varies from a few m^3/h to 100 m^3/h in naturally ventilated houses and is on average twice as large in those ventilated mechanically. The rate of air exchange between a bedroom and the rest of the dwelling varies from a few m^3/h to 200 m^3/h without any significant difference between naturally and mechanically ventilated houses.

The passive tracer gas technique used, has been shown to be appropriate for investigating the difference in ventilation performance in naturally and mechanically ventilated houses. The comparison has been facilitated by the fact that all houses are similar and that the tracer gas experiments have been performed in essentially the same manner in all houses during the same time.

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