ABSTRACT

This paper describes a study of reduced performance of mechanical exhaust systems in 42 Dutch houses after several years of operation. It also describes the effect of reduced ventilation on air quality and the perception and use of the ventilation system by residents. The guanine contents of dust samples taken from the sleeping room were determined to assess the risk of allergy.

In 93% (n=42) of the houses the reduction of the exhaust rate was more than 10% of the value demanded by Dutch building regulations that applied when the houses were built. Deterioration of the system started within 2 years. After 5 years the average reduction of the exhaust rate was 50% of the initial rate.

Interviews of the residents revealed that the systems could not be cleaned and maintained easily. Grids and fanlights in the vicinity of seats and benches were in a closed position because residents fear cold draught. To avoid noise production, residents selected the lowest speed of the exhaust fan. They did not know that minimum ventilation demands are only met at the highest speed level.

INTRODUCTION

In a large survey of 5625 houses in Sweden Engdahl (1998) found that 66% of the ventilation systems do not perform conform the regulations that applied when the system was brought into operation. Insufficient flow rates, missing air supply and exhaust units and contamination of exhaust air ducts were the most important reasons that systems did not pass the test.

A well performing ventilation system is necessary to maintain indoor air quality at the desired level. This can be achieved if the system is well designed and maintained, and dwellers use the system as it was originally designed to.

The aim of our study was to investigate the performance of ventilation systems that are in use for several years under Dutch circumstances. Deterioration of the ventilation system can be due e.g. to wear out of the fan, precipitation of dust and grease in air ducts and valves, and incorrect adjustment of air valves.
after cleaning activity by dwellers. In this study the emphasis is not only on the physical aspects, such as reduced air rates, but also on the behavioral aspects with respect to dwellers use of the ventilation system. The study also examines the effects of deterioration of the system on the quality of indoor air and the risk of allergic reactions caused by the house dust mite.

In most Dutch houses the ventilation system consists of naturally driven air supply and mechanically driven exhaust. In general, the fan of the exhaust system can run at three speed levels. Only at the highest level the ventilation rate meets the minimum demands of the Dutch building regulations. The lower speed levels are meant for use during periods in which dwellers are not at home. The air inlet openings in the outer walls, in general, consist of fan lights or grids provided with insect nets. Air outlets are found in the kitchen, the toilet and the bathroom and consist of a valve connected with the exhaust tube system that leads to the exhaust fan situated at the roof level.

Ventilation systems with both naturally driven supply and exhaust can be found in houses that are older than approximately 50 years. Mechanically driven supply and exhaust with heat recovery are found in houses built during the last decade. This is due to the energy saving potential this system offers.

In contrast to other European countries such as Sweden, Dutch building regulations do not set any demands on maintenance or performance of the ventilation system during the time of operation. Dutch regulations only apply to new houses. Maintenance is considered as a private responsibility.

The philosophy behind the ventilation demands in the Dutch building regulations is that ventilation should only take account for the removal of substances that can not be prevented to penetrate the indoor air, such as carbon dioxide, water vapor and bio effluents that result from human activity and physiological processes. Chemicals of building materials and furniture should be avoided or their emissions should be reduced to prevent concentration levels that can harm human health. Table 1 gives minimum values of ventilation rates according to Dutch building regulations.

<table>
<thead>
<tr>
<th>Space</th>
<th>Minimum ventilation rate $[m^3\cdot s^{-1}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Every m² residential space</td>
<td>0.9 x 10^{-3}</td>
</tr>
<tr>
<td>Kitchen</td>
<td>21 x 10^{-4}</td>
</tr>
<tr>
<td>Toilet</td>
<td>7 x 10^{-3}</td>
</tr>
<tr>
<td>Bathroom</td>
<td>14 x 10^{-4}</td>
</tr>
</tbody>
</table>

Bio effluents cause foul smelling odors and complaints of the residents. Extensive experiments show that the number of complaints increases significantly at CO$_2$ levels above 1200 ppm (ECA, 1992; Van der Linden, 1996). Thus, to avoid odor nuisance the CO$_2$ levels should not exceed 1200 ppm.

The removal of moist air is important to reduce the development of biological agents that affect human health. Bacteria, fungi and house dust mites can cause allergic reactions. These organisms can only survive if the temperature and relative humidity of the air are within certain limits; e.g. house dust mites can extract water from moist air by osmosis if the relative humidity is above the critical equilibrium humidity (CEH). At the critical equilibrium humidity the loss of water equals the gain. This CEH depends on temperature and ranges from 50% at 15°C to 70% at 35°C (Arlian and Veselica, 1981). Below 16°C the house dust mite does not show any significant growth or multiplication.

For fungi and bacteria that are commonly found indoors, the optimum temperature and humidity range from, respectively 0 to 35°C and 70 to 95% RH (Brock and Madigan, 1988).

In this study the investigation of air quality and human health focuses on CO$_2$ concentrations, relative humidity levels, and the amount of house mite allergen. Poor ventilation will lead to high relative humidity values and therefore create a good environment for the development of micro-organisms and house mites. Thus increasing the risk of allergic reactions of dwellers. Poor ventilation also leads to high levels of carbon dioxide and elevated risks of odor nuisance.
METHODS

In this study 42 houses were investigated to determine the deterioration of the exhaust system. The age of these houses ranged from 1 to 12 years. Most (84%) of these houses were apartments (flats) in multifamily houses and equipped with an individual mechanical exhaust system. The rest consists of single family houses. About 50% of the houses were inhabited by two adults, most seniors; 25% were inhabited by families with 2 adults and 2 children. Single persons reside in 25% of the houses.

In these 42 houses the exhaust air rate was measured using an air tube (Wallac AM 300) with an anemometer (Envic DM 100). During these measurements all windows and doors were in a closed position. Exhaust rates of the ventilation systems were examined for the first time immediately after the houses were built. At the end of 2001 the exhaust rates were measured for the second time. The deterioration of the system was determined from the difference between these two rates.

From this set of 42, another set of 25 houses was selected for a more detailed examination. The residents of these 25 houses were interviewed about their perception and use of the ventilation system. They were asked:

- If the ventilation system meets their demands and expectations, and if they have any complaints;
- about the period during which the various air inlets (grids, fan lights, window vents, doors) of the house are in a opened position, and the reason why some are closed;
- which speed level of the exhaust fan is chosen during day and night, and during special activities such as cooking and bathing;
- if they ever turned off the exhaust fan and why;
- about the frequency of cleaning the air inlet grids and outlet valves, exhaust ducts and fan.

Then, the house was examined for signs of moist related problems, such as spots of fungi, and obstructions of the airflow through the house. Special attention was paid to the chink below doors inside the house. According to Dutch building tradition these chinks are used to support a continuous airflow from one room to another.

The air quality was examined by determination of relative humidity and carbon dioxide concentration. These measurements occurred during approximately 7 days and took place alternating in the living room and sleeping room. Residents were asked to register the number of persons that were present in the room and the time they entered and left the room.

The total air change not only depends on the ventilation rate (driven by the exhaust fan), but also on aeration activities of the residents by opening windows or doors. The total air change rate was investigated from the time course of CO\(_2\) concentrations. In this approach the carbon dioxide produced by the residents is used as a tracer gas. As residents leave the room, the carbon dioxide concentration will reduce due to ventilation. From these data the air change rate (a) can be calculated from:

\[
a = \ln \left( \frac{(C_0 - C_b)}{(C_t - C_b)} \right)/t,
\]

in which \(C_0\) is the concentration [kg \(m^3\)] at the start of the experiment directly after CO\(_2\) injection, \(C_b\) the concentration in the outside air and \(C_t\) the concentration at time \(t\) [s] is.

To determine the effect of reduced ventilation rates due to deterioration of the system, the CO\(_2\) concentrations are inappropriate because these concentrations are the result of the combined effects of (reduced) ventilation and other aeration activities. Therefore the effect of deterioration of the exhaust system was approached by means of a simple computer simulation model. The simulations offer the possibility to study the effects of (reduced) mechanical ventilation separately from other aeration activities. The mathematical equations constituting the model can be formulated by using the mass balance of carbon dioxide in the air. The CO\(_2\) concentration is given by the differential equation:
\[ V^*(dC/dt) = q - a^*V^*C, \quad (2) \]

where \( V \) is the volume of the room \([\text{m}^3]\), \( C \) the concentration \([\text{kg m}^{-3}]\), \( t \) the time \([\text{s}]\), \( q \) the production rate of carbon dioxide \([\text{kg s}^{-1}]\), and \( a \) the air change rate \([\text{h}^{-1}]\).

For the initial condition \( C = 0 \) at \( t = 0 \) the carbon dioxide concentration \( C_t \) at time \( t \) is given by:

\[ C_t = q/(a^*V) * (1 - e^{-at}), \quad (3) \]

The final equilibrium concentration that is reached after the residents stayed for a long period in the same room is expressed as:

\[ C_t = q/(a^*V), \quad (4) \]

As the residents leave the room, the source term \( q \) becomes zero and the solution of equation 2 is then written as:

\[ C_t = C_1 * e^{-at}, \quad (5) \]

in which \( C_1 \) is the initial concentration at the moment the last person leaves the room.

Besides, equation (1) follows directly from equation (5).

The carbon dioxide production rate used in the simulations is deduced from the metabolic rate as the human body is at rest (basal metabolism). Then, the energy consumption rate amounts to 1 kcal per minute (Zander, 1973) which is equal to 0.75 met (ISO, 1990). In general, energy production in living organisms is obtained from the oxidation of glucose. Under aerobic conditions the energy yield is given by:

\[ C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \quad - 2843 \text{ KJ mol}^{-1} \text{ glucose}, \quad (6) \]

Then, the carbon dioxide production rate follows from the energy consumption rate of the human body at rest and equation (6) and amounts to \( 6.5 \times 10^{-6} \text{ kg/s} \) per person. (With a specific mass and volume of respectively, 44 kg/kmol CO\(_2\) and 22.4 m\(^3\)/kmol CO\(_2\), the basal carbon dioxide production rate can also be expressed as 12 L CO\(_2\)/h).

Samples of the floor dust were taken in bedrooms to determine the amount of house mite allergen. The amount of allergens was assessed by measuring the guanine content of the floor dust (Le Mao et al., 1989). If the guanine concentration is below 0.6 mg/g dust, there is no risk of allergic reaction. If the concentration is in the range 0.6 to 10 mg/g dust asthmatic reaction can occur and residents sensitivity for house mite allergens will increase. At concentration levels above 10 mg/g there is an elevated risk of severe asthmatic attacks.

**RESULTS**

From the interviews it appeared that residents were used to air sleeping rooms after waking up. If the living room is on the lee-side of the house, they also opened one or more windows or fan lights as long as they stayed in the living room. If the living room is faced to the wind, all windows and grids were closed. Grids and fan lights in the vicinity of benches and seats were closed, even at the lee-side. Dwellers fear cold draught. These results agree with a survey of Van Dongen and Steenbekkers (1993) on the use of
ventilation facilities by Dutch residents. They found that with ambient temperatures around zero in 90% of the sleeping rooms all air inlets are closed during the night. With ambient temperatures above 13°C in only 45% of the sleeping rooms air inlets are opened during the night. Thus, even if the temperature is at a reasonable level, more than 50% of the sleeping rooms have insufficient supply of fresh air.

The exhaust fan normally run at the lowest speed level, except for approximately 30 to 45 minutes during preparation of the hot meal. Then the highest speed level was chosen. None of the residents knew that the minimum ventilation demands of the building regulations are only met at the highest fan speed. Noise appeared to be the main reason for selecting the lowest speed.

In 93% (n=42) of the houses the reduction of the exhaust rate was more than 10% of the value demanded by the regulation that applied when the houses were built (figure 1). This figure applies to all houses regardless of the age of the house. These results imply that deterioration of the ventilation systems was a serious problem in this set of houses. The deterioration became significant after approximately 2 years (figure 2). After 5 years the average reduction of the exhaust rate was equal to about 50% of the initial rate.

![Figure 1. Reduction of the exhaust rate relative to the demands of the regulation that applied when the house was built](image1.png)

![Figure 2. Reduction of the exhaust rate as percentage of its initial rate as a function of the age of the house](image2.png)
Insufficient maintenance and cleaning were considered to be the main reason for this result. From the interviews it appeared that residents try to clean the inlet grids from the outside by vacuum cleaning of the grid housing. In general, the grids could not be dismounted easily. Therefore, residents were not able to clean insect nets properly. Inspections of the grids showed that the majority was clogged with dirt. For the same reason the residents only clean the outer part of the exhaust valves in the kitchen, toilet and bathroom and none of them cleaned the exhaust fan. Comparison between the exhaust rates of the kitchen and bathroom showed that the rate in the kitchen was more reduced than in the bathroom. This was probably caused by precipitation of greasy vapors in the exhaust system due to cooking activities. In 20% of the houses the residents dismantled twice a year the cone of the exhaust valve in the kitchen to clean the inner parts of the valve. With this action, however, there is a serious risk that the cone is not remounted in its original position. If it is mounted deeply in the valve the exhaust rate will be too small, otherwise it will be too large.

In the living room as well as the main sleeping room the carbon dioxide level ranged from 500 to 2000 ppm. The air change rates varied between 0.2 and 0.7 times per hour in the living room and between 0.5 and 0.8 times per hour in the sleeping rooms. The air change rate in Dutch houses show a tendency to decrease during the last decades, from 1.3 to 1.1 for the living room and 2.7 to 1.3 for the sleeping room (Bloemen, 1992). In general, the air change rate of sleeping rooms is larger than of living rooms due to the smaller volume of the sleeping room.

To investigate the effect of the reduced exhaust rates on carbon dioxide concentrations computations were made using the equations 3 to 5. There is a good agreement between the numerical results of this model and experimental results (figure 3). The results shown in this figure pertain to a living room in open connection with a kitchen with a total volume of approximately 100 m$^3$ at Veenkade 111A in The Hague. Three adults stayed for 4 hours in the living room. After 4 hours the carbon dioxide concentration slightly exceeded the 1200 ppm, threshold level of odor nuisance.

Figure 4 gives the results of two simulation runs: one run with an exhaust rate at the minimum level demanded by Dutch building regulations and one at 50% of the demanded rate. In these simulations 4 adults stayed in the room for 5 hours. This can occur, for example, when a family arrive at home at 5.00 p.m., dines, watches television and goes to bed at 11.00 p.m.
The threshold of 1200 ppm is not exceeded if the ventilation rate agrees with the minimum value demanded by the building regulations. If the exhaust rate is equal to 50% of the demanded value, the threshold of 1200 ppm is exceeded after approximately 1.5 hours. Then, complaints of odor nuisance can be expected. Besides, the maximum concentration of 1653 ppm is reached after 5 hours. This concentration lies between the 500 and 2000 ppm as measured in this survey.

The reduced exhaust rate can be due to deterioration of the exhaust system, but can also result from a low fan speed chosen by the residents. Both situations give rise to elevated risks of complaints about the air quality.

In this survey dust samples were taken of the floor in sleeping rooms. The guanine concentrations range from 0 to 9.7 mg/g dust. In 32% (n=19) of the houses the guanine concentrations were lower than 0.6 mg/g. In these houses no risk of allergy is expected. In 68% of the houses the guanine content ranged from 1.2 to 9.7 mg/g indicating a risk of increasing sensitivity of the dwellers for dust mite allergens.

Figure 5 shows that there is no clear relationship between reduction of the exhaust rate and the risk of dust mite allergy. There is a large spread in the guanine contents for exhaust rates lower than the minimum rates demanded by Dutch building regulations. However, it seems that if the exhaust rates are equal to or better than the minimum value of the regulations, there is no elevated risk of dust mite allergy.
Moist is considered as one of the most important factors determining the number of house dust mites. Therefore, a correlation could be expected between the guanine content in house dust and signs of moist related problems and elevated humidity. However, also this relationship was not clear.

Examination of the chinks below doors revealed that in 25% (n=25) of the houses this chink was blocked by carpets or doorsteps. Especially the chink below the door of the bathroom appeared to be essential to avoid growth of fungi in the bathroom. Obstruction of the airflow reduces the removal of water vapor in the bathroom.

CONCLUSIONS

In 90% of the houses of this study the exhaust rate was more than 10% reduced compared to the minimum rates that applied when the houses were built. Between 2 and 5 years the exhaust rate reduced, on average, by 50% of the initial rate. Computations revealed that exhaust rates of 50% of the minimum level (e.g. due to deterioration) could lead to CO₂ concentrations above 1200 ppm indicating risks of odor nuisance.

Deterioration of the exhaust system probably results from a combined effect of filthiness of the system and incorrect adjustment of the exhaust valves during cleaning activities of the residents. Building regulations should set demands on maintenance of ventilation systems. Ventilation facilities (valves, grids) should be designed in such a way that they can be cleaned easily.

Residents fear cold draught and close air inlet facilities in the vicinity of seats and benches even if these air inlets are at the lee-side of the house. It is therefore recommended that the ventilation system is designed with a surplus capacity of air supply units (grids, fan lights). This gives the residents enough opportunities to close some of the grids while a minimum level of air supply rate is guaranteed.

Residents did not know that ventilation demands are only met at the highest speed level of the exhaust fan. It is recommended to add symbols to the speed switch to inform the residents about the status of the speed levels. These symbols can, for example, depict the number of adults that are present in the room.

Obstruction of the chink below the door of the bathroom will lead to growth of fungi. The obstruction of the chink was due to carpets and doorsteps. Since an undisturbed flow is essential to avoid growth of fungi, a grid or fanlight should replace the chink.

There is no clear relationship between reduction of the exhaust rate and the risk of dust mite allergy. This is due to a large spread in the guanine contents for exhaust rates lower than the minimum rates demanded by Dutch building regulations. However it seems that if the exhaust rates are equal to or better than the minimum value there is no elevated risk of dust mite allergy.

Maintenance of HVAC systems and education of their users is crucial for proper operation of the system. This results in higher flows and, most likely, better health conditions.
LITERATURE


Zander, J. 1973, Principles of Ergonomics, Agricultural University Wageningen