

## Why this crisis in residential ventilation?

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### SUMMARY

Ventilation is the cornerstone of good indoor air quality. Ventilation requirements have major attention in building regulations, but ventilation in practice is often poor, resulting in increased concentration of pollutants and hence exposure to health risk. Inspection of 500 houses with interviews of occupants provide the data to link residential ventilation with regulations, performance and user behavior.

The chain of activities from design through execution to use and maintenance of ventilation systems shows weak links. Noise of fans limits the use of higher set points for the required ventilation volumes. Bedrooms become polluted because air circulation is poor and the ventilation capacity is not sufficient. Ventilation services are poorly maintained and after a few years the capacity is reduced with 30-50%. When compensation for the effects of technical deterioration is not available, complaints about poor indoor air are more likely to occur. Recommendations are given for ventilation functions per individual room, for regulations in support of higher volumes in practice and for maintenance protocols. The study highlights the difference between theory and practice of residential ventilation.

### KEYWORDS

Ventilation, Regulations, Performance, User behaviour, Indoor health

### INTRODUCTION

#### Practical background

Ventilation is intrinsically problematic because of the complex interaction between technical performance and use by occupants. When dealing with complaints about poor ventilation or poor indoor air quality, the cause is either in the technical service, the maintenance quality, or the cause is poor use, maybe because of poor performance of the technical service. Who is then responsible for problems: the builder c.q. owner or the occupant? The user would like the indoor air to be of good quality, without considering operation of controls, windows and other inlet and exhaust openings. When the senses warn that better ventilation is required, the occupant is confronted with dilemmas: fresh air or saving energy cost, fresh air or risk of draught or outdoor noise entering the room and even trespassers. These dilemmas often result in the choice to flush for a short time and to keep systems at lowest set point. The market of new ventilation products focuses mainly on the lowest cost for meeting the requirements of the building decree, less on user preferences. Performance testing and maintenance after installation are neglected. But ventilation is the cornerstone of healthy indoor air and poor ventilation leads to more health complaints (Hasselaar, 2002).

#### Scientific background

The relationship between occupant behaviour and technical services in dwellings represents an interdisciplinary research field that links the social and technical sciences. Methods such as

observation and interview techniques and data analysis are taken from the social sciences. Work in this field started with involvement in trouble shooting and expanded towards studies of user complaints about environmental health. The home visits provide data for the study of the relationships between user friendliness, technical performance, perception and behaviour.

The objective is to improve the ventilation of dwellings, by studying both technical features and user behaviour. The research focuses on the evaluation of the quality of ventilation systems in practice.

Research questions are:

1. What is the quality of ventilation of dwellings in practice?
2. How does lack of maintenance influence the ventilation quality?
3. How do occupants use ventilation systems?
4. What recommendations can be given for better ventilation, in the field of regulations, system design, user friendliness and maintenance?

## METHODS

The context is the housing stock in the Netherlands. When examples are given, the reference is a single family house with two storeys and an occupied attic under a sloped roof. Criteria that determine the quality are selected on the basis of previous research projects. Practice is the basis for this paper, implying that performance is often different from what systems are supposed to deliver. "Ventilation in practice" (Hasselaar 2002) is an important source of data and is based on 500 home visits with inspection and interview. In a number of dwellings the ventilation volumes are measured. The air change rate has been calculated on the basis of CO<sub>2</sub> concentration. The home visits included discussion with the occupants on how and when ventilation services were used, with a special focus on winter conditions, when ventilation is more in conflict with energy cost and comfort. Involvement in diagnosing complaint situations and mediation has resulted in better insight in how occupants and professional housing managers deal with ventilation problems and associated health risks (Hasselaar 2006). Ventilation effectiveness in practice is compared with building regulations. The quality and effect of maintenance is reviewed on the basis of interviews and inspections. This analysis leads to recommendations for stricter regulations, better maintenance and for performance contracts between owners and maintenance firms.

## RESULTS

The ventilation services are presented in Table 1. A broad definition of ventilation is applied: including basic ventilation, flushing and infiltration.

Table 1. Ventilation functions and ventilation services.

<b>Ventilation functions</b>	
basic ventilation: to remove building related pollutants	
active ventilation: to remove occupancy related pollutants	
flushing: to remove peak emissions and to reduce the effect of overheating	
<b>Ventilation services</b>	
Inlet	Damper, line grate, trickle vent, sash window, other window types
Circulation	Location and surface area of inlet + exhaust, pressure/temperature differences
Exhaust	Door slit, damper (of mechanical exhaust ), stairwell, stack, cross flow
Infiltration	Location of seams in envelope, supported by cross flows, stack effect
Peak exhaust	Flush window, door, cooker hood, peak exhaust set point of mechanical system

Basic ventilation removes the emissions from the building: material emissions, moisture from the crawl space, humidity from leakage. Flushing serves two major purposes: to remove peak emissions and heat absorbed in thermal mass. Burglar proofing, draught prevention, ease of cleaning and control of set-points are the criteria for optimal use of the services. The focus is on active ventilation, but including the contribution of infiltration and flushing.

### **Air-tightness and infiltration**

Air-tightness was measured with a blower door test to study parameters of infiltration. Monitoring of pressure differences in the Ecobuild-Research project (Ginkel, 2005) show average pressure difference of 15-20 Pa during sampling periods of 10 minutes, with extreme averages of 65 Pa. The pressure difference increases with smaller openings. On the basis of infiltration parameters indicators were selected: the infiltration effect can be roughly evaluated on the basis of construction method, seam length and type of sealing. For instance: a door has a typical seam length of about 600 cm, with single or double stripping, or none. Seams around window frames and doors and the leakage of the roof support a basic air exchange even while exhaust systems are turned off. The ACH (Air Change rate per Hour) caused by infiltration depends on wind and pressure differences between indoors and outside, but ranges overall between 0.05 ACH (very low for sealed envelopes and opening in one façade of a room), to 0.3 ACH average and up to 1 ACH with large seam length in opposite façades without sealing and in windy conditions. This level shows that infiltration contributes a great deal to indoor air quality. Better sealed buildings rely upon controlled ventilation for good indoor air quality. In these buildings mechanical exhaust ventilation or balanced flow systems are needed. The performance of these mechanical systems depends on design and construction quality, on maintenance and use by the occupants, while in older buildings the performance depends more on infiltration, that tends to be high in living rooms (with two façades and large windows, often including a door) and low in bedrooms (with one façade and one smaller window).

### **Inlet systems of fresh air**

#### *Natural inlet systems*

Natural fresh air inlet implies that air enters with outdoor quality. In cold periods the air flow can cause draught and a cold zone near the window. Trickele vents and larger line grates allow simple control. Windows require elaborate user interaction, which creates a user problems in the windy and rainy periods. Openings stay closed more often when the control of set-points is poor, for instance when the choice is (wide) open or completely closed. Recently introduced systems try to solve user problems by demand-controlled inlet openings on the basis of CO<sub>2</sub> concentration or by using “ventostats” with control scenarios that reflect occupancy patterns (Op't Veld, 2006). CO<sub>2</sub> controls that produce a light signal when certain preset concentrations are exceeded sometimes irritate occupants, when maximum open inlets do not prevent high CO<sub>2</sub> concentration.

Insect nets in line grates get clogged with dirt and the effective ventilation surface decreases rapidly, to 30-50% of nominal surface area. Curtains, blinds and sunshades can also block the inlet opening. Obstruction has impact on the volume of fresh air, especially in bedrooms that rely on controlled ventilation rather than infiltration. Inlet openings are not used sometimes to prevent noise from outdoors entering the house.

#### *Ducted inlet systems*

Balanced-flow ventilation is applied for the purpose of heat recovery from exhaust air (hence the acronym HRV for heat-recovery ventilation). The preheated air is ducted into each room.

According to the Dutch Building Decree the volumes must be based on floor areas, not on people present, which can cause capacity problems in small bedrooms with two people. Self-reported respiratory problems in houses with HRV in Amersfoort (Ginkel, 2007) point at poor air change rates. Health complaints are more apparent in houses with HRV than with conventional natural inlet and mechanical exhaust systems (CMV). These complaints are similar to the sick building syndrome: headaches, running nose, irritated eyes (contact lenses), itch, fatigue, poor overall condition. Also, many occupants do not understand how the system works and how it should be controlled. In practice units and ducts are hardly ever cleaned or with an interval of more than 15 years. Filters get clogged with dust within a few weeks, especially in urban areas and near heavy traffic, but the cleaning interval is only 6 months to one year. Tests in the International Laboratory of Air Quality and Health (ILAQH, Brisbane Australia) indicate that the units and ducts accumulate as much dust as the filters, especially in the PM10 size range (Hasselaar, 2004). The deposition is not stable: dust clouds are released after pressure differences, vibrations etc.

### **Natural exhaust**

Air flow in vertical ducts depends on the length of the duct, the temperature difference, wind and the location of the exhaust opening on the roof. In single-family houses, the duct that connects the exhaust point in the kitchen with the rooftop supports a constant exhaust volume except on warm summer days. Measured exhaust volumes (n= 80) under different climatic conditions indicate that on average 40 - 60% of standard values are reached. The bathroom tends to have less favourable conditions due to the location under the roof, with little stack effect in the exhaust duct. Occasionally reversed airflow can create comfort problems. Natural exhaust ducts are never cleaned in practice, and the capacity is likely to be reduced because even spider webs can block the airflow. Maintenance is also needed to correct construction failures. Inspection from the rooftop of 30 natural exhaust ducts revealed design failures, wrong inlets and outlets, obstruction of flow by dirt or flexible ducts and bad location of outlets on the roof (Hasselaar, 2002).

### **Mechanical exhaust**

Mechanical systems are likely to perform poorer than the design requires, Control of construction quality is poor, the fan units are installed only one or two days before delivery, meaning that there is little time to check the performance of ventilation systems. In newly constructed projects 45 to 80% of the damper volumes does not meet the requirements for minimum exhaust volumes (Dongen 2007).

During the user period the capacity tends to reduce, due to dirt and maladjustment by the occupants. The capacity of mechanical exhaust systems at delivery was compared in different housing blocks with the capacity after 1, 3, 5, 10 and 11 years (see Figure 1). This capacity falls back due to dirt on the fan blades, tear and wear of the ball bearings of the fan motor and also dirt in dampers and certain parts of the ducted system. The regression calculation indicates a reduction in exhaust volume of about 10% per year (n=60) (Ginkel, 2002).

More than 70% of exhaust fans in the total housing stock are older than 5 years. On the basis of the reduction in capacity an estimated 70% of all mechanical exhaust systems in the Netherlands performs with less than 60% of standard volumes and 30% with less than half of the minimum volume required in the building decree. A correlation is found between the age of the fan box and the period used per day: the older, the shorter the period of use. In practice the mechanical exhaust volume in the kitchen is roughly 25-35% lower than with natural exhaust and about equal to 20% less in the bathroom (Hasselaar 2006).

Dirty filters create more imbalance between inlet and exhaust volumes, depending on the dirt load. In the Ecobuild-Research test house the effect of dirty filters on air volume was 15-25% (Römer, 2002). Maintenance visits can restore the capacity, when the capacity is measured and dampers are adjusted. Cleaning the fan alone does not restore the capacity.

### **Balanced flow**

Balance flow systems are installed with three setpoints. Depending on the noise level and the perception of the occupant about the need of ventilation, the dominant setpoint is 1 or 2. Setpoint 1 provides 10-15% of nominal volumes, setpoint 2 provides 40-60% of minimum requirements, higher in the first 6 months, but gradually lower due to dirt composition on filters and in some unit types wear of the fans. Setpoint 3 is used for about 45 minutes a day, during cooking.

### **Air change rates**

A survey in 86 houses in the Netherlands showed that in 10% of the houses the air change rate was below 0.3 ACH and in 33% below 0.5 ACH (n=82). This is an average ACH, based on passive tracer gas techniques, with samples taken over a period covering three months in the heating season in the living room and the master bedroom (Gids 2004).

The air change rate in 38 houses was calculated on the basis of CO<sub>2</sub> data logging over periods of 1-10 days per room and include a diary written by the occupants. An estimate was made of the effect of inlet openings on the air change rates in bedrooms with typical surface areas of 8-12 m<sup>2</sup>. Well-sealed windows are applied in this block and the bedrooms have an opening in one façade, meaning that the contribution of infiltration is relatively minor. The range is from 0,2 to 1,6 ACH. We found no correlation between ACH and actual exhaust volume, which indicates that the use of windows (cross flow and infiltration) determines the ACH rather than the type of ventilation system.

The resulting ACH for normal weather conditions in April/May and November are:

all closed	0.1 - 0.3 ACH
door to circulation area (indoors) open	0.5 - 0.7
window open, door closed	0.5 - 0.7
window and door open	0.7 - >1.2

### **User behaviour**

Mechanical ventilation with individual control is often kept on the lowest set point. Collective systems provide the “norm” value 24 hours/day. New mechanical systems tend to be used longer and even for 24 hours, but this habit is mostly changing over time and the effect is clearly visible within 6 months to one year after new installation. Of the houses with mechanical ventilation (58% of n =324) 14% has turned the system off for 23 -24 hours a day. Of the 86% that uses the system, the lowest set point is on for an average period of 17 hours a day, the highest set point on average for 7 hours a day and this includes collective systems without individual controls. Individual systems are switched to a high set point for a relatively short period per day: 30-45 minutes. Of all cases with mechanical ventilation 21% has a mechanical cooker hood, in houses with natural ventilation this is 18%. The cooker hood is used for about 45 minutes per day. The low set point chosen by the occupant and the reduced capacities indicate that the exhaust system does not contribute to good ventilation: this effect depends to a large extent on cross flow, infiltration and the stack effect of a stairwell in combination with openings in the roof (Hasselaar 2006).

Two people in a bedroom of 14 m<sup>2</sup> require an air change rate of 1.4 ACH to keep the CO<sub>2</sub> concentration below 1000 parts per million. In average dwellings a window must be open during the night (500 cm<sup>2</sup> net opening) to sustain this condition.

## **DISCUSSION**

In the housing industry a shift can be seen since 1965: before 1965 all houses were equipped with natural ventilation, and when in 1965 the building decree claimed mechanical systems in dwellings with the floor higher than 13 m above ground level, mechanical exhaust was introduced into the market. In 1975 a mechanical exhaust was required when the floor plan included a kitchen with open connection to the living room. In 1992 the requirements for achieving the ventilation volumes became stricter and it stopped the application of natural ventilation systems. The introduction of energy performance regulations in 1996 resulted in more attention for heat recovery ventilation and the application boosted to 40% of newly built dwellings after the energy performance requirements became stricter in 1998 and in 2001. User problems with HRV and an increasing number of complaints about poor indoor air quality and mould growth in modern, well sealed dwellings with mechanical exhaust ventilation, put the topic of ventilation on the public agenda. In 2006 the occupants of a neighbourhood in Amersfoort, who were backed up by major media attention, caused a crisis in the application of HRV. Competing systems based on automatic inlets or demand controlled automatic ventilation gain market influence. The attention for so-called hybrid ventilation (“natural as long as possible, mechanical when needed”) seems to grow. The manufacturers claim great effects on energy savings, based on sometimes unclear household characteristics. There is growing awareness that the calculated performance is a poor reflection of actual performance. Poor occupant understanding of how to use ventilation systems, poor maintenance of systems to sustain volumes, the limiting effect of noise from fans on the use of the required high setpoints and also poor recognition of complaints of users are elements of ventilation practice. The health effects of poor ventilation is part of the debate, and evidence on the relationship is available now (Dongen, 2007; Ginkel, 2007) The discussion is about energy performance and health, that are depicted as opposing topics sometimes, and frustrates energy saving policies. Also, the paradigm prevails that the occupant is “stupid” and the ventilation systems must become “smart”, to prevent that energy goals and good indoor air quality are obstructed by wrong user behaviour. Three other reasons for the ventilation crisis can be pointed out:

1. The industry focuses on meeting the minimum requirements in building regulations; the innovations are ‘regulation’- and technology oriented, with poor results in the field of user friendly control and ease of maintenance;
2. The building industry neglects the quality of ventilation and there is a knowledge gap in the design stage, in the stages of commissioning, installation, delivery and maintenance; the project developer does not control nor claim that the installations deliver what is required, and the authorities do not substitute what is missing;
3. The occupant is not heard and has overall poor influence on housing.

The industry and many consultants tend to replace the remark under 3) for: the occupant behaviour leads to poor ventilation. During inspection visits, especially in dwellings with indoor air problems, there were always technical problems with the ventilation system, or poor user options, because of noise, risk of burglary through openings, too little air volumes. Occupant behaviour is an element, of course, which needs attention through “self-learning” controls and systems that are “not perceived as present”. Personal instruction can help but the effect of written information such as user manuals is largely overestimated.

The following criteria for better performance are based on the inspection visits and discussions with occupants and exchanged with experts in the field.

1. Occupants can identify the effect of control of the ventilation services either by fast effect on air quality or by exact reading of air volumes that support the occupants in learning how fast the air quality will be normal.
2. A range of services is available per room, to meet the needs of occupants, that are different during day and night, summer and winter, with noise outside, wind or rain etc..
3. The basic ventilation is very quiet (<28 dB(A) and the volume is adapted to the specific room conditions.
4. The control of ventilation follows intuitive protocols; because indicators for this quality are not available, the design of new products follow participative design techniques and user tests.
5. Fresh air comes from a clean source and enters the room with outdoor quality; filters, units, ducts and dampers are designed for good inspection and frequent cleaning and adjustment.
6. Capacity reduction is inevitable: new systems have surplus capacity while the nominal performance is guaranteed by cyclic maintenance during the user period of a dwelling.
7. The exhaust capacity of the bathroom is doubled when air from other rooms is used for removal of moisture, compared to ventilation with fresh air from outside.
8. The kitchen has a mechanical cooker hood with peak capacity and acoustic level does not apply for peak ventilation periods.
9. During the heating season energy efficiency is important and heat recovery ventilation is the starting point, but without heating demands natural ventilation is suggested (=hybrid).
10. The acoustic level is maximum 28 dB(A) for basis ventilation and during the night, with sufficient ventilation for two persons sleeping in a bedroom (14 dm<sup>3</sup>/sec).

## CONCLUSIONS

The performance of ventilation systems is generally poor. Indoor air quality is controlled with natural openings mainly, but depends greatly on infiltration. The performance in terms of ventilation volume and effectivity does in practice not differ much between the three major systems applied: natural ventilation, natural inlet and mechanical exhaust and heat recovery ventilation. Besides technical deterioration, there is the problem of poor use by the occupants. One of the major reasons for poor use is avoiding noise from fan units. Indoor air problems tend to occur when users have few options to compensate for poor systems performance. Natural systems are used often as compensation. Performance criteria are listed in Table 2.

Table 2. Ventilation performance criteria.

Functional	Technical	Use
air from a clean source	acoustic level 28-32 dB(A)	flexible choice of services
air from clean installations	no draught in living area	permanent basic ventilation
fine control functions	inlet per room	demand controlled
effect predictable, readable	exhaust/overflow per room	in two hours dry shower
range of services	HRV when heating required	sufficient ACH during sleep
burglar safe	mechanical cooker hood	prevent spread of pollutants
optimised per room	flushing per room	filtercleaning /2 weeks
natural summer cooling	double exhaust enclosed room	volume adjustment /3 years
feedback from users	fan replacement within 8 years	unit, ducts clean /5 years

The energy performance of the three systems does not differ much either, and the cost efficiency of natural systems is likely to be the best, including energy effect. However, when

heat recovery ventilation is improved and supports a proper use, this system can provide the best options, first for energy performance, second for cost and third for healthy indoor environment. The “passive house” strategy deserves for that reason attention.

Building regulations set minimum requirements, that in practice are maximum quality levels. In the requirements the dwelling is viewed as one well stirred space, with fixed exhaust points in the kitchen, bathroom and toilet, while the inlet function is calculated on the basis of surface area of occupied spaces. The regulations do not secure enough inlet and exhaust volumes per individual room, or sufficient indoor air quality. During the user period, the maintenance of ventilation systems is poor.

## REFERENCES

- De Gids WF, Op't Veld PJM. 2004. Onderzoek naar ventilatie in relatie tot gezondheidsaspecten en energiegebruik voor een representatieve steekproef van het Nederlandse woningbestand. Delft, TNO Bouw (in Dutch).
- Dongen JEF. Vos H. 2007. Gezondheidsaspecten van woningen in Nederland, TNO, Delft.
- Ginkel JT. van, Hasselaar E. 2002. De ontwikkeling van afzuighoeveelheden bij mechanische woningventilatie, oorzaak en gevolg, Onderzoeksinstituut OTB, Delft (in Dutch).
- Ginkel JT. van, Itard LCM. 2005. Ecobuild Research fase 2, Gezondheids- en milieuaspecten, OTB, Delft (in Dutch).
- Ginkel JT. Van. 2007. Inventarisatie woninggerelateerde gezondheidsklachten in Vathorst. report for Municipality of Amersfoort, OTB, Delft (in Dutch).
- Greml A. 2004. Technischer Status von Wohnraumlüftungsanlagen, Vienna, Haus der Zukunft (298 pages in German).
- Hasselaar E. 2002. Ventilatie in de praktijk, Onderzoeksinstituut OTB, Delft (in Dutch).
- Hasselaar E. Jamriska M. 2004. Quantification of aerosol losses in mechanical exhaust and balanced air flow ventilation systems, in *Proceedings of CIB 2004 conference Building for the future*, pp. 1-9, Toronto, Canada, Institute for Research and Construction.
- Hasselaar E. 2006. Health performance of housing, indicators and tools. TUD Technische Universiteit Delft (PhD thesis, 298 pages). Amsterdam, IOS Press.
- Op't Veld PJM. 2006. oral presentation at symposium Ventilation and EPC=0,8. Delft University of Technology, Delft (in Dutch).
- Römer JC. Jong MJM. Bakker EJ. Van Helden WGJ. Maassen W. Berben J. 2002. Vergelijking tussen numerieke gebouwsimulaties en experimentele gegevens op woningniveau, Petten, ECN (in Dutch).