URBAN PLANNING INSTITUTE of the REPUBLIC of SLOVENIA
Trnovski pristan 2, p.p. 4717, 1127 Ljubljana, SLOVENIA
Phone: +386 1 420 13 00, fax: +386 1 420 13 30
E-mail: info@uirs.si, web: http://www.uirs.si

ENHR International Conference
Ljubljana '06
Ljubljana, Slovenia, 2-5 July 2006

Workshop 5 - The Residential Context of Health

Indoor air quality influenced by ventilation system design

Jan van Ginkel
j.v.ginkel@otb.tudelft.nl

Evert Hasselaar

Paper presented at the ENHR conference
"Housing in an expanding Europe:
theory, policy, participation and implementation"
Ljubljana, Slovenia
2 - 5 July 2006

Indoor air quality influenced by ventilation system design

J.T. van Ginkel, E. Hasselaar

OTB Research Institute for Housing, Urban and Mobility Studies.
P.O. Box 5030, 2600 GA Delft, The Netherlands
E-mail: j.v.ginkel@otb.tudelft.nl

Abstract
This study focuses on the influence of the use of air inlet and exhaust devices on the air change rates per hour (ACH) in 37 residential dwellings in the Netherlands. The ACH in living rooms varied from 0.1 to 1.9, whereas in bedrooms it varied from 0.1 to 3.6. Computations of relative humidity and carbon dioxide using a simple mathematical model and measured values of ACH revealed risks of poor indoor air quality in bedrooms and bathrooms. In building regulations more attention should be paid to ventilation requirements for bedrooms and bathrooms.

Introduction
Health complaints related to poor indoor air quality occur in approximately 15% of the Dutch houses (Passchier-Vermeer et al., 2001). 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 influence of the ventilation system design and the ventilation behaviour of dwellers on the air change rate per hour (ACH) under Dutch circumstances.
In many 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 the highest speed level meets the minimum ventilation 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 supply and exhaust both naturally driven, 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 system offers a good energy saving potential.
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 vapour 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.
Bio effluents cause foul smelling odours 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 odour nuisance the CO_2 levels should not exceed 1200 ppm..

Table 1. Minimum ventilation rates as demanded by Dutch building regulations

Space	Minimum ventilation rate [$m^3\ s^{-1}$]
Every m^2 residential space	0.9×10^{-3}
Kitchen	21×10^{-3}
Toilet	7×10^{-3}
Bathroom	14×10^{-3}

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 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 15ºC to 70% at 35ºC (Arlian and Veselica, 1981). Below 16ºC 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 35ºC 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 and relative humidity levels. 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 odour nuisance.

Research method
We selected 37 houses from various projects ranging from 10 to 100 years old; 9 single family houses with mechanical and 3 with naturally driven exhaust, 10 multi family houses with mechanical and 5 with naturally driven exhaust.
Measurements
We measured the ACH in the living room and the bedroom under the following ventilation conditions:

1. all closed (including the mechanical ventilation set to zero)
2. open door inside the house between the room and the main corridor
3. open window
4. open window and exhaust running

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:

$$a = \ln [(C_0 - C_b)/(C_t - C_b)]/t, \qquad (1)$$

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.
The CO_2 - monitor used in this study was based on non-dispersive infra-red detection which makes use of the property of a gas to absorb energy from an infra-red light source. The

resultant heat generated is detected as a volumetric change. The monitor has a resolution of typically +/- 50 ppm.
The CO_2 -concentration was measured over a period of 8 to 10 days. The occupants wrote in a diary how many people were present, the opening of grids, windows and doors and the moments changes occurred.

Simulation
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:

$$V*(dC/dt) = q - a*V*C, \tag{2}$$

where V is the volume of the room [m^3], C the concentration [kg m^{-3}], t the time [s], q the production rate of carbon dioxide [kg s^{-1}], and a the air change rate [h^{-1}].
For the initial condition C = 0 at t = 0 the carbon dioxide concentration C_t at time t is given by:

$$C_t = q/(a*V) * (1 - e^{-at}), \tag{3}$$

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

$$C_t = q/(a*V), \tag{4}$$

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

$$C_t = C_1 * e^{-at}, \tag{5}$$

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:

$$C_6 H_{12} O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2 O \qquad - 2843 \text{ KJ mol}^{-1} \text{ glucose}, \tag{6}$$

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 10^{-6} 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).

Results

The average dimensions of the living rooms and bedrooms were 34 m^2 (88 m^3) and 12 m^2 (31 m^3), respectively.

If all ventilation equipment is closed the average ACH is approximately 0.2 tot 0.3 [s^{-1}]. This is due to infiltration. Opening the door between the room and the corridor results in a minor increase of the ACH, whereas the effect of an open window is strong. The maximum ACH measured in the living room was 1.9 and in the bedroom 3.6 [s^{-1}].

In all scenarios the simulated carbon dioxide concentration exceeded the critical value of 1200 ppm (figure 2). This means that, on average, an open window is not enough to guarantee healthy conditions in a bedroom. Calculations show that the minimum air change rate should be as high as 1.6 to keep the CO_2 level below 1200 ppm for a bedroom of 12 m^2 used by two adults.

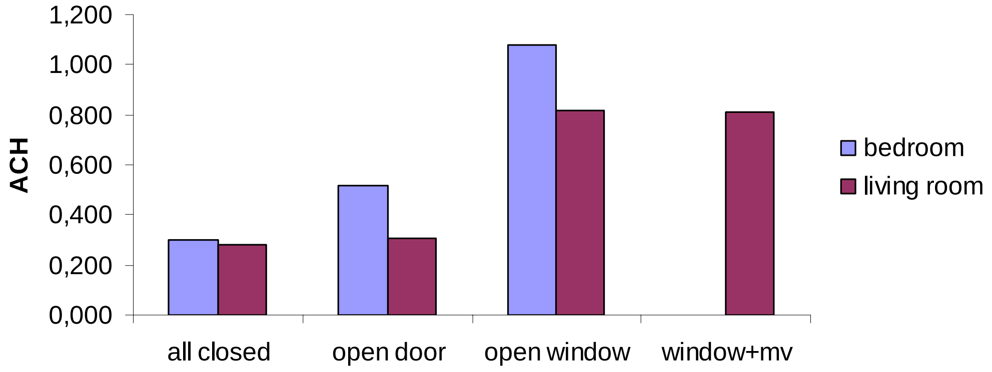

Figure 1 Average air change rates based on CO_2-monitoring (mv = mechanical exhaust)

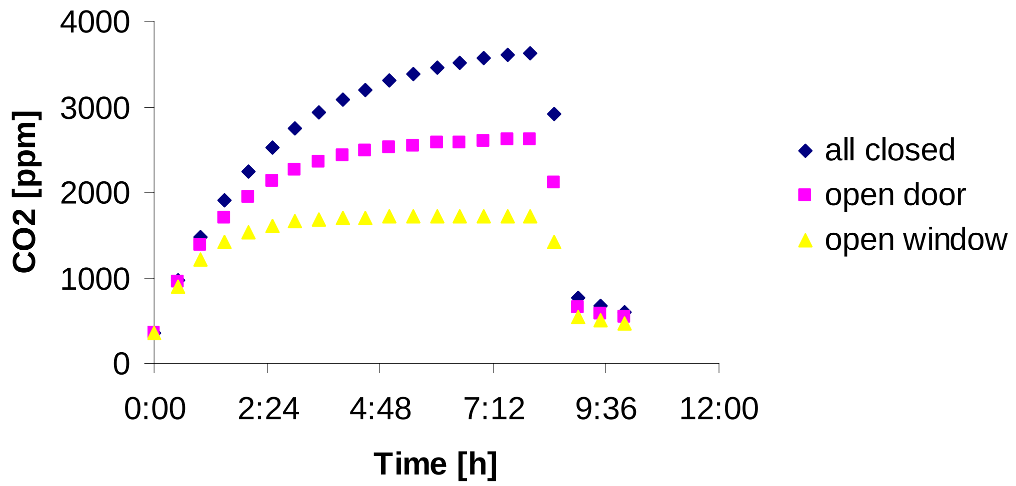

Figure 2 Simulated carbon dioxide concentrations in a bedroom occupied by two adults; scenarios: all closed (ACH 0.3), open door (ACH 0.5), open window (ACH 1.0)

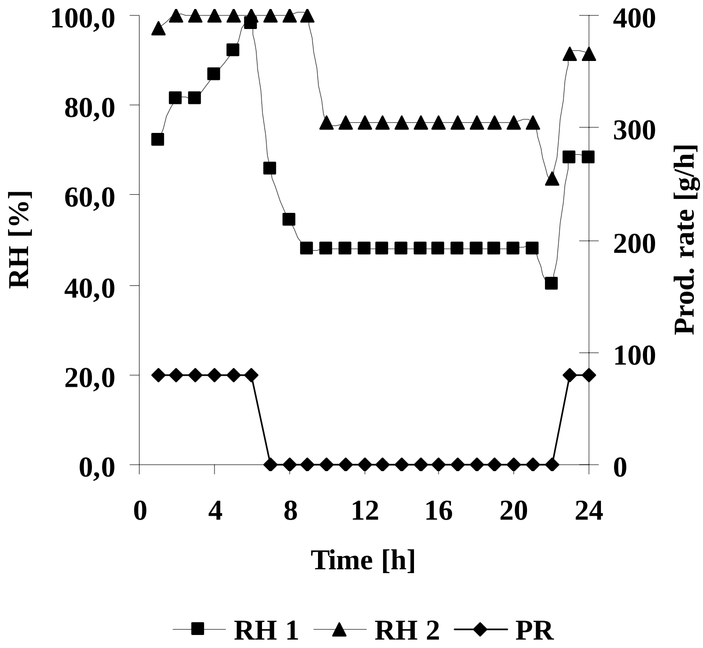

Figure 3 Simulated relative humidity in a bedroom used by two adults (ACH = 0.6). Scenarios: outdoor air supply (1), indoor air supply (2)

We simulated the time course of the relative humidity for two scenarios (figure 3). In scenario (1) the air supply is assumed to originate from outdoors, whereas in scenario (2) the air is supplied from the corridor (indoor air supply). This second scenario occurs when the door to the corridor is open while the window is closed. This occurs quite often when dwellers fear cold draught. With indoor air supply the relative humidity increases to 100%. This condition is conducive to the development of fungi en house dust mite and thus posing a threat on dwellers health.

Discussion and conclusions

The minimum Dutch ventilation rates might be too small for bedrooms. According to Dutch building regulations (table 1) the minimum ventilation rate is 9 $l/s/m^2$. For a bedroom of 12 m^2 (31 m^3) this means that the ACH should be at least 1.25. Previously, we calculated that the ACH should be 1.6 to prevent carbon dioxide concentration larger than 1200 ppm. We therefore recommend that for rooms large enough to harbour two adults, the minimum ventilation rate should be equal to 50 m^3/h. This level is also prevents moist conditions. Dwellers fear cold draught. Van Dongen and Steenbekkers (1993) studied the use of ventilation facilities by Dutch dwellers. 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 13ºC 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. In scientific research and building regulations more attention should be paid to means that avoid cold draught.

References

Arlian, L.G., and Veselica, M.M., 1981, Reevaluation of humidity requirements of the house dust mite *Dermatophagoides farinae*, J. Medical Entomology 18: 351 -352

Brock, T.D., and Madigan, M.T., 1988, Biology of micro-organisms, Prentice Hall int. ed., 5th ed., 835 pp.

ECA (European Collaborative Action “Indoor Air Quality and its Impact on Man”, COST Project 613), 1992. Guidelines for ventilation requirements in buildings. Report No. 11, EUR 14449 EN. Office for official publications of the European Communities, Luxembourg, p.9.

ISO Standard, 1990. Ergonomics, Determination of metabolic heat production.

Passchier-Vermeer, W., e.a., 2001. Milieu en gezondheid: overzicht van risico’s doelen en beleid. TNO-rapport PG/VGZ/2001.95. TNO Preventie en Gezondheid. Leiden (in Dutch)

Van der Linden, A.C., 1996, **Bouwfysica**, Spruyt, Van Mantgem & De Does BV, Leiden (in Dutch).

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