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Supply and Demand of Indoor Air Qualities in Dwellings

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Abstract

Indoor air quality (IAQ) influences the health of humans, the young and the old being generally more susceptible. In this study we examined how supply and demand of indoor air quality in dwellings are matched. On the supply-side, we evaluated ventilation systems, including natural ventilation, balanced ventilation, and adaptive systems. Two major health-related aspects are flexibility (both a secure base level and a high on-demand level) and the size of the air-exposed surface of the inlet part of the ventilation system. The indoor air quality in Dutch dwellings, as a result of ventilation system and (activity by) inhabitants, was evaluated from continuous measuring in 37 different dwellings for a whole week each during winter time. CO_2 concentration, humidity class, ventilation rate and fine particle ratio (indoor versus outdoor) were used as quality parameters. On the demand-side, three population groups with different sensitivity towards air quality were identified: healthy adults (up to 49 years of age), elderly and young (aged over 49 years or under 20 years), and chronic lung sufferers.

Complaint percentages in different air qualities derived from literature, and actual IAQ levels in dwellings were compared. IAQ criteria for the different population groups were derived from literature. In none of the dwellings an acceptable IAQ for the most susceptible group was present, whilst only 1 dwelling met the standards for the group of young and elderly persons. This indicates that for most of the population IAQ at home is less than optimum. Especially pollution-reservoirs should be avoided, and maintenance must be simple and effective. At present, ventilation is inadequate. Within an ageing population and an increasing incidence of airways-related diseases, ventilation facilities should be directed towards the actual needs of the persons concerned. Managing IAQ in dwellings through adaptive sensor-controlled ventilation systems may be a way to avoid health risks from indoor air for the elderly and other susceptible populations.

Introduction

Most Dutch dwellings are ventilated either naturally or with extract fans only. Newer systems including balanced ventilation, demand-adaptable ventilation and others have less than 1 percent penetration at the moment, but are growing. Supply and outflow characteristics of these systems are different, giving rise to differences in indoor air quality (IAQ). Complaints of dwellers indicate that the prevailing ventilation systems are unable to supply adequate ventilation. Upcoming systems contain both negative and positive elements towards a healthy indoor environment.

Indoor air quality influences the health of humans, especially susceptible persons (Snijders, M. C. L. et al. 2001). In the last decades, ventilation strategies have changed due to the advent of environmental consciousness, and so has the amount of outdoor air that is brought in. In reaction, classifications of indoor air were aimed at limits to specific parameters: concentration of VOC's, CO or CO_2 (Norbäck, D. et al. 1995). Other approaches aim at a limit of complaining persons: indoor air quality satisfying 70-85% of all inhabitants, allowing up to 30% to be dissatisfied (Kort, H. S. M. et al. 1990;Comite Europeen de Normalisation 1997).
Within an ageing population and an increasing incidence of airways-related diseases, normalization of IAQ should be more directed towards the actual needs of the individual persons concerned. In this study present and future domestic ventilation systems are evaluated for health implications. Actually supplied IAQ in 37 dwellings is compared with the needs of groups of the Dutch population with a different need for indoor air quality.

Materials & methods

The ventilation systems in Dutch dwellings are divided in 3 categories according to NEN 1087. We use furthermore 3 or 4 subdivisions per category to identify specific positive or negative health-related properties (Table 1). Characteristics of each system were selected that may influence IAQ and bears therefore health risks.

Table 1. Ventilation systems (Koren, L. G. H. et al. 2001)			
Main system	Subsystems		
Naturally ventilated type A	A1 Grids or windows	A2 Grids or windows, vertical ducts (chimneys)	A3 Supply-controlled grids	
Mechanical ventilation, exhaust only type C	C1 Grids or windows, exhaust fans in bathroom, toilet and kitchen	C2 Demand-controlled exhaust ducts, supply through grids	C3 Demand-controlled and natural exhaust, supply through grids (hybrid)	
Mechanical ventilation, supply and exhaust type D	D1 Constant supply and exhaust	D2 Demand-controlled supply and exhaust of air	D3 Demand-controlled supply and exhaust of air, with heat-recycling	D4 Demand-controlled and natural supply and exhaust of air (hybrid)

To establish the impact of IAQ on human diseases, data were obtained by literature study, including Medline and Science Citation Index (1965-2001). The external determinants of the indoor air related disease were obtained from Dutch handbooks on health status quo and prospectives (Ruwaard, D. and Kramers, P. G. N., 93;Ruwaard, D. and Kramers, P. G., 97).

Population statistics (Centraal Bureau voor de Statistiek 2002;Smit, H. A. et al. 2000) were used to determine the population size suffering from the most relevant indoor-air related diseases and to establish age groups at risk. Health complaints on low and higher levels (5 - 20%) from literature were taken as limits to determine levels of indoor air suitable to satisfy different risk groups.

Actual frequency of the levels of indoor air quality was established in 80 dwellings. The dwelling sample was compared with the total dwelling stock of the Netherlands to indicate validity. The following parameters were measured: CO_2 concentration as a measure of the presence of irritants of biological nature and of cooking and heating gasses; temperature and relative humidity from which the humidity class was established, a measure that is related with allergen levels originating from mites and fungi (Schober, G. et al. 1995); and the number of fine dust particles ($\geq$ 0.3 micron) indicating both organic and inorganic irritants. In each dwelling, measurements were performed continuously during a week in the living room.

From individual diaries and CO_2 measurements, ventilation rate was assessed as follows: we assumed that (a) sedentary occupants were the only source of pollution, (b) the outdoor CO_2 concentration was 350 ppm, and (c) both ventilating air and pollutants were uniformly distributed throughout the ventilated space. Children and employed adults were assumed to spend on average 7 hours per day in the living-room, elderly persons on average 10 hours (Spengler, J. D. et al. 1996;Lawton, M. P. 1990). As CO_2 level rises when occupants are present, the 80th percentile (P_{80}) concentration was used of 24 hours CO_2 monitoring. This P_{80} concentration refers to 50% of occupied time in the living-room. Based on these assumptions, a first-order differential equation was used to calculate the room ventilation rate form the P_{80} concentration.

Measuring equipment included a datalogger (Almemo type 2290-8, Ahlborn, Holzkirchen, Germany); a CO_2 sensor, being a diffusion-based non-dispersive infrared (NDIR) spectrometer (Valtronics 2045, Envico, Zoeterwoude NL); and a combined temperature and humidity sensor, respectively a NTC-element type N and a capacitive sheet sensor (Almemo FH A 646, Ahlborn, Holzkirchen, Germany). Ambient air pressure was obtained from a weather station of the Royal Dutch Meteorological Institute (KNMI, De Bilt, The Netherlands), closest to the sampled dwelling.

Results

In order to evaluate the health risks of domestic ventilation systems we first have to identify the pertaining diseases. The most relevant diseases with external determinants that are related to indoor air quality are chronic bronchitis and lung emphysema (together: COPD, chronic obstructive pulmonary diseases) and asthma (Ruwaard, D. and Kramers, P. G., 97;Bronswijk, J. E. M. H. van et al. 1999). The prevalence of these diseases in the Dutch population age groups includes at least 460.000 persons in total. On average, 1 to 2 percent of the population is suffering from either of these diseases (Smit, H. A. et al. 2000).

Risk groups

We selected three age groups that constitute most different prevalence. The young, aged below 20, are 50 to 150% more at risk in case of asthma than the group of 20 to 49 years of age. The group aged 50 and older is especially vulnerable in case of COPD, 10 to 20 times more than the younger ages. The main victims in case of COPD are men, mainly due to a larger percentage of smokers among men. COPD percentages of the male population involve a rise from 3% at 65 years of age to 15% or more at 80[+] (Centraal Bureau voor de Statistiek 2002). Trends are that more women take up smoking and that COPD prevalence of women increases accordingly (Woods Robinson et al. 1993).

Among hyperresponsive COPD and asthma sufferers, complaints from indoor air are already present at low levels of irritants. Typically, a CO_2 concentration of 1000 –1200 ppm induces irritant effects in healthy young adults, whereas in sensitive individuals effects are established at 30% to 40% lower concentrations (Rajhans, G. S. 1983).

Although fine dust particles are known to cause irritation and induce asthma exacerbation, the levels at which complaints start are not conclusive (Gavett, S. H. et al. 2001). This is probably due to the large variation in the origin and nature of these dust particles.

Ventilation systems

The technical aspects of ventilation systems that influence health and are not so much related to specific design, but to concept, are compared for each system (Table 2). First of all the efficiency of removing pollutants is important. Natural ventilation does not guarantee a satisfactory dilution of pollutants. Primarily during the summer period the absence of a indoor-outdoor temperature difference as a driving force causes ventilation to stagnate. The standard three-point exhaust ventilators (C1) are at the moment set at the minimum of the desirable volume, and are not capable to compensate pollution peaks. High airflow rates are to be expected from - usually high placed - inlet windows. From 1992 on, mostly ventilation grids are installed in the Dutch dwellings.

Maintenance of all ventilation parts is important, but especially the air inlets. One of the aspects of the Sick Building syndrome of office buildings is the mechanical supply of air. Only an adequate maintenance prevents the advent of airway symptoms. At the supply side the health risk aspects point at the surface size of the air inlet pipes, and the filters. The latter should be of sufficient capacity, remain dry (relative humidity < 70%) to avoid germinating of bacteria or moulds, and changed regularly. The interior of the inlet channels will be polluted by the small fraction of particles escaping the filters and by condensation or interacting gasses. Of course, when filters are not changed regularly or get moist and fungal ridden, more intensive pollution of the interior will take place. Efficient cleaning of ventilation ducts is not possible at the moment. Attempts to clean the soiled ducts in office buildings by way of mechanical brushing or spraying of chemicals appeared not effective (Brosseau, L. M. et al. 2000).

Table 2. Characteristics of ventilation systems with regard to health risks. In bold: problematic levels regarding asthma and COPD

System	Removal of pollutants from the indoor air*	Air flow (draught)[#]	Size of air-exposed surface of installation[o]		Polluting risk of installation[†]	
			supply	exhaust	supply	exhaust
A1	**varies**	**varies**	small	small	low	low
A2	**varies**	**varies**	small	large	low	high
A3	**varies**	low	small	small	low	low
C1	**average**	**low – high**	small	large	low	high
C2 -C3	high	low	small	large	low	high
D1	**average**	low	**large**	large	**high**	high
D2 -D3 -D4	high	low	**large**	large	**high**	high

*varies: varies from dwelling to dwelling depending on design and location, may be capable to remove incidentally high concentrations; **average**: not capable; **high**: high removing capacity; [#]**low**: below 0.15 m/s; **high**: over 0.15 m/s; **varies**: depends on location; [o] **small**: surface up to 2 times the initial opening or exit to the outdoor air (in cm^2); **large**: surface 10 times or more this opening; [†] **low**: maintenance usually once a year, handling easy, delay non-fatal; **high**: maintenance more often and/or handling difficult and/or delay fatal (total clean-up necessary, with imperfect result)

Outleading ducts are much more polluted but generally less important, although redistribution of the trapped material is possible when the system goes off or inversion. In case of air recycling maintenance is of increased importance: the indoor air contains in general more particles than the outdoor air. In systems with heat recovery outgoing air is supposed to exchange only heat with fresh air. However, a small percentage of leakage may be expected (Op 't Veld, P. et al. 2000).

IAQ criteria

The objective of current guidelines is to achieve acceptable responses from at least 80% of all occupants (ASHRAE 1989;Comite Europeen de Normalisation 1992). In this study we assume that this 80% refers mostly to healthy adults, and only a small part of the more susceptible groups are satisfactorily served with this level.

The air quality levels supplied and measured in dwellings are accordingly classified to the demand of the selected groups. A complaint level of 5% of the individuals of each group is accepted. Aiming at lower percentages is less feasible and difficult to validate (Jokl, M. V. 1997); furthermore, this part of the group does not correspond to the most highly susceptible within the group.

Only a limited time of excess may be allowed: short periods of increase of pollutants are known to induce exacerbation of hypersensitive symptoms (Bronswijk, J. E. M. H. van et al. 1999). We used levels of 15 minutes per day (named P_{99}, an excess level of 1% equaling 14.4 minutes per day) and 1 hour per day (named P_{95}, equaling 1.2 hours a day).

The weakest odour level that healthy adults can register corresponds to a 94% satisfaction rate (Jokl, M. V. 1997). Chronic lung disease sufferers are considered to be more susceptible to the health effects of air pollution (European, concerted action, 91;Maroni, M., Seifert, B., and Lindvall, T.,eds., 95) and require an indoor air quality that satisfies at least 90% of all occupants (Jokl, M. V. 1997). The other occupant groups are also satisfied at this health level. The least susceptible group, healthy adults, will be generally satisfied within the 80% level. We assume that the susceptibility of children and elderly persons lies in the middle of these two levels, equalling an 85% satisfaction rate.

Ventilation rates satisfying susceptible groups were assessed from design criteria for the indoor environment (Woods, P. S. et al. 1993). Threshold levels for each level are deduced from the added pollution of occupants and indoor materials, assuming occupancy of 0.05 person per square metre.

The humidity class is established from temperature and humidity measurements through calculation of the difference between indoor (I) and outdoor (O) water vapour pressure (AH_{in-out}) (van Hees, R. P. 1986). This value, originally a month-average, indicates the prevalence of moulds and mites. Both produce allergenic substances and irritants, moulds may also produce toxins. Indoors, mite and fungal growth depend primarily on humidity (Koren, L. G. H. 1995). A sharp increase of mite and fungal growth has been related to the boundary between humidity class II and III. Looking at intervals of excess humidity, de Boer (Woods, P. S. et al. 1993) found that a period of 3 hours a day or more suffices to sustain mite growth in an otherwise dry environment. This allows a P_{90} level (2.4 hours a day) to suffice for most groups. As humidity variation in the rooms is not taken into account, a safety level of P_{95} (1.2 hours) is chosen for the most susceptible group.

A hygienic level for dust particles has not been established yet. In this study we use the outdoor air level as a reference and take a tenfold increase in number of particles as a limit.

Thus air quality levels for chronic asthmatics and COPD sufferers, young and old, and healthy adults are deduced (Table 3) (Snijders, M. C. L. et al. 2002).

Table 3. Demanded air quality level, based on the requirements of inhabitant groups with different susceptibility, for CO_2 concentration, humidity class and room ventilation rate as environmental indicators.
P-values denote the time period of a day [Snijders et al., 2001]

Air quality level for	Requirements		
	CO_2 [*]	Humidity class	Room ventilation rate
Chronic lung disease sufferers	$P_{99} \leq$ 680 ppm	$P_{95} \leq$ II	≥ 2.4 $1s^{-1} m^{-2}$
Children and elderly persons	$P_{99} \leq$ 865 ppm	$P_{90} \leq$ II	≥ 1.5 $1s^{-1} m^{-2}$
Healthy adults	$P_{99} \leq 1085$ ppm	$P_{90} \leq$ II	$\geq 1.05 1s^{-1} m^{-2}$

[*]CO_2 concentration at standard temperature (20°C) and pressure (1013 mbar)

Supplied IAQ

Sixty percent of the dwellings in the Netherlands have natural ventilation only and 40% extract fans, usually in bathroom, toilet and kitchen (Gids, W. F. de 2000). In 2000, these extract fans are present in approximately 2 million dwellings. Up to 11% of newly built dwellings (60,000 a year in total) were provided with balanced ventilation systems (Adan, O. C., Dongen, J. E. F. van, and Gids, W. F. de, 00).

To examine whether the demanded air quality levels are presently supplied a group of 37 dwellings was examined. The characteristics of these dwellings mimic the Dutch situation to a large degree, although the size of the sample is too small to be a valid sample for the Dutch dwellings. Among the differences is an under representation of apartments in favour of family homes.

Estimated ventilation rate in the studied dwellings was in the range between 0.3 to 0.5 air changes per hour, and in 34 of 37 dwellings CO_2 levels were over 865 ppm for more than a quarter of an hour each day. From the indoor air measurements we calculated P_{90}, P_{95} and P_{99}-intervals of 4 indoor quality parameters for each dwelling. Using Table 3, dwellings were counted that satisfied the requirements of each susceptibility group. Dwellings that are apt for chronic lung sufferers also satisfy the other two groups (Table 4). It appears that in only 1 of 37 dwellings measured, recalculated, values meet IAQ criteria for elderly, no dwellings are health sustaining for COPD sufferers.

Table 4. Dwelling fitness for 37 dwellings according to CO_2 level, humidity class, ultra fine particle I/O ratio and assessed room ventilation rate in Dutch living-rooms during winter (n=37). Overall classification based on set of indicators (highest class found). The figures indicate for each parameter fitness fit to accommodate consecutively chronic lung disease sufferers, young and old persons (under 20 or above 49 years of age), and healthy adults. [*]CO_2, humidity class and room ventilation rate; [**]CO_2, humidity class, room ventilation rate and ultra fine particle I/O ratio.

Susceptibility level	Number of dwellings satisfying requirements according to					
	CO_2	Humidity class	Room ventilation rate	Ultrafine particle I/O ratio	Set of 3 indicators [*]	Set of 4 indicators [**]
Chronic lung sufferers	1	5	0	5	0	0
Young (<20) or elderly ($\geq$50)	3	10	3	5	1	1
Healthy adults	6	36	13	5	4	1
Not satisfying any level	31	0	24	16	32	35
Not classified	0	1	0	16	1	1

Discussion

For the Dutch situation and for most of the western countries (Thiam-Daniel, Goh Yam et al. 1999), asthma and COPD appear to be the diseases most influenced by indoor air quality. In asthma especially the young, and in COPD the elderly are involved, although evidence exists of a large underscoring of asthma in the elderly too (Hurd, S. 2000). Persons already suffering from asthma or COPD are prone to ongoing airway inflammation and demand an even higher quality of air than the - healthy - below-20 and above-49 age groups. The suggested levels are deduced from limited data on airway complaints of the different risk groups in low, mediocre and high air quality, usually based upon one variable. In our study we combined levels on three parameters to reveal possible variation between these parameters, thus inducing the necessity to use more than one. Indeed, at least 16 of 37 dwellings were classified in more than one level.

The practical effectiveness of the ventilation facilities in the 37 dwellings was measured during a period of a week. This longer examining period is important to establish peak levels and the periods exceeding above complaint levels during activities at home. As healthy ventilation demands are in most cases not met, we have looked at what is supplied. In these dwellings ventilation systems of the types A (natural) and C1 (extract fans) are installed. Since 1980 the capacity of the C1 systems is leveled to reach $0.9 \ dm^3/(s.m^2)$, which is however in many cases the maximum. Infiltration, that is, ventilation through unintended openings around windows and other parts of the building envelope, has decreased in the same period from more than $300 \ dm^3/s$ (at 10 Pa pressure difference) to an average of $100 \ dm^3/s$ (Cornelissen, H. J. M. et al. 1996).

The high CO_2 and low ventilation rate values indicate that ventilation is in general low, despite extract fans. Improper technical installation, absence of ventilator maintenance and closing of ventilation (inlet) grids will all be part of the cause. A preliminary study revealed that in 25% of all new dwellings the intended ventilation level is not reached (Hasselaar, E., 01). Maintenance of the outflow ventilator unit is low or absent, whereas ventilator capacity falls back significantly in only 5 years. Use of ventilation grids and especially the special ventilation windows are prone to the good will of the user. If awkwardly placed these are either kept tight or used irregularly in at least 1 in 3 dwellings, because of draught or difficulty to open and close these windows and grids.

The presently studied ventilation systems A and C1 are in practice not adequate to sustain a healthy environment for population groups with an increased susceptibility for asthma or COPD. The reasons are both technical and user-derived. The latter may, however, be mixed with poor design. For example, grids and other air inlets are not cleaned because they are too high, too difficult to open or remove, or do not fit into the dishwasher. Out leading ventilators are turned off because of increased noise (Hasselaar, E., 01). In some of the dwellings adequate ventilation is difficult despite a properly functioning ventilation system, because of the dwelling design: air inlet is only possible through low-placed windows that are draughty and unsafe, or traffic noise prohibits use of air inlets.

Alternative systems (C2 - C3, D1 - D4) were at first designed to reduce energy meanwhile taking care of adequate ventilation. We opt for those systems that are taking care of healthy ventilation in disregard of a bonus energy reduction. The most promising systems are the ones that allow dwellers to increase or decrease themselves at the location they want, meanwhile taking care of sound base ventilation. These adaptive sensor-controlled systems must also be easy to handle and to clean. The ones most responsible for proper implementation are at first the designer and the installer. The user, of any age, is then only the last, and intentionally least important party to sustain a healthy indoor environment.

We are unaware of a field study that shows that any of the new ventilation systems functions properly in presence of a variety of dwellers. From the risk characteristics (Table 2) the systems

that may have the demanded qualities are the C2 and C3 systems. A further study into the practical use of these is wanted.

Conclusion

For most of the population IAQ at home is less than optimum in the winter period, especially for elderly lung sufferers. Present systems lack flexibility (both a secure base level and a high on-demand level), whereas in some of the upcoming systems the size of the air-exposed surface (ducts) of the ventilation system itself is an intrinsic risk. Adaptive, easy maintained and handled systems without ducts for inflowing air are the most promising systems to contribute to a healthy home environment for all.

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