Effect of household specificity on exposure time to CO_2 when balanced ventilation systems are used

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SUMMARY

The purpose of this study is to evaluate the relevance of household characteristics on exposure time to CO_2 in houses with balanced ventilation. Statistical tests were conducted to measure the significance of household differences on time indoors. Household scenarios and ventilation scenarios were constructed to determine the level of CO_2 indoors. The production of CO_2 was calculated with the metabolic rate per age of the members of the household. Households are exposed to levels of CO_2 higher than 1000 ppm in houses with low infiltration rate. In practice, the air flow does not comply with the requirements because of the use of the system and for lack of maintenance. High levels of CO_2 (over 5000 ppm) were not shown to be a risk in this study, but exposure to levels of CO_2 between 1000 and 2000 is used as an indicator of other pollutants indoors.

INTRODUCTION

CO_2 emissions in the indoor environment may have negative effects on the occupants. The effects produced by exposure to CO_2 have been studied extensively in the past [1,2]. Under concentrations less than 5000 ppm, CO_2 is not particularly toxic, but is accepted as an indicator for the presence of other contaminants and therefore for indoor air quality. Concentrations above 1000 ppm are related to complaints like fatigue or headache. Some studies tend to show that certain subjects already show these complaints at concentrations as low as 600 ppm [1,2] In the indoor environment of dwellings, CO_2 emissions, as an indicator of air quality, may affect more vulnerable occupants, such as children, the elderly, and people with poor health condition, because they tend to spend more time in the dwelling [3]. In reducing such effects, ventilation has a prominent role. The volume flow rate of ventilation needed to keep the carbon dioxide concentration at the desired level depends on the production rate of CO_2 in the indoor environment. CO_2 levels depend on several factors closely related to household composition, size of household, age and activities of the dwellings occupants. Building regulations set minimal ventilation flow rates per squared meter but recent studies have shown that these minimal ventilation rates may not be sufficient for bedrooms [2]. This research aims to study if differences in households can lead to differences in exposure to CO_2, and therefore, to different requirements of ventilation flow rates.

In order to calculate the indoor exposure to CO_2 in Dutch dwellings, it is necessary to determine the time of exposure, the type of activities realized indoors and the sources of CO_2 found indoors. For this, the Dutch Time Budget Survey (TBO) was used. The exposure time was analyzed by statistical means in order to test the influence of occupants' and households' characteristics on the exposure to CO_2. Scenarios of exposure per household were constructed to test the relevance of differences on exposure time. CO2 production and needed ventilation flow rates for the different household scenarios are then modelled, calculated and compared.

METHODS

Household specificity

The data of the TBO were collected by means of a self-administered diary. Respondents were asked to record their daily activities and place of activities during a period of one regular week. Only groups of subjects with a sample large enough for the statistical analysis were used. Mean times were calculated for the total time indoors, the time spent in spaces of the house and the type of activity realized (table 1).

Table 1. Categories of activities

Category (Place and activity level)	Sub-category (Activities)
Kitchen (medium level)	Cooking
Living room (medium level)	Sporting, household work, caring for pets and plants, playing indoors, childcare
Living room (low level)	Eating, studying and writing, group activities, working at home, hobbies, telephoning, reading, watching TV
Bedroom (very low level)	Sleeping
Bathroom (low level)	Personal care

The survey collected information of 1813 respondents from 12 years and older, therefore, the exposure times of children below 11 years old is not taken into account. It was realized during regular days, so variation in exposure time in other days such as holidays is neglected. In the case of non-response, it can be attributed to lack of time due to a special activity (e.g. birthday), therefore it does not cause bias in the data collected [4]

Statistical Analysis

In the Kolmogorov-Smirnov and Shapiro-Wilk tests of normality, the distributions per place and level of activity were shown to be non-normal with a large percentage of the Sig. values falling below 0.05; though the histograms of some activities showed resemblance with a normal distribution, and the normal probability plots showed a reasonable straight line. Therefore, a non-parametric test was conducted to evaluate the significance of the differences in exposure time within the groups. The Kruskal-Wallis test showed very significant results, therefore adding the fact that the sample is large, parametric tests were conducted to identify the location of the differences in exposure time within the groups, as well as the magnitude of the differences. An independent-samples t-test was conducted for groups of gender, and ANOVAs for groups of age and household size. In order to determine the magnitude of the differences, the eta-squared per variable was obtained, considering an eta-squared of 0.02 as a small effect, 0.06 as moderate effects and 0.12 as large effect [5].

Differences in exposure time attributable to gender

An independent samples t-test (ANOVA) was conducted to analyse the relevance of the differences in exposure time in different places indoors that are attributable to gender. The test showed that there is no significant difference for time spent in the bedroom (p-value=0.379) and the bathroom (p-value=0.745). The differences are significant for the time spent in the living room (p-value=0.013) and the kitchen (p-value=0.00). The differences between time spent in the different spaces were shown to be small for the living room (eta-squared=0.01), bedroom (eta-squared=0.029), and bathroom (eta-squared=0.013). The differences for the time spent in the kitchen do show a large effect (eta-squared=0.16). The results of the t-test showed that there is a significant difference for low level activities (p-value=0.00) and high level activities (p-value=0.00). The differences in the mean of low level activities show a small effect (eta-squared=0.001), while high level activities showed to have large effect (eta-squared=0.18). In other words, gender affects principally the time spend doing high level activities in the kitchen.

Differences in exposure time attributable to household size
A one-way analysis of variance test was conducted for analysing the relevance of the differences in mean times within groups of household size. Subjects were grouped according to the size of the household they belong. The households of 3 persons were not further considered because of the lack of representation within the sample. The results showed that there is a significant difference for the mean scores of the time spent in the living room (p-value=0.00), bedroom (p-value=0.012), and kitchen (p-value=0.005). There is no significant difference for the time spent in the bathroom (p-value=0.72). An eta-squared calculation showed that the differences for time spent in bedroom (eta-squared=0.007), and kitchen (eta-squared=0.008) have a small effect; while the differences for the time spent in the living room (eta-squared=0.059) shows a moderate effect. Post Hoc comparisons showed that 2 person's households spend more time in the living room, followed by 4 person's households. Singles tend to spend less time in the living room. 4 person's households spend more time in the bedroom, while singles and couples spend less time. The time spent in the kitchen is lower for couples than is for singles and 4 person's households. Low and high level activities showed to be significantly different among the groups (p-value=0.00). Nevertheless, the eta-squared calculation showed only a small effect for low level activities (eta-squared= 0.058), and moderate effect for high level activities (eta-squared=0.035). Post Hoc tests showed that singles spend less time in high level activities than 4 person's households and couples. Couples are the households that spend more time involved in high level activities. Households of 4 persons and singles spend less time in low level activities than couples.

Differences in exposure time attributable to age
A one-way analysis of variance test was conducted to estimate the effect of age in variations of mean times in the indoor environment. Six groups were formed according to the age range of the subjects (Group 1: 12-24, Group 2: 25-34, Group 3: 35-44, Group 4: 45-54, Group 5: 55-64, Group 6: 65 and older). The results of the ANOVA for the time spent in different places showed a significant difference for the time spent in the living room (p-value=0.00), kitchen (p-value=0.00), and bedroom (p-value=0.00). The mean differences for the time spent in the bathroom did not show significant difference (p-value=0.095). An eta-squared calculation showed large effects in the differences on the means for time spent in the living room (eta-squared=0.20), and in the kitchen (eta-squared=0.15). The effect is moderate for the time spent in the bedroom (eta-squared=0.06). Post Hoc comparisons showed that the time spent in the living room and in the kitchen increases with age. The time spent in the bedroom also increases with age, except for group 1 (12-24 years), which tend to spend more time in the bedroom. Significant differences were found to have large effects for low level activities (p-value=0.00, eta-squared=0.26), and high level activities (p-value=0.00, eta-squared=0.13). The time spent in high activities increases with age. The time spent in low level activities increases with age, except for group 1 (12-24 years) which tend to spend more time than groups 2, 3 and 4; but not as much as groups 5 and 6.

The trends on time spent indoors are shown in table (2). The exposure time in all cases is higher for women and elderly people. Though there is a relation between household size and mean times, the variations do not show a clear trend. The time spent in the bathroom is considered not to be different for the different groups, and the time spent in the bedroom shows little variation.

Table 2: Trends in time spend in different rooms per occupants' characteristics

Place / activity level	Gender		Household size		Age range	
	Effect	Trend	Effect	Trend	Effect	Trend
Bathroom	-	-	-	-	-	-
Bedroom	-	-	Small	4>2,1	Moderate	Increases with age
Living room	Small	Females > males	Moderate	4,2>1	Large	
Kitchen	Large	Females > males	Small	4,1>2		
Low level activities	Small	Females > time	Small	2>4,1		
High level activities	Large	Females > time	moderate	2>4>1		

Based on these data, four different scenarios are identified that could cover the bandwidth of Dutch households. The household's scenarios are: 1a) single male adult 20-24 years old, 1b) single female elderly, 2a) 4 person's household composed by two adults and two children (12 years), and 2b) 4 person's household composed by two adults and two children (20 years)

Method for the calculation of exposure to CO_2

For this research we assumed that CO_2 is produced only by human beings. Other sources of CO_2 production like cooking hobs, boilers and plants are neglected. The CO_2 volume flow rate in a room qco2(m^3/s) can be described in steady state as:

qco2 = V.(Ci-Co)

Where Co is the CO_2 concentration of the fresh air supplied to the room (usually about 350 ppm) and Ci is the concentration of CO_2 in the air leaving the room. V is the volume flow rate of air. It is assumed that the quantity of air leaving the room is equal to the quantity of air supplied to the room. For Dutch living rooms and bedrooms of average dimensions steady state conditions are assumed to be achieved after 2 hours constant occupancy when the air change rate (ACH) is above 0,8 h-1 [2]. Once qco2 and V are known, it is possible to calculate the concentration of CO_2 in the room (Ci).

Calculation of the CO_2 production rate qco2

In general, energy production in living organisms is obtained from the oxidation of glucose, see equation 1.

C_6 H_{12} O6 + $6O_2 \rightarrow 6CO_2 + 6H_2O$ - 2843 KJ mol-1 glucose, (1)

Under aerobic conditions the energy consumption by this reaction is 2843 kJ per mol glucose. At the same time, 6 mol of CO_2 are produced. This means that the consumption of 474 kJ by the human body produces 1 mol of CO_2. With the specific volume of CO_2 being 22,4 m3/kmol, an energy consumption rate of 1.0 J/s will result in $4.7x10^{-8}$ m^3/s of CO_2.

The carbon dioxide production rate follows therefore from the energy consumption rate of the human body. This energy consumption rate is called metabolic rate and is dependent on the activity performed and the surface area of the body. The calculation of the metabolic rate is conducted according to [6]. It is assumed that the metabolic rates at a same level of activity and age are identical for men and women. The surface area of the body Adu (m^2) is calculated using the formula of DuBois [6].

Adu= 0.202.W0,245 .H0.725

where W is the body weight in kg and H the body height in m.

In table 3, calculated metabolic rates and CO_2 production rates are given as a function of age and activity.

Table 3: Metabolic rates and CO_2 production per age

Age	Weight (m)	Height (kg)	CO_2 production [m^3/s] per level of activity			
			Sleeping	Low	Middle	High
12	28	1.54	2.4 x10^{-6}	5.4 x10^{-6}	8.9 x10^{-6}	12x10^{-6}
20	74	1.84	4.1 x10^{-6}	9.3 x10^{-6}	15 x10^{-6}	21 x10^{-6}
35	70	1.7	3.8 x10^{-6}	8.5 x10^{-6}	14 x10^{-6}	20 x10^{-6}

Calculation of the concentration of CO_2 at room and dwelling level

The concentrations are calculated for a typical Dutch terraced house with three bedrooms. The Dutch Building Decree prescribes the following minimum flow rates given in table 4 [11]. The floor areas and the minimum ventilation flow rates for this dwelling calculated according to the Dutch building decree are summarized in table 5.

Table 4: Minimum flow rates

	Living area (bedrooms and living room)	Kitchen	toilet	Bathroom
Flow rate (m^3s^{-1})	0,9x10^{-3} per square meter with a minimum of 7 x10^{-3} total	21x10^{-3} total	7 x10^{-3} total	14 x10^{-3} total

Table 5: Areas and minimum flow rates for typical Dutch house

	Living room + kitchen	Bedroom 1	Bedroom 2	Bedroom 3	Bathroom
Area (m^2)	37,1	9,9	9,7	6,0	6,6
Flow rate (m^3s^{-1})	33,4 x10^{-3}	8,9 x10^{-3}	8,7 x10^{-3}	7 x10^{-3}	14 x10^{-3}

To limit costs, balanced ventilation systems are mostly designed to meet the requirements on the minimum ventilation rates, but not more. Furthermore, the legislation prescribes that these minimum ventilation flow rates must be achieved by the system when it runs at its highest level (level 3). Balanced ventilation systems in dwellings are mostly equipped with switches that can be put in levels 1, 2 or 3. Studies by Hasselaar [7] and Soldaat [8] show that the systems are running most of the time in level 2 in which only 50 % of the capacity is available. At night time, the system mostly runs in level 1 due to noise pollution from the ventilator, with only 30 % of the capacity. Furthermore, studies have shown [9] a reduction of the capacity of 10% a year, due to a too low level of maintenance (cleaning). After 5 years, the maximum capacity is reduced to 65 % of the original capacity. The total amount of fresh air supplied to the dwelling is also dependent on the air-tightness of the construction. The air-tightness of Dutch new dwellings should not exceed 200 dm^3/s per 500 m^3 building volume. For the reference dwelling studied, the air flow rate should be lower than 200 dm^3/s, which is about 1.5 dm3/sm2. In the calculations shown in this paper, we used this value as the upper limit of the infiltration flow rate, referred as “high infiltration rate” in the graphics. In the Dutch mandatory energy performance norm [10], it is assumed that an air infiltration flow rate lower than 0.4 dm3/sm2 cannot be achieved. We used this value as the lower limit for the infiltration rate (referred as “low infiltration rate” in the graphics).

Four household scenarios and six ventilation scenarios are studied for the reference dwelling. The household scenarios were described earlier in this paper. The six ventilation scenarios are:

1. Non optimal use of a 5 year- old system: 50 % maximum capacity in living room, kitchen and bathroom, 30 % maximum capacity in bedrooms (night). The maximum capacity is 65 % of the mandatory capacity as given in table 4. With 1) low infiltration rate and 2) high infiltration rate

2. Non optimal use of a new system: 50 % mandatory capacity in living room, kitchen and bathroom, 30 % mandatory capacity in bedrooms (night). With 1) low infiltration rate and 2) high infiltration rate
3. Optimal use of a new system: 100% mandatory capacity in living room, kitchen, bathroom and bedrooms. With 1) low infiltration rate and 2) high infiltration rate

Calculation of exposure time

The time spend doing an activity (sleeping, low level or high level) is calculated from the statistical data for each room (living room, three bedrooms, kitchen en bathroom) and each person of each household type (1a, 1b,2a, 2b). The CO2 concentration per room per activity is calculated according to the method described here above, taking into account the number of persons present in the room. The exposure time per person per household is then obtained by adding the times of exposure to a certain level in the different rooms of the house. Four types of exposure levels are distinguished, according to the findings reported in the introduction. These exposure levels are above 2000 ppm, between 1000 and 2000 ppm, between 600 and 1000 ppm and lower than 600 ppm.

RESULTS

For single person households, scenarios 2 and 3 (fig 2 and 3) have a good performance; there is only a slight variation in exposure to CO2 levels between the optimal and non-optimal use of the new system. The exposure to higher levels of CO2 increases in dwellings with low infiltration rate and non-optimal use of 5 years old system (scenario 1.1). Scenario 1.2 (high infiltration rate and non-optimal use of old system) shows also a good performance for single person households (fig 1). For four person households, there is little difference between old and new ventilation systems when these are not optimally used. In dwellings with low infiltration rate, the exposure to levels of 1000 to 2000 ppm is very high. The exposure decreases in dwellings with high infiltration rate, in which the exposure is mainly to levels of 600 to 1000 ppm. The exposure decreases drastically for scenario 3 (fig 3), but the exposure is still high for households of 2 adults and 2 children of 20.

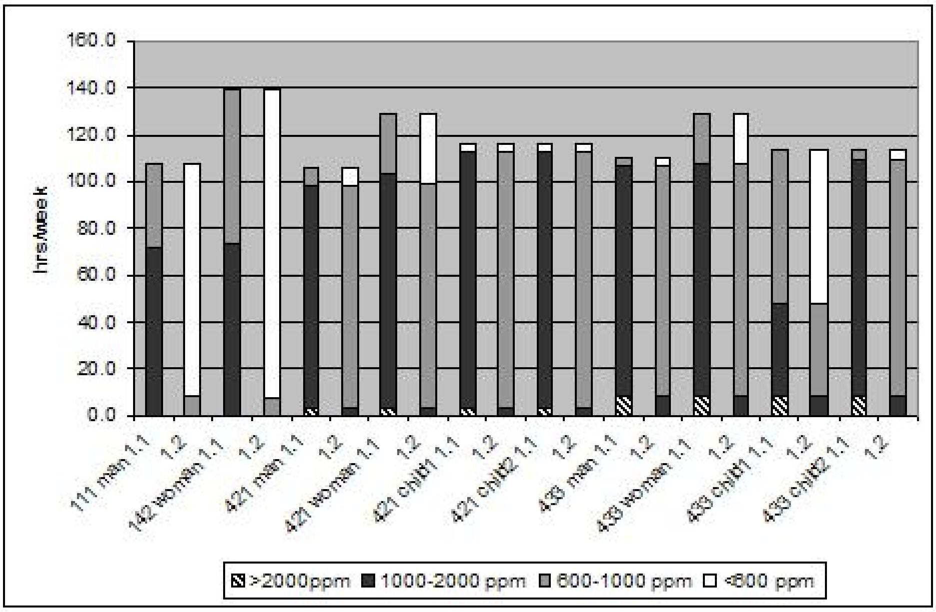

Figure 1: Time of exposure to levels of CO2 per occupant in ventilation scenario 1.1) airtight dwelling, and 1.2) no airtight dwelling, child1= bedroom 2, child2= bedroom 3

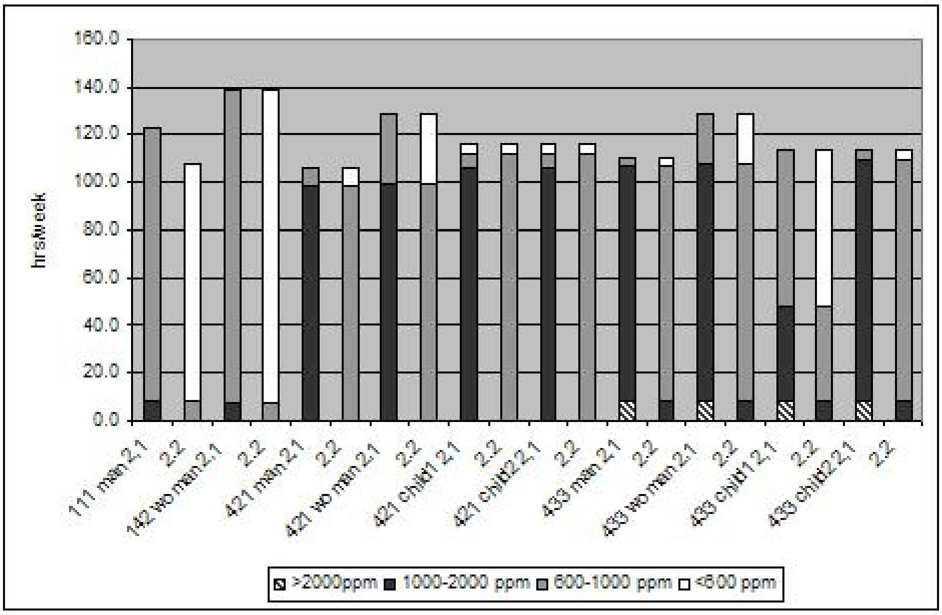

Figure 2: Time of exposure to levels of CO2 per occupant in ventilation scenario 2.1) airtight dwelling, and 2.2) no airtight dwelling, child1= bedroom 2, child2= bedroom 3

In dwellings with low infiltration rates with a ventilation system not used at its optimal capacity, all occupants show a high exposure time to CO2 levels of 1000 to 2000 ppm. In addition, large households may be at risk of exposure to levels of CO2 of more than 2000 ppm for few hours per week. For these dwellings, if the ventilation system is optimally used, the time exposed to high levels of CO2 decreases; though the occupants may be still exposed to CO2 levels of 600 to 1000 ppm. In dwellings with a high infiltration rate, regardless the age or use of the ventilation system, large households are exposed to levels of CO2 of 600 to 1000 ppm, which is under the level recommended by the Ashrae standards; and singles are not exposed to harmful levels. Nevertheless, the exposure of children to possible harmful levels increases when the ventilation system is older than 5 years.

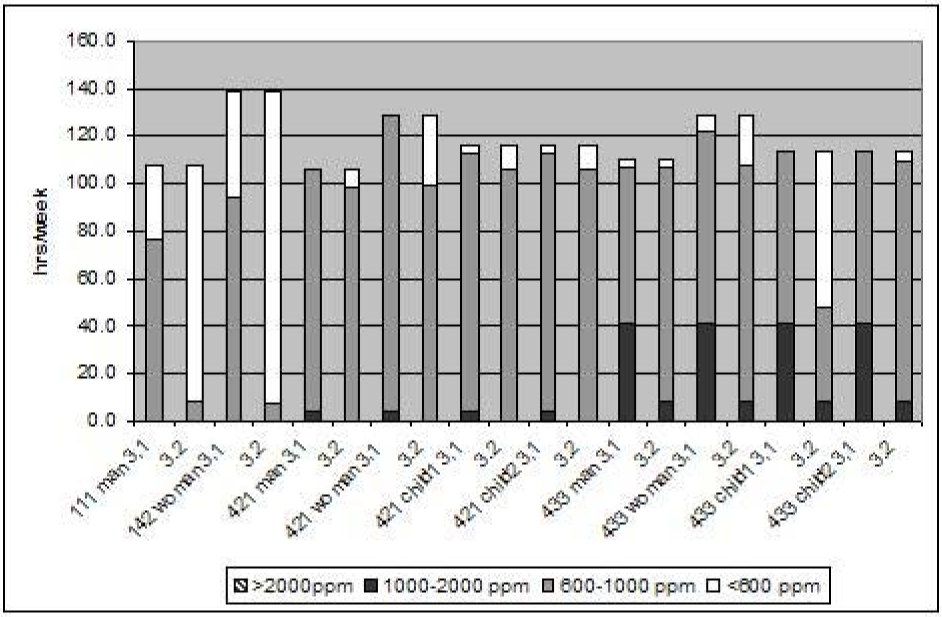

Figure 3: Time of exposure to levels of CO2 per occupant in ventilation scenario 3.1) airtight dwelling, and 3.2) no airtight dwelling, child1= bedroom 2, child2= bedroom 3

CONCLUSION AND DISCUSSION

From this study, we can conclude that the regulation on air flow rates does not comply with the needed ventilation for large households composed by 4 adults. Therefore, large household are at risk, which confirms some results of Hasselaar [7].

Because of the use of the system (users regulate the levels), the ventilation is in practice not enough. This could be solved by having the minimal rates already obtained in the lower levels. In addition, lack of maintenance of the ventilation systems decreases their capacity of satisfying the needed flow.

The statistical analysis of time spent indoors, showed significant differences within different age ranges and gender, nevertheless, differences in exposure between one person household may be neglected under the assumptions we made in this paper.

This research showed that differences in exposure time can be relevant for determining the ventilation required for a good indoor air quality. Though carbon dioxide does not cause health effects at the concentration levels considered for the analysis, it can be used as an indicator of the presence of other harmful substances in the indoor environment. Some groups of people are more exposed to the effects of the indoor environment. The statistical analysis of the time spent indoors showed that the elderly and women tend to spend more time in the indoor environment (table 2). The calculation of exposure time to CO2 showed that large households are more exposed to higher levels. For the statistical analysis, only Dutch people older than 12 years were considered. The exposure time of young children, and households with non-Dutch backgrounds should be considered for further research. Exposure to levels above 2000 ppm exists only for short time. In our calculations, this time is probably overestimated, because we worked with steady state concentrations. In case of short staying times, the steady state conditions would probably not be achieved. In further work, this should be taken into account.

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