Influence of different ventilation levels on indoor air quality and energy savings:
A case study of a single-family house

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Abstract

The influence of different ventilation levels on indoor air quality (IAQ) and energy savings were studied experimentally and analytically in a single-family house occupied by two adults and one infant, situated in Borlänge, Sweden. The building studied had an exhaust ventilation system with a range of air flow rate settings. In order to find appropriate ventilation rates regarding CO_2, relative humidity (RH) and temperature as indicators of IAQ, four ventilation levels were considered, as follows:

I) A very low ventilation rate of 0.10 $L \cdot s^{-1} \cdot m^{-2}$

II) A low ventilation rate of 0.20 $L \cdot s^{-1} \cdot m^{-2}$

III) A normal ventilation rate of 0.35 $L \cdot s^{-1} \cdot m^{-2}$

IV) A high ventilation rate of 0.70 $L \cdot s^{-1} \cdot m^{-2}$

In all cases, the sensor was positioned in the exhaust duct exiting from habitable spaces. Measurements showed that, for case I, the CO_2 concentration reached over 1300 ppm, which was higher than the commonly-referenced threshold for ventilation control, i.e. 1000 ppm, showing unacceptable IAQ. In case II, the CO_2 level was always below 950 ppm, indicating that 0.20 $L \cdot s^{-1} \cdot m^{-2}$ is a sufficient ventilation rate for the reference building. The case III showed that the ventilation rate of 0.35 $L \cdot s^{-1} \cdot m^{-2}$ caused a maximum CO_2 level of 725 ppm; showing the level recommended by Swedish regulations was high with respect to CO_2 level. In addition, measurements showed that the RH and temperature were within acceptable ranges in all cases. An energy savings calculation showed that, in case II, the comparative savings of the combined energy consumption for ventilation fan and ventilation heating was 43 % compared with case III, and 72 % compared with case IV.

Keywords: Indoor air quality; Site measurements; Ventilation level; Energy savings

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Nomenclature

ach	air change rate per hour, h^{-1}
BBR	Swedish Boverket's building regulations
C_{CO_2}	CO_2 concentration in room above outdoor level, ppm
C_i	decipol, perceived IAQ polluted by 1 olf and ventilated by 10 $L \cdot s^{-1}$ of outdoor air
CO_2	carbon dioxide
c_p	specific heat capacity of air, 1005 $J \cdot kg^{-1} \cdot K^{-1}$
D_h	degree hours per year, $^oC \cdot h \cdot year^{-1}$
E_{vent}	energy for ventilation heating, $kWh \cdot year^{-1}$
HVR	high ventilation rate
IAQ	indoor air quality
LVR	low ventilation rate
n	the number of measurements during steady state conditions
NVR	normal ventilation rate
olf	pollution from one sedentary person with metabolic equivalent of 1 met (4.184 $kJ \cdot kg^{-1} \cdot h^{-1}$) with hygienic standard equivalent to 0.7 $bath \cdot day^{-1}$
PPD	predicted percentage dissatisfied, %
PPD_{CO_2}	CO_2 level-based PPD
PPD_{vent}	ventilation rate-based PPD
ppm	parts per million
q	ventilation rate, $m^3 \cdot s^{-1}$
$q_{vent,person}$	ventilation rate per person, $L \cdot s^{-1} \cdot person^{-1}$
$Q_{ventloss}$	specific ventilation heat loss, $W \cdot K^{-1}$
RH	relative humidity, %
SD	standard deviation
U value	heat transfer coefficient of building materials, $W \cdot m^{-2} \cdot K^{-1}$
VAV	variable air volume
VLVR	very low ventilation rate
VOCs	volatile organic compounds
x_i	measured data
x_m	mean value of measured data
ρ	air density, 1.2 $kg \cdot m^{-3}$

1. Introduction

The main purpose of ventilation systems is to remove contaminants, create a good indoor air quality (IAQ) and decrease the risk of health problems by introducing and circulating fresh air throughout the building [1-3]. Research by the European Union (EU) Joint Research Centre (JRC) [4] showed that indoor pollutants are much more dangerous than outdoor air pollutants. Hence, it is essential to have a sufficient ventilation rate inside buildings where people spend approximately 90 % of their time [5]. There are different methods of ventilating buildings, including natural and mechanical types, or a hybrid of the two types. In Sweden, more than 90 % of single-family houses built before 1975 are ventilated naturally, and heated traditionally by some type of fossil fuel furnace [6]. Based on the Swedish Boverket's regulations for buildings (BBR), all residential buildings should be ventilated by at least 0.5 air changes per hour (ach) of fresh air [7].

However, in 2010 more than 37 % of single-family houses and 21 % of multi-family houses were found to be ventilated by less than 0.3 ach [8]. The insufficient ventilation rate in those buildings would cause unacceptable IAQ. Based on the American Society of Heating, Refrigerating, and Air-Conditioning Engineers Standard 62 (ASHRAE-62) [9], the definition of an acceptable IAQ is when 80 % or more of the occupants express no dissatisfaction, and there are no known contaminants at harmful concentrations causing significant health risks. Therefore, in order to create better IAQ when retrofitting buildings, an energy-efficient ventilation system should be implemented, such as a mechanical supply and exhaust with heat recovery system, that is, a system to transfer heat from outgoing air to preheat incoming air [10]; or a variable air volume (VAV) ventilation system, that is, a system designed to supply fresh air based on the occupants' needs [11].

In VAV systems, in contrast to the constant air volume system, the ventilation rate is varied depending on the demand. A VAV system is

used with the aim of finding a balance between IAQ and energy savings [12]. Typically, the controlled variable indicating IAQ is the carbon dioxide (CO_2) level [13]. CO_2 is a good indicator of the acceptability of IAQ since the exposure to CO_2 corresponds directly to the number of people present and the amount of unpleasant human odours generated based on their activity level [14-17]. It should be noted that the CO_2 level in residential buildings is not harmful for human health, and is used only as an indicator of IAQ. CO_2 becomes a dangerous pollutant at concentrations exceeding 5000 parts per million (ppm) [18], causing symptoms such as headaches, dizziness, shortness of breath, and anxiety [19]. This level seldom occurs in residential buildings.

In addition to the VAV system providing sufficient fresh air and better IAQ, it also saves energy as less outdoor air has to be handled, that is, heated, cooled, or dehumidified. The concept of VAV has been known since the 1970s; however, some barriers such as cost, complexity and unreliability of sensors have delayed this system from becoming popular [20]. Nevertheless, recent technologies showed VAV is now cost-effective, together with simple and reliable control. Due to more unpredictable variations and high occupancy, however, VAV is a more common solution in large assembly buildings, such as lecture halls, conference rooms, or theatres [21] than in residential buildings.

Laverge et al. [22] assessed four types of VAV system for a single-family house in Belgium in terms of IAQ and energy savings. The control was based on the relative humidity, the presence or absence of occupants, the CO_2 level, and a combination of all three strategies. The combination of all three strategies gave the highest savings, that is, 60 %; however, the strategy with the CO_2 level control showed a significant reduction in peak exposure to metabolism-related pollutants. Pavlovas [23] evaluated three modes of VAV for Swedish multi-family buildings. The control modes were based on the CO_2 level, the relative humidity, and occupancy detection. The results showed that controlling the ventilation rate according to the CO_2 level caused both acceptable IAQ and high energy savings. Nielsen and Drivsholm [24] proposed a simple method of VAV for a single-family house in Denmark. In their method, the ventilation rate varied between two levels based on the difference between the CO_2 levels and moisture content of the exhaust air and the supply air. The upper air flow rate level was set as a minimum required flow rate by Danish building

regulations, and the lower level was set based on indoor air quality standard EN 15251. Their in-site measurements showed that 37 % of the time the ventilation rate decreased to a lower rate while keeping the CO_2 level and moisture levels within an acceptable range. This value corresponded to 23 % savings in ventilation heating demand, and 35 % lower ventilation fan consumption. The application of VAV systems in a recently-built single-family house was theoretically investigated by Hesaraki and Holmberg [25]. Their results showed that decreasing the ventilation rate from 0.375 to 0.100 ($L·s^{-1}·m^{-2}$) during un-occupancy from 8:00 until 18:00 may result in unacceptable volatile organic compound (VOC) concentration levels at 18:00 when people arrive home. This was due to high emissions of VOCs from building materials during the early years after construction. Therefore, to improve IAQ regarding VOC concentrations, the suggestion was to increase the ventilation rate for two hours before the home was occupied, that is, during 8:00-16:00. Compared with a constant ventilation rate of 0.375 $L·s^{-1}·m^{-2}$, this strategy caused savings in ventilation heating requirements and electricity consumption of the ventilation fan by 20 % and 30 %, respectively. In older buildings, however, VOC emissions from building materials are assumed to be of no concern due to the age of the building. Therefore, in old buildings there is no need to increase the flow rate and remove VOC concentrations before people arrive home.

Shan et al. [12] proposed and implemented a new VAV strategy with a CO_2 sensor in the main return air for detecting the number of people and flow meter in each individual zone for office buildings in Hong Kong. Their results showed acceptable IAQ and up to 50 % energy savings by using this VAV system. Nassif [26] proposed a multi-zone CO_2-based demand controlled ventilation for office buildings in which due to having better IAQ in critical zones the CO_2 was controlled in supply air instead of return air. The results indicated up to 23 % energy savings with good IAQ when using the proposed system. Pollet et al. [27] studied the performance of a multi-zone demand-controlled ventilation in residential buildings in detail for three cities of London, Brussels and Aberdeen. The comparison was made between conventional exhaust ventilation system, heat recovery system, single-, and multi-zone demand-controlled ventilation system. Their results showed that in multi-zone ventilation systems the IAQ was significantly improved compared to other systems while reducing the primary heating energy consumption and annual fan electricity consumption by 50-65 %.

The required ventilation rates depend on both the number of people and on emissions from building materials. BBR [7] recommends two levels of ventilation rates for residential buildings: one of 0.35 L·s^{-1}·m^{-2} of floor area (0.50 ach in a room of height 2.5 m) in the occupied part of the building to dilute contaminants generated by people and by building-related source pollutants; and the other of at least 0.10 L·s^{-1}·m^{-2} of floor area (0.14 ach in a room of height 2.5 m) for the unoccupied parts of the building to take care of building-related source pollutants. This shows that 0.36 ach, that is, the difference between 0.50 and 0.14 ach, is needed to remove pollutants from occupants alone. CO_2 concentrations of 700 ppm above outdoor levels have been recognised as an acceptable level for indoor CO_2 [9]. In terms of body odour perception, this level causes 20 % dissatisfaction of visitors or un-adapted persons. Referring to this acceptable CO_2 concentration, the required floor area for one person can be calculated by dividing the CO_2 generated by people by the ventilation rate. Mass balance calculation showed that the CO_2 level reaches 700 ppm above outdoor levels in a 32 m^2 room with a height of 2.5 m, ventilated by 0.36 ach, and polluted by one person generating 0.02 m^3·h^{-1} of CO_2 during rest and low activity work. Therefore, ventilation systems in Swedish buildings are designed with consideration of one person occupancy per 32 m^2. However, statistics showed that in Sweden between 2001 and 2013, on average one person occupied 47 m^2 of heated area [28, 29], see Table 1. Therefore, it is obvious that in most residential buildings, ventilation rates set based on the designated population density causes energy to be wasted on conditioning unnecessary outdoor air and also on electric energy for the ventilation fan.

The focus of this study is on the Swedish building regulations which, as shown by the statistical investigations in this study, assigned a higher ventilation rate that is actually needed in most residential buildings. We chose a case study building in order to investigate the IAQ and the potential of energy savings when the ventilation rate is adjusted based on the number of people instead of having a normal rate recommended by regulations. In the case study building, different ventilation rates of 0.10, 0.20, 0.35, and 0.70 L·s^{-1}·m^{-2} were considered. Two levels were taken from the BBR, one of 0.10 L·s^{-1}·m^{-2} for 'unoccupied', and one of 0.35 L·s^{-1}·m^{-2} for 'occupied' buildings. In each case, the indoor air quality and energy savings were studied experimentally and analytically.

1.1. Description of the Building

We chose a single-family house with 100 m^2 living area on two floors, built in the 1950s, and located in Borlänge in the central part of Sweden (see Figure 1). Two adults and one infant, representing half a person, were living in this building. Therefore, during experiments the number of occupants of this building varied between two (before the child was born) and two-and-half, considering both parents and infant. The mechanical exhaust ventilation system in the case study building could be set to different levels of flow rates. In the central exhaust ducts of ventilation system, in addition to the exhaust duct from toilet and bathroom, exhaust ducts from habitable spaces, including living room and bedrooms, were added. The purpose was to measure IAQ indicators, including CO_2 level, relative humidity (RH) and temperature, from habitable spaces.

Table 1 Heated floor area per person during 2001-2013 in Sweden [28, 29]

	-01	-02	-03	-04	-05	-06	-07	-08	-09	-10	-11	-12	-13
Heated floor area, million m^2	415	421	436	428	425	425	426	429	437	451	450	467	475
Population, million	8.9	8.9	9.0	9.0	9.0	9.1	9.2	9.3	9.3	9.4	9.5	9.6	9.6
Area per person, m^2·person^{-1}	47	47	48	48	47	47	46	46	47	48	47	49	49

Table 2 Different ventilation rates used in case studies involving a single-family building

Case	Ventilation rate	ach (L·s^{-1}·m^{-2})	Deviation from reference of NVR, %
I (VLVR)	Very low ventilation rate	0.14 (0.10)	72 % lower
II (LVR)	Low ventilation rate	0.30 (0.20)	40 % lower
III(NVR)	Normal ventilation rate	0.50 (0.35)	0 %
IV(HVR)	High ventilation rate	1.00 (0.70)	100 % higher

Figure 1. The two-storey single-family house in Borlänge selected for the study

2. Method

We used two methods in this study – an experimental approach and a mathematical model. For different ventilation rates, we measured CO_2 level, temperature and relative humidity as indicators of IAQ, and performed an experimental investigation of ventilation fan electricity consumption. In addition, we used analytical models to investigate energy savings of ventilation heating demand, and predicted percentage dissatisfied (PPD) related to CO_2 level and ventilation rate.

2.1. Measurements

We set four airflow levels for the ventilation system of the reference building, as shown in Table 2. In case I, the ventilation rate was set at 0.10 $L \cdot s^{-1} \cdot m^{-2}$ (0.14 ach), this being considered a very low ventilation rate (VLVR), corresponding to the minimum required ventilation rate in the BBR [7]. In case II, we used a ventilation rate below the recommended ventilation rate set by BBR for an 'occupied' building, that is, 0.20 $L \cdot s^{-1} \cdot m^{-2}$ (0.30 ach), this being considered a low ventilation rate (LVR). For case III, the flow rate was based on a value recommended by BBR for an 'occupied' building, that is, 0.35 $L \cdot s^{-1} \cdot m^{-2}$ (0.50 ach), this being considered a normal ventilation rate (NVR). In case IV, we used a high ventilation rate well above the recommended level, that is, 0.70 $L \cdot s^{-1} \cdot m^{-2}$ (1.00 ach), this being considered a high ventilation rate (HVR).

The indoor CO_2 level, temperature and RH are never uniform throughout a room [30]. Therefore, to detect a mean value, the sensor should be placed either in the breathing zone, or in the exhaust valve. In this study, the latter was chosen, and the sensor was placed in the exhaust removing pollutants from habitable spaces. For different flow rates, the 'Testo 480 IAQ Probe' was used to measure IAQ indicators for every ten minutes. The accuracy of this instrument for measuring CO_2 levels below 5000 ppm is ±50 ppm. Regarding the RH and

temperature, the device has the accuracy of ±2.5 % and ±0.5 °C, respectively.

In order to consider the ventilation rate through the mechanical ventilation system alone, and thus to exclude the influence of natural ventilation through opening windows and doors, all measurements were conducted during winter. In addition, to have only airflow rate through habitable spaces during measurements, the exhaust duct in the bathroom was blocked, and an exhaust fan in the kitchen was not used. Furthermore, to measure the energy consumption of the ventilation fan, we installed an electric meter on the fan. The outdoor relative humidity during winter was between 80−85 %. Also, depending on the day of experiment, the outdoor temperature varied between -2 and 6 °C.

2.2. Uncertainty Analysis

To analyse the uncertainty integrated in the measurements, the standard deviation (SD) of variables representing statistical error was considered during steady state conditions. Since the entire population were studied, population standard deviation was used; see equation (1).

$$SD = \sqrt{\frac{1}{n} \sum_{i=1}^{n}(x_i - x_m)^2} \qquad (1)$$

where n is the number of measurements during steady state conditions, x_m is the mean value of measured data, and x_i is measured data.

2.3. Analytical Model

Indoor air quality can be quantified using the Fanger model [31] regarding the olf and decipol units, which are based on odour. The olf is a quantified factor showing the strength of the source in polluting the indoor air, and the decipol gauges perceived air pollution to quantify whether the building is healthy. One olf represents the pollution from one sedentary person with metabolic equivalent of 1 met (4.184 $kJ \cdot kg^{-1} \cdot h^{-1}$) and with hygienic standard equivalent to 0.7 bath·day^{-1}. One decipol is the perceived IAQ polluted by one olf and ventilated

by 10 L·s⁻¹ of outdoor air, that is, 1 decipol is equal to 0.1 olf · (l/s)⁻¹. Using these concepts, IAQ can be analysed with respect to the predicted percentage dissatisfied (PPD), based on the ventilation rate per person and the PPD of visitors (newly-introduced people) to the level of body odours, corresponding to the CO_2 level above the outdoor level– see equations 2, 3a and 3b [32]. Using ventilation rate-based PPD, IAQ can be classified as A, B, or C, as defined by the Commission of the European Communities, in its 'Guidelines for Ventilation Requirements in Buildings' report [32]. Category A shows a PPD lower than 15 %, category B from 16 to 20 %, and category C from 21 to 30 %.

$$PPD_{CO_2} = 395 \cdot \exp(-15.15 \cdot C_{CO_2}{}^{-0.25}) \qquad (2)$$

$$PPD_{vent} = 395 \cdot \exp(-1.83 \cdot q_{vent,person}{}^{0.25})$$
for q ≥ 0.32 L·s⁻¹·person⁻¹ $\qquad$ (3a)

$$PPD_{vent} = 100 \quad \text{for q < 0.32 L·s⁻¹·person⁻¹} \qquad (3b)$$

where C_{co2} is the CO_2 concentration in the room above the outdoor concentration (ppm), and $q_{vent, person}$ is the ventilation rate per person (L·s⁻¹·person⁻¹).

The decipol value can be calculated based on the PPD related to the ventilation rate per person – see equation (4) [19]. For a healthy building, the decipol value, C_i, is less than 1, that is, a PPD less than 15 %. A decipol value of 10 represents an unhealthy building with more than 60 % PPD. Based on the decipol value, the indoor air quality can be classified into three categories: A for a decipol value less than 1, B for a decipol value greater than 1.1 but less than 1.4, and C for a decipol value greater than 1.5 but less than 2.5 – see Table 3.

$$C_i = 112 \; \left[\ln(PPD_{vent}) - 5.98\right]^{-4} \qquad (4)$$

In addition, we calculated the specific ventilation heat loss using equation (5):

$$Q_{ventloss} = q \cdot \rho \cdot c_p \qquad (5)$$

where q is the ventilation rate (m³·s⁻¹), ρ is the air density (kg·m⁻³), and c_p is the specific heat capacity (J·kg⁻¹· K⁻¹).

The degree-hours method was used to estimate the ventilation heat demand over the year – see equation (6). This is a simplified method for calculating the building heating demand for active heating (E_{vent}). The degree hours depend on the building's location and the limit temperature, which is determined by the chosen comfort temperature and the indirect/passive heat supply. The heating contribution from the limit temperature to comfort temperature is given by indirect/passive heating. In Borlänge, the degree hours (D_h) per year is 115,080 °C·h·year⁻¹ for an assumed limit temperature of 17 °C and a mean outdoor temperature of 4.2 °C [33].

$$E_{vent} = Q_{ventloss} \cdot D_h \qquad (6)$$

3. Results and Discussion

Indoor air quality parameters including CO_2 concentration, temperature, and RH were measured for three to four days in each scenario with different ventilation rates. In this section, only the results of 24 hours starting from 18:00 on the second day of experiments are shown. In the following subsections, the results and discussion of energy savings and IAQ are presented for each case separately.

3.1. Case I: a Very Low Ventilation Rate (VLVR)

A very low ventilation rate scenario was set during 4th, 5th, and 6th February 2013 with average daily temperatures of -5, -4 and -2 °C, respectively. Figure 2 (left) shows CO_2 concentrations, relative humidity and indoor temperature with a ventilation rate of 0.1 L·s⁻¹·m⁻², on a working day when no one was at home during typical working hours. It can be seen that, when the occupants, that is, two adults, arrived home at around 20:00, the CO_2 level increased to over 1300 ppm, a level that was maintained throughout the night. Using equation (3a), the ventilation rate-based PPD with 0.14 ach was approximately 34 % which was not even within indoor air quality category C, for which the maximum PPD is 30 %. By this very low ventilation rate, however, other indicators of indoor air quality were within the acceptable ranges, that is, relative humidity was between 31-40 % and average indoor temperature was 19.3 °C, see Figure 2 (left). Figure 2 (right) shows the PPD related to the ventilation rate and the CO_2 concentration above the outdoor level based on equations (2) and (3a). As Figure 2 (right) shows, with this very low ventilation rate there was a maximum 26 % dissatisfaction for newly-introduced people in terms of body odour perception. Using equation (4), the perceived indoor air quality corresponds to 3.1 decipols – see Figure 2 (right). This value is greater than 1, showing that the building is not healthy and not even in category C. Therefore, this very low ventilation rate is not sufficient and caused rather poor IAQ with respect to the CO_2 level.

3.2. Case II: a Low Ventilation Rate (LVR)

During 11th-14th February 2014 with mean daily temperature of 2 °C for all four days, the ventilation rate was set to 0.3 ach in the case study building. Increasing the ventilation rate to 0.2 L·s⁻¹·m⁻² caused lower CO_2 concentrations compared with case (I) – see Figure 3 (left). As can be seen from Figure 3 (left), for this level of ventilation the CO_2 level never exceeded 950 ppm when two adults and one infant living in this 100 m² house. This level was lower than the commonly referenced value of 1000 ppm. In addition, as can be seen in Figure 3 (left) the indoor temperature and RH were within the acceptable ranges of 20.2 °C and 39-42 %, respectively. Ventilating with 0.2 L·s⁻¹·m⁻² (0.3 ach), the PPD related to this ventilation rate and the perceived indoor air quality were around 18 % and 1.2 decipols, respectively, which are defined under IAQ category B – see Figure 3 (right). In addition, as can be seen in Figure 3 (right), this ventilation level caused a maximum of around 18 % feeling of dissatisfaction for a newly-introduced person entering the house. Thus, this low ventilation rate is sufficient for the studied building and created acceptable IAQ. However, it should be noted that this level is appropriate when having two adults and one infant in the house, and it should be increased when more people are home.

3.3. Case III: a Normal Ventilation Rate (NVR)

In the case study building, the normal ventilation rate of 0.5 ach was set during 4th-7th February 2014. This level of 0.35 L·s⁻¹·m⁻², as the value recommended by BBR for an 'occupied' building, caused a maximum level of 725 ppm of CO_2, that is, much lower than the threshold level of 1000 ppm. Figure 4 (left) shows the results of CO_2 concentration, RH and temperature for 5th and 6th February 2014 with average daily temperatures of 0 and 2 °C, respectively. As Figure 4 (left) shows, RH and indoor temperature were acceptable; that is, between 34-43 % and 20.3 °C, respectively. This ventilation strategy conformed to IAQ category A, with a PPD related to ventilation rate of 11 % and a perceived IAQ of 0.7 decipols – see Figure 4 (right). Therefore, this normal ventilation rate is too high for the studied building, and there is no need to increase the ventilation rate to the level recommended by BBR.

3.4. Case IV: a High Ventilation Rate (HVR)

This high ventilation rate was set during 7th-10th January 2015 in the case study building. This high ventilation rate of 1.0 ach, that is, 0.70 L·s⁻¹·m⁻², caused an average CO_2 level of 470 ppm during occupancy, which was close to the outdoor CO_2 level of 400 ppm. This level was much lower than the threshold level of 1000 ppm. Figure 5 (left) shows CO_2 concentration, RH and temperature for 8th and 9th January 2015 with average daily temperatures of 6 °C and 1 °C, respectively. With this high ventilation rate, the mean indoor temperature was 21.3 °C, and relative humidity ranged between 30-35 %. As can be seen in Figure 5 (right), the PPD related to ventilation rate was 6 %, and the perceived indoor air quality was 0.36 decipols, corresponding to indoor air quality category A.

3.5. Uncertainty Analysis of Measurements

Calculations of uncertainty analysis were done for measurement during steady state conditions which were reached during night after occupants fell asleep; that is, constant metabolic rate with constant activity level, and constant moisture production excluding showering or cooking. Therefore, the measured data during 24:00 - 6:00 were used for analysis; see Table 4. As Table 4 shows, all standard deviations were within 1-3 % of the average value for all parameters studied.

3.6. Occupants' Reaction on Different Ventilation Rates

After measurements, occupants were asked about their opinions on different flow rates. With case I and case II, occupants did not notice any changes regarding indoor air quality and thermal comfort. However, with case III and specially with case IV, occupants felt draft close to the building envelope. In addition, occupants detected noise problem with higher ventilation rate created by the ventilation fan, which they could hear it through the ducts in the bedroom. With high ventilation rate in case IV, however, occupants were very satisfied that smell from cooking was vanished immediately.

3.7. Energy Performance

Figure 6 shows the ventilation heating demand and the electric consumption by ventilation fan for all cases studied. Considering case III as a reference case due to the level recommended by BBR, energy savings for the other cases were calculated using equations 5 and 6. As can be seen from Figure 6, the energy savings with the VLVR is 71 % compared with the NVR. As shown in section 3.1., however, occupants were

Table 3 Indoor air quality categories based on PPD related to ventilation rate and perceived indoor air quality

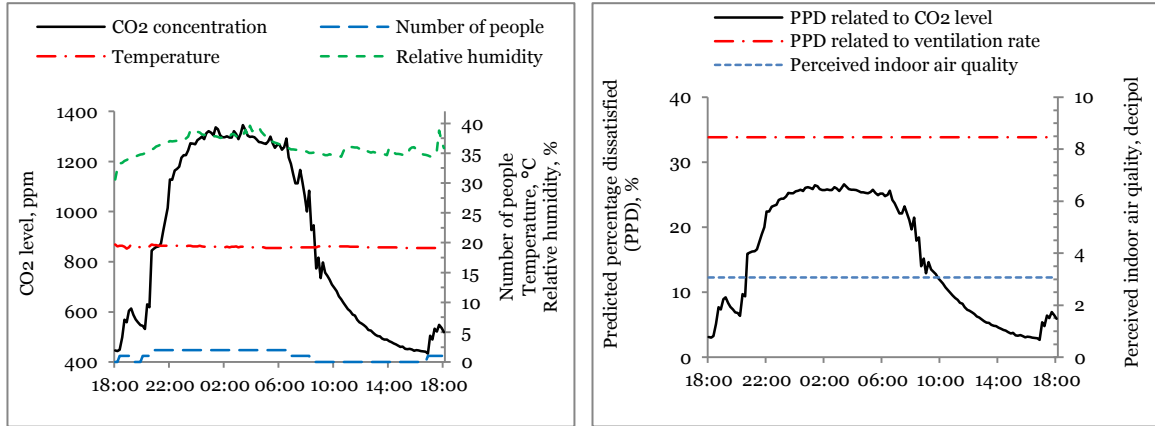| IAQ category	Ventilation rate-based PPD	Perceived indoor air quality
A	Less than 15 %	Less than 1
B	Between 16 and 20 %	Between 1.1 and 1.4
C	Between 21 and 30 %	Between 1.5 and 2.5

Figure 2. CO_2 levels, temperature and relative humidity during a working day with a very low ventilation rate of 0.14 ach (on the left), and PPD related to CO_2 level and ventilation rate and perceived indoor air quality for a very low ventilation rate (on the right)
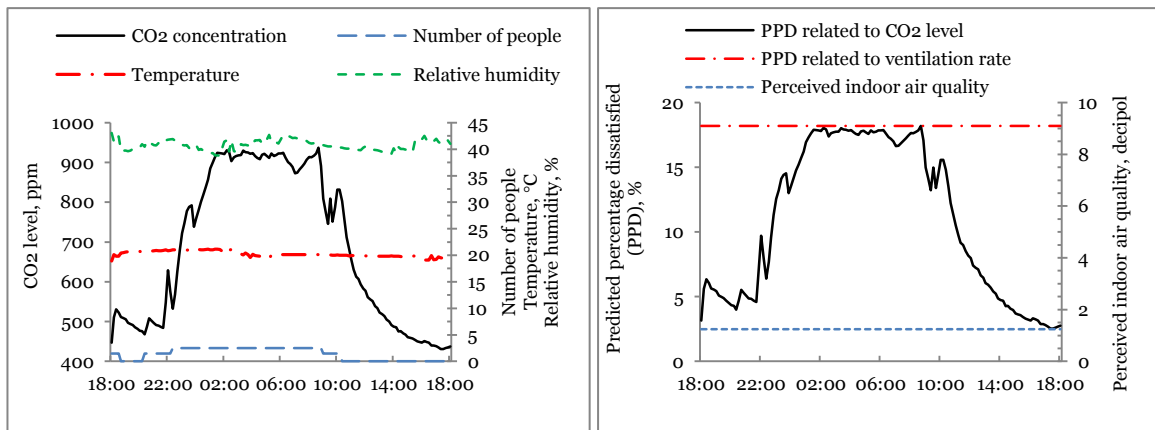
Figure 3 CO_2 levels, temperature and relative humidity during a working day with a low ventilation rate of 0.3 ach (on the left), and PPD related to CO_2 level and ventilation rate and perceived indoor air quality for a low ventilation rate (on the right)
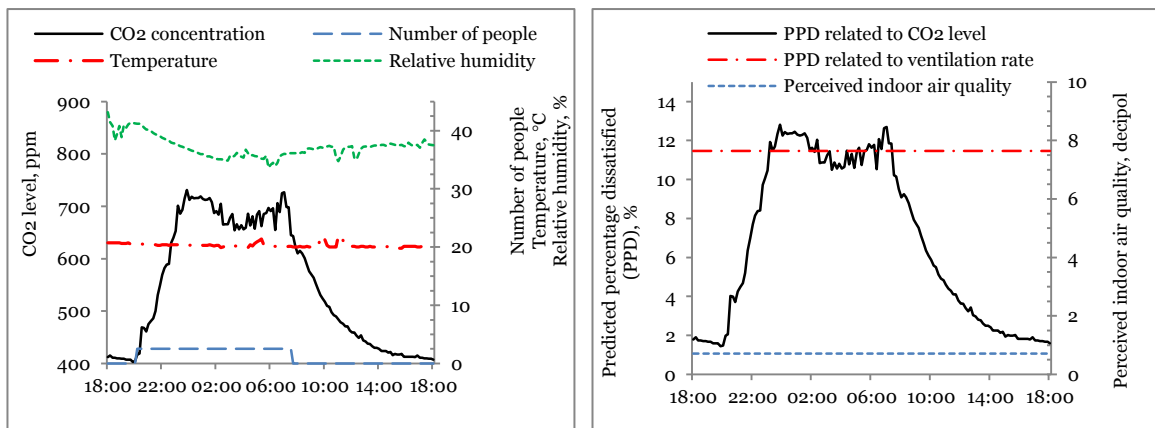

Figure 4 CO_2 levels, relative humidity and temperature during a working day with a normal ventilation rate of 0.5 ach (on the left), and PPD related to CO_2 level and ventilation rate and perceived indoor air quality for a normal ventilation rate (on the right)
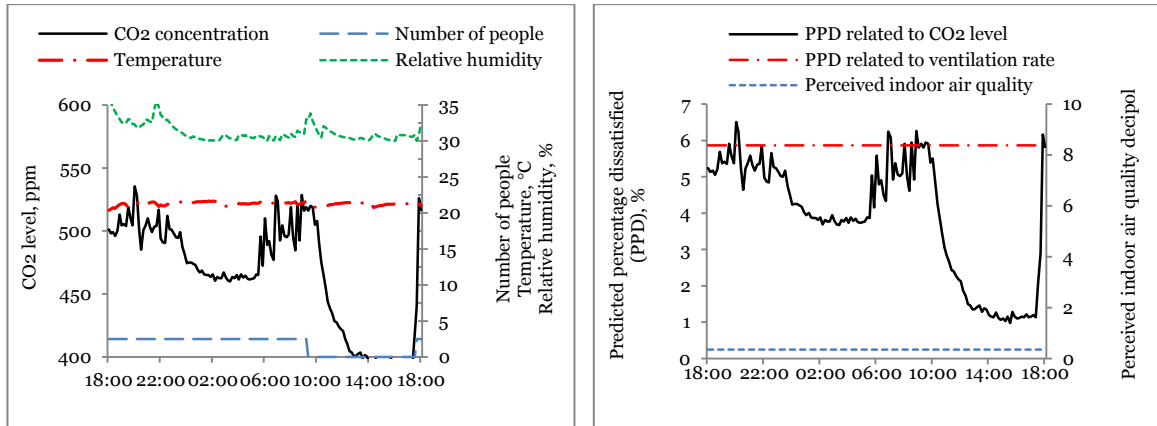
Figure 5. CO_2 levels, temperature and relative humidity during a working day with a constant high ventilation rate of 1 ach (on the left), and PPD related to CO_2 level and ventilation rate and perceived indoor air quality for high ventilation rate (on the right)

Table 4 Standard deviation of measured parameters

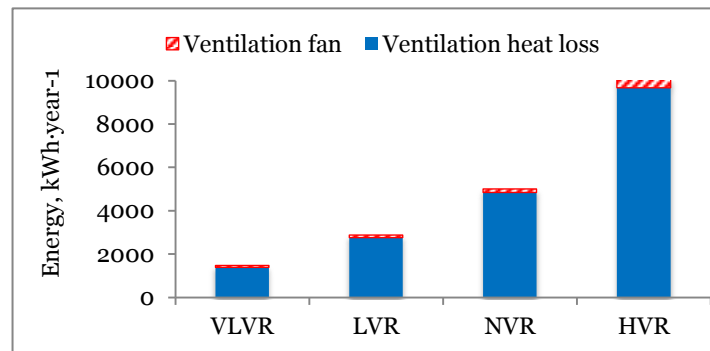| Standard deviation	Air temperature	Relative humidity	CO_2 level
Very low ventilation rate (VLVR)	1 % (0.1 °C)	2 % (0.7 %)	2 % (20 ppm)
Low ventilation rate (LVR)	3 % (0.5 °C)	3 % (1.0 %)	3 % (30 ppm)
Normal ventilation rate (NVR)	2 % (0.3 °C)	2 % (0.6 %)	3 % (22 ppm)
High ventilation rate (HVR)	1 % (0.2 °C)	1 % (0.3 %)	2 % (10 ppm)

Figure 6. Energy consumption for ventilation heat loss and ventilation fan electricity consumption for all cases

Table 5 CO_2 levels, PPD related to IAQ and energy consumption for different ventilation rates

Case	Air flow rate, L·s⁻¹·m⁻² (ach)	Max. CO_2, ppm	Ave. CO_2 during occupancy, ppm	Max. PPD-CO_2, %	PPD-vent, %	Perceived IAQ, decipols	Category	Energy for ventilation heating (fan), kWh·year⁻¹
I, VLVR	0.10 (0.14)	1337	1231	26	34	3.07	-	1381 (88)
II, LVR	0.20 (0.30)	923	869	18	18	1.24	B	2762 (114)
III, NVR	0.35 (0.50)	725	648	13	11	0.71	A	4833 (175)
IV, HVR	0.70 (1.00)	586	490	8	6	0.36	A	9667 (438)

exposed to unacceptable indoor air quality in this case. For case II with a LVR, energy savings for ventilation heating and ventilation fan were 43 % compared with the NVR. The HVR needed almost twice as much energy as the NVR case. The specific fan power was 0.14 W/(m³·h⁻¹) at a pressure of 100 Pa, and with an airflow of 250 m³·h⁻¹ for the fan used in the reference building. Due to this very low specific fan power, there was not a great deal of saving in terms of ventilation fan power when the flow rate was lowered. CO_2 concentrations, PPD related to IAQ and energy consumption for all cases are shown in Table 5.

4. Conclusion

The main aim of this study was to show the overestimation of ventilation rate in Swedish building standards, BBR, in which the ventilation system is designed considering one person living per 32 m², despite of the fact given by statistical data that one person is living per 47 m². Therefore, it was suggested to have flexibility in ventilation levels based on the number of people per heated floor area. In order to indicate the fact that the normal ventilation level is high, we chose a single-family house occupied by two adults and one infant, located

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in the central part of Sweden. In this case study building, the influence of the ventilation reduction on indoor air quality and the potential of energy savings were studied. To find a suitable ventilation level, four cases were considered, with very low (0.14 ach), low (0.30 ach), normal (0.50 ach) and high (1.00 ach) ventilation rates. In order to evaluate each case, we took into account: indoor air quality regarding CO_2 concentration levels, relative humidity, temperature, predicted percentage dissatisfied (PPD), and energy savings of ventilation heat demand and ventilation fan electric energy consumption. Results showed that a ventilation rate of 0.14 ach caused the lowest energy consumption; however, with poor indoor air quality due to a CO_2 concentration of over 1300 ppm during occupancy. This very low ventilation rate caused a PPD of 34 %. Ventilating the building with 0.30 ach caused a maximum CO_2 concentration of 923 ppm, which was lower than the commonly-referenced threshold level of 1000 ppm. This low ventilation level caused a ventilation rate-based PPD of 18 %, conforming to the indoor air quality category B. Following the BBR recommended normal ventilation rate of 0.50 ach, the CO_2 level was around 700 ppm. This strategy caused a ventilation rate-based PPD of 11 %. Increasing the ventilation rate to 1.00 ach showed an average CO_2 level of 470 ppm during occupancy, which was not much higher than the outdoor CO_2 concentration. This level caused a 6 % ventilation rate-based PPD. In all cases, relative humidity and temperature were within the acceptable ranges. Our results indicated that, for the studied building with two adults and one infant, a ventilation rate of 0.30 ach was sufficient during occupancy. This low level gave energy savings of 43 % compared with 0.50 ach, while providing an acceptable IAQ. This shows the potential to save energy without harming the IAQ can be achieved by lowering the ventilation rate in a residential building based on the number of people living in the house instead of using the normal ventilation rate of 0.50 ach recommended by BBR. In case of changing family composition, the ventilation rate should be changed accordingly. The results presented in this study are only an indication of the energy savings potential if the ventilation rate is adjusted to the number of people instead of using a normal rate recommended by regulations. When more occupants are in the house, however, the upper level can be increased to more than 0.30 ach. This could be achieved by using a switch button to increase the ventilation rate to 0.50 or even 1.00 ach.

Acknowledgements

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