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Airtightness and Ventilation of a Naturally Ventilated House in Finland

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SYNOPSIS

This paper illustrates the airtightness and ventilation performance of a recently built ecological house in Helsinki, Finland. The wood frame house, which is built with no plastic vapour retarder, has a satisfactory air tightness (3 ach at 50 Pa). The ventilation measurements show that the outdoor ventilation rate provided by the natural ventilation system tended to be lacking (i.e., less than the required value of 0.5 ach) even though the measured CO_2 concentrations were generally satisfactory (i.e., below 1000 ppm) when the bedroom doors were open. Extrapolating the measured ventilation data shows that the ventilation rate is expected to be about 0.45 ach (10% below the required value) in the winter and about 0.25 ach (50% of required value) in the summer when the windows are closed. When the windows are open in the summer, the outdoor ventilation rate will be higher.

1.0 INTRODUCTION

It is necessary to ventilate buildings with outdoor air because occupants, buildings and the surrounding environment produce volatile organic compounds, radon, dust, bacteria, mould, odours, carbon dioxide (CO_2), and other gases, which affect indoor air quality (IAQ) and health (Sundell, 1996). The purpose of outdoor ventilation is to dilute the concentration of indoor contaminants and since occupants represent a key source of contaminants, the concentration of CO_2 is often used to estimate IAQ (Schell and Int-Hout, 2001, ANSI/ASHRAE Standard 62-1999 and National Building Code of Finland – D2, 1987). For example, the National Building Code of Finland – D2 (1987) states that 4 L/s of outdoor air per occupant must be supplied to non-smoking spaces, the air change rate of rooms of normal height shall not be less than 0.5 ach and the metabolical concentration of CO_2 must not exceed 1500 ppm. Typically outdoor ventilation rates are set with the assumption that the building envelope and furniture are sources of contaminants. However, for carefully selected components, it is possible that the building envelope and furniture can act as contaminant sinks and actually improve the IAQ. If a building envelope is made from porous materials, the diffusion of pollutant gases through the envelope can reduce the indoor concentration of pollutants. For the house investigated in this paper, the diffusion of CO_2 and SF_6 through the envelope increase the effective ventilation rate by about 10% and 5% respectively when the ventilation rate is 0.5 ach (Simonson, 2000 and Simonson and Salonvaara, 2000). In addition, the permeable and hygroscopic envelope can reduce the peak indoor humidity by 20% RH at 0.5 ach (Simonson et al., 2001a). Since the perception of air quality is closely linked to humidity (Fang et al. 1998), moisture transfer between indoor air and building structures, could possibly reduce the needed ventilation rate. Reducing the ventilation rate would have a significant impact on energy consumption because the energy required to condition ventilation air typically constitutes 20 to 50% of the thermal load (Orme, 2001 and ASHRAE, 1997).

In most cases, adequate ventilation can provide good IAQ, but the indoor temperature and relative humidity have an important effect on comfort and IAQ as well (Simonson et al., 2001b and 2001c). Indoor temperatures are often specified assuming that the building is equipped with a mechanical HVAC system, but recent research has shown that occupants in naturally ventilated buildings adapt to their environment and can accept (and, in fact, prefer) a larger range of indoor temperature (Brager and de Dear, 2000). During cold weather, occupants of naturally ventilated buildings accept cooler indoor temperatures and during hot weather, they accept warmer indoor temperatures. This finding is based on the analysis of 21 000 sets of data from 160 different office buildings on four continents. Therefore, there is strong evidence that naturally ventilated buildings can provide acceptable IAQ and comfort, while greatly reducing energy consumption. The energy required to provide outdoor ventilation air can be further reduced by applying energy recovery devices and natural ventilation systems or hybrid systems (IEA ECBCS Annex 35).

2.0 TEST HOUSE CONSTRUCTION

The house monitored in this study is 2-storey (plus basement) single-family house located in the Tapanila district of Helsinki, Finland (Figure 1). The floor area and volume of the living space is 178 m^2 and 470 m^3, including the basement. All results in this paper will be based on the internal volume of 470 m^3. The wood frame envelope is insulated with 250 mm of wood fibre insulation in the walls and 425 mm in the roof. The house has no plastic vapour retarder to permit diffusion mass transfer between indoor air and the porous building envelope. A natural ventilation system provides outdoor ventilation, and district heating and a wood-burning fireplace provide space heating. The thick insulation is intended to keep energy consumption low, whereas the porous envelope and natural ventilation systems are examples of passive methods of controlling the indoor climate and IAQ. This paper presents the airtightness of the building envelope and the performance of the natural ventilation system, while the energy performance is presented by Simonson (2001) and the performance of the other passive systems is presented by Simonson (2000).

Figure 1. Pictures of the south facade and dining area of the test house (Riikka Kostiainen). The triple pane windows are concentrated on the south facade to take advantage of solar heat gains in the winter and to provide natural lighting to the house

3.0 BUILDING AIRTIGHTNESS

A building with poor airtightness may have uncontrolled airflow through the building envelope, which can lead to problems related to: moisture, thermal comfort, energy consumption, ventilation performance and noise. To minimise air leakage and moisture transfer, wooden buildings in cold climates often use polyethylene on the warm side of the insulation. Because of its dual function (i.e., moisture and air barrier), polyethylene is often specified and the safety of envelopes with air and vapour barriers other than polyethylene is often questioned. The good moisture performance of the house presented in this paper is demonstrated by Simonson (2000) and Simonson and Ojanen (2000) and the air tightness of the envelope is presented in this section.

The airtightness of the whole house and one bedroom (2*nd* floor west bedroom in Figure 2) were measured with a lower pressure indoors than outdoors, resulting in infiltration airflow (Charlesworth, 1988). A variable-speed fan was ducted through a 5 mm thick, high-density wood fibre board that was sealed in a basement window during the tightness measurement of the whole house and in the door connecting the bedroom and the house during the tightness measurement of the bedroom. A calibrated orifice plate was used to measure the flow rate of air exhausted from the house and bedroom. In all tests, the natural ventilation supply vents were removed and sealed with tape. During the test of the whole house, the chimney and exhaust vents were sealed with polyethylene plastic and tape on the roof. All windows and external doors were closed during the pressure tests, but typically were not sealed with tape. Measurements were also performed in the bedroom with the balcony door and windows sealed to determine their leakage characteristics. During the pressure test it was noticed that the main leakage paths were the front door of the house and the balcony door in the bedroom.

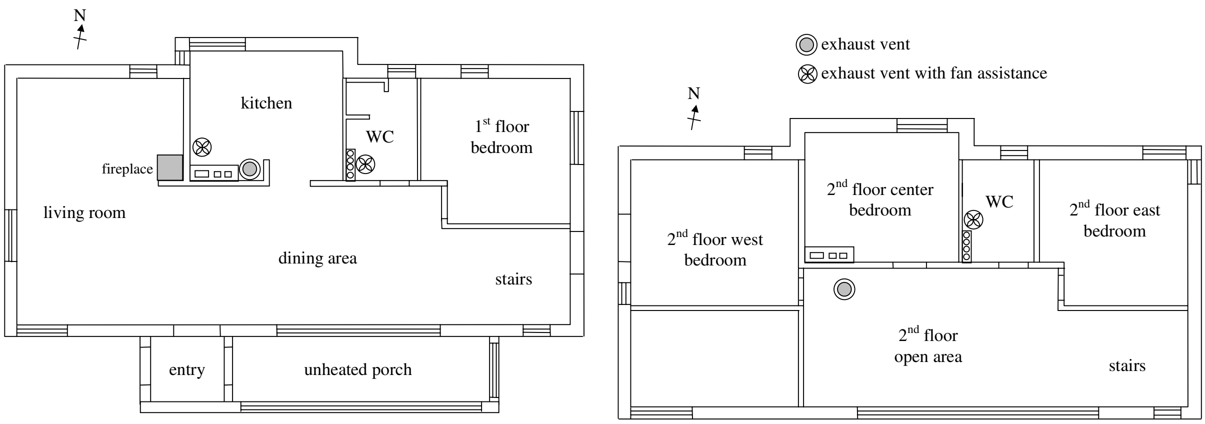


Figure 2. The first (left) and second (right) storey floor plans have been designed with an open layout to improve the distribution of ventilation air and natural lighting.

During the tightness measurement of the whole house, the pressure difference across the building envelope was measured on both the first and second floors. The measured pressure differences on the first floor were only slightly higher (usually less than 3 Pa) than the pressure differences on the second floor, indicating good mixing. During the measurement in the bedroom, the main door of the house was kept open to minimise pressurisation of the house. The pressure difference between the house and outdoors was typically less than 1 Pa. The results of the airtightness test are summarised in Figure 3 and show that the house is moderately airtight and that the bedroom has less air leakage than the whole house, especially when the balcony door is sealed with tape. At an underpressure of 50 Pa, the air infiltration through the building envelope is estimated to be 3.1 ach, while the air infiltration into the bedroom is 2.2 ach and 1.5 ach when the balcony door and windows are unsealed and sealed respectively. This tightness is in the lower range of normal houses in Finland according to the classification of Laine and Saari (1998), which is: good (1-2 ach), normal (3-4 ach) and leaky (>5 ach). The airtightness is also in the range of 1 to 3 x 10^{-5} $m^3/(s \cdot m^2 \cdot Pa)$ (0.5 to 1.5 $L/(s \cdot m^2)$ at 50 Pa) as recommended by Uvslokk (1996) and Ojanen (1993).

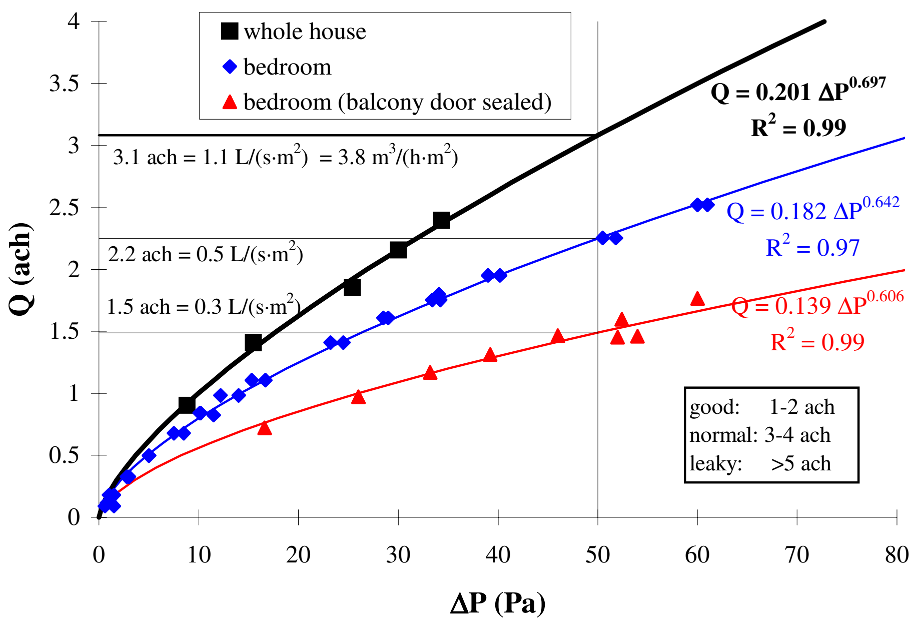


Figure 3. *Airtightness of the test house and the 2nd floor west bedroom.*

4.0 PERFORMANCE OF THE NATURAL VENTILATION SYSTEM

As shown in Figure 2, the house has been designed with an open layout to improve the distribution of ventilation air. Outdoor air enters the house through vents located in the upper window frame and in the exterior wall above the hot water radiators as shown in Figure 4.

Figure 4. The house contains 13 supply air vents located in the upper window frame and 7 in the exterior wall above the hot water radiators. The occupants can control both types of supply vents. The supply vents above the radiators are seldom open, especially in the winter.

The natural ventilation exhaust vents (Figure 5) are located in the open areas of the house (Figure 2) and therefore the position of bedroom doors has a large impact on the ventilation rate of the bedrooms. The performance of the natural ventilation system was assessed by measuring the concentration of CO_2 in the house for several months, measuring the exhaust airflow rate through the natural ventilation during different weather conditions and predicting the ventilation rate throughout the year.

Figure 5. Measuring the airflow rate through one of the exhaust vents. In total there are 8 exhaust vents, of which 4 are fan assisted (bathrooms, sauna and range hood). Each exhaust vent is ducted separately to the roof to reduce cross contamination.

4.1 Concentration of CO_2

CO_2 is a dangerous contaminant only at concentrations of 30000 ppm to 50000 ppm, but is often used as a surrogate for other occupant-generated contaminants (Janssen, 1994 and ANSI/ASHRAE Standard 62-1999). People at an activity level of 1.2 met produce 5 ml/s, which means that the steady-state indoor concentration of CO_2 can be calculated as follows,

$$C = \frac{QC_{out} + 5000}{Q} \qquad (1)$$

where Q is the ventilation rate is L/s and C_{out} is the outdoor concentration of CO_2 in ppm. At a ventilation rate of 7.5 L/s per person and an outdoor CO_2 concentration of 300 ppm, the indoor CO_2 concentration will be 1000 ppm. Therefore, indoor CO_2 concentrations below 1000 ppm are recommended and often indicate that the ventilation rate is satisfactory. Since the outdoor concentrations were measured to be nearly 400 ppm, a steady-state indoor concentration of CO_2 of 1650 ppm will indicate an outdoor ventilation rate of 4 L/s per person as required in the National Building Code of Finland – D2 (1987). If the average indoor concentration of CO_2 throughout the entire house is less than 800 ppm, then the air change rate for the house will satisfy the requirement in the National Building Code of Finland – D2 (1987) (i.e., 0.5 ach). Based on this, the CO_2 concentrations in Figure 6, which were measured with a sensor based on infrared adsorption having an accuracy of ±5%, indicate that the ventilation rate is seldom below 4 L/s per person in the bedrooms and generally above 0.5 ach outside the bedrooms. This means that the general ventilation rate is adequate and that the IAQ is good, as the owners of the house have personally noticed.

The peak concentrations of CO_2 in the bedrooms are between 1400 and 1800 ppm when the bedroom doors are closed and between 800 and 1000 ppm when the bedroom doors are open. The CO_2 concentration outside the bedrooms is usually less than 800 ppm. The measured concentrations of CO_2 in the summer and winter are nearly the same, while the air flow rate through the ventilation ducts is clearly lower in the summer than in the winter (Figure 7 and Figure 9). This shows that the occupants open the windows to enhance the ventilation rate during warm weather.

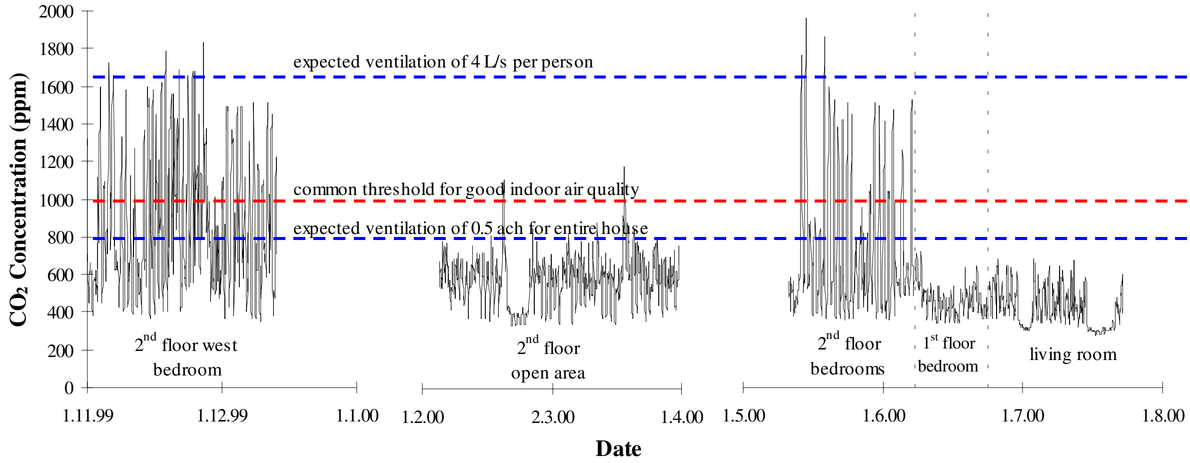


Figure 6. Measured concentration of CO_2 in different rooms during normal occupation. The concentrations indicate that the ventilation rate is often above 4 L/s per person in the bedrooms and 0.5 ach in the rest of the house. A common threshold for CO_2 is 1000 ppm.

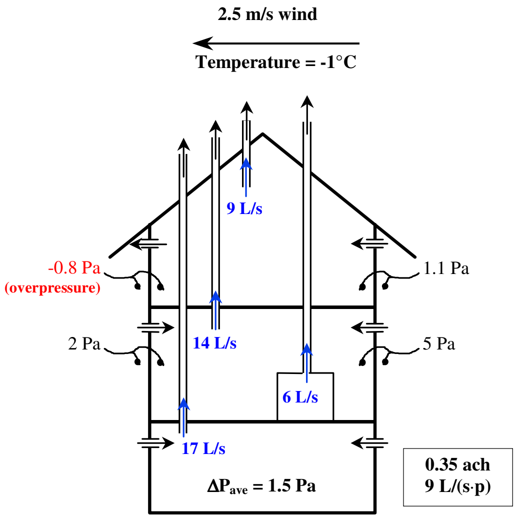
4.2 Exhaust air flow rates

The purpose of these measurements is to determine the airflow rate through the natural ventilation system under controlled conditions using a flow nozzle and an anemometer as shown in Figure 5. The flow nozzle was an AM300 flow nozzle and the flow anemometers were GGA-65P and GGA-26 from ALNOR. The flow rate is calculated by multiplying the measured velocity with a constant, according to:

$$Q = k\ v = 5.8\ v \tag{2}$$

where Q is the flow rate is L/s, k is the constant (L/m) and v is the measured air speed (m/s). The uncertainty in measured flow rate is expected to be ±10%. The flow rate through each exhaust vent was measured separately, except for one of the exhaust vents in the basement that was partially covered by a bookshelf. Since the bookshelf covered only part of the exhaust vent, it was assumed that the flow rate through this vent was equal to the flow rate through the other exhaust vent in the basement, which was less than 2 m away and in the same large room. The exhaust flow rate through the chimneys (fireplace and sauna) was estimated with a velocity traverse of the chimneys near the roof. The fireplace and sauna dampers were closed during this measurement and therefore the flow rate was quite small and the associated uncertainty is therefore quite high (~±25%). During the measurements, all external windows and doors were closed, all bedroom doors were open and all bathroom doors were closed. Before and after the measurement of the exhaust flow rates, which took about 2 hours, the pressure difference between indoors and outdoors was measured in several locations on both the first and second floors. In addition, the outdoor temperature and the wind speed and direction were measured. The wind speed was measured on the roof of the house.

The measured pressure differences between indoor and outdoor air on the windward and leeward sides of the house and the measured exhaust flow rates during the March 10 test are presented in Figure 7 (left). Figure 7 (right) presents the outdoor ventilation rate for other measurement times. The data covers a range of temperatures from –1°C to 27°C and wind speeds from 1.3 m/s to 2.9 m/s and the ventilation rate varies between 0.35 ach and 0.14 ach (10 L/(s·person) to 4 L/(s·person) for the 5 occupants). All the measured ventilation rates in Figure 7 are below the required air change rate of 0.5 ach in the national building code of Finland – D2 (1987), even though the ventilation rate per person is satisfactory (i.e., 4 L/(s·person)). The measured ventilation rates are also below the rate specified in ASHRAE Standard 62.2P (Sherman, 1999), which is 0.4 ach for a house of this size. The distribution of outdoor ventilation air is also important and Figure 7 shows that the second floor has a lower exhaust ventilation rate than the basement and first floor. This may be a problem because there are three bedrooms upstairs. When the bedroom doors are open, however, the CO_2 concentrations (Figure 6) indicate that there is adequate mixing in the house.



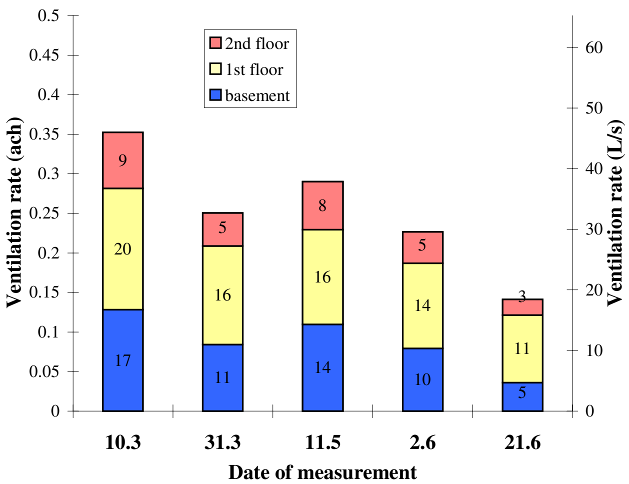


Figure 7. Flow and pressure distribution on March 10, 2000 (left) and measured ventilation rates for each test showing the distribution between the three storeys (right). All windows are closed during the measurements

4.3 Extrapolation

In order to predict the ventilation rate in conditions other than the 5 measurements, a simple model is developed in this section. The model is based on the basic equations for pressure differences due to wind and stack effects (Orme, 1999, Walker and Wilson, 1998, ASHRAE, 1997 and Walton, 1989) and are as follows,

$$\Delta P_{wind} = Cp\frac{\rho v^2}{2} = C_{wind}\, v^2 \text{ and} \tag{3}$$

$$\Delta P_{stack} = \frac{P}{R}\left(\frac{1}{T_{out}} - \frac{1}{T_{in}}\right)gh = C_{stack}\left(\frac{1}{T_{out}} - \frac{1}{T_{in}}\right) \tag{4}$$

where Cp is the wind pressure coefficient, ρ is the density of air (kg/m³), v is the wind speed (m/s), P is the absolute air pressure (Pa), R is the specific gas constant of air (J/(kg·K)), T is the absolute temperature (K), g is the acceleration due to gravity (m/s^2), h is the height between the inlet and outlet (m) and subscript out and in refer to the outdoor and indoor temperatures respectively. The total pressure differences between indoors and outdoors is calculated by simple addition superposition of the wind pressure and the stack pressure (Walker and Wilson, 1993) rather than including the interaction of pressure effects given in Walker and Wilson (1998), which was found necessary for a wider range of leakage distributions. The total pressure difference is therefore,

$$\Delta P = \Delta P_{wind} + \Delta P_{stack} \tag{5}$$

and the ventilation flow rate uses the standard exponential relation,

$$Q = C\Delta P^n \tag{6}$$

where C and n are constants.

Equations (3) to (6) describe the model used to calculate the outdoor ventilation rate from the temperature difference and wind speed. The unknown constants in the equations, that must be determined from the measured data, are C_{wind}, C_{stack}, C and n. By fitting the measured data, the ventilation flow rate can be calculated as,

$$Q = 0.125\left(0.07\,v^2 + 3650\left(\frac{1}{T_{out}} - \frac{1}{T_{in}}\right)\right)^{0.602} . \tag{7}$$

Using equation (7), the ventilation rate at various wind speeds and outdoor temperatures can be predicted for the house by assuming a constant indoor temperature of 22°C (Figure 8). The measured ventilation rates and associated wind speeds are also included in Figure 8 and show that the model fits the experimental data quite well. The main discrepancy is that the model predicts a lower flow rate than that measured when the outdoor temperature is 27°C. This difference can be partly explained by the fact that the uncertainty in the measured ventilation rate is highest for the 27°C test because the ventilation through the chimneys was nearly half of the total ventilation. (As discussed in section 4.2, the uncertainty of the flow rate through the chimney is much higher than the uncertainty of the ventilation rate through the natural ventilation ducts.)

Figure 8 also includes the ratio Q/Q_{code} where Q_{code} is the ventilation rate specified in the National Building Code of Finland – D2 (1987) (i.e., 0.5 ach). The ratio Q/Q_{code} is often less than 1, which shows that it is quite difficult to meet the building code requirement when the windows are closed, unless the wind velocity is high and the outdoor temperature is low. At a wind speed of 4 m/s, a ventilation rate of 0.5 ach will be realised when the outdoor temperature is below -10°C. For wind speeds less than 3 m/s, the outdoor temperature must be below -15°C before the ventilation rate is expected to reach 0.5 ach. The results in Figure 8 show that additional ventilation is likely always needed to satisfy the building code when the outdoor temperature is above 0°C. Opening windows or operating the bathroom and sauna exhaust fans could provide this ventilation.

To estimate the performance of the natural ventilation system during the year, equation (7) is applied using the hourly weather data for Helsinki (1979) and an indoor temperature of 22°C

(Figure 9). The average wind speed measured at the weather station was 4 m/s for the whole year, which is slightly higher than the measured wind speeds at the test house. Therefore, the measured wind speeds were reduced by 25% to account for the local wind shielding. Figure 9 includes the predicted daily, monthly and yearly average ventilation rate.

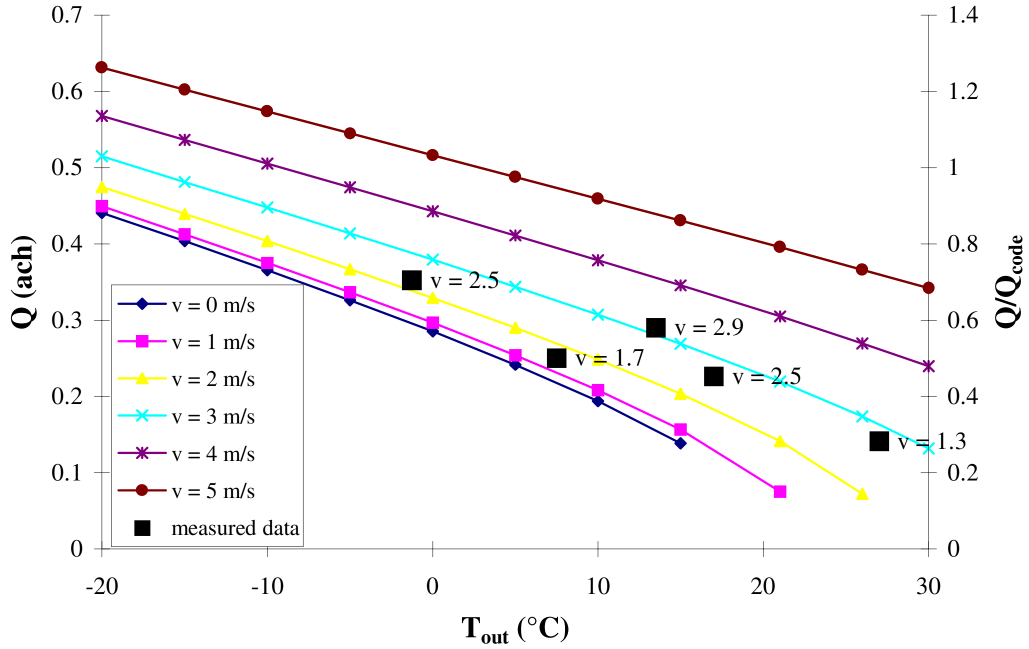


Figure 8. Expected ventilation rate and ratio to the code requirement (i.e., 0.5 ach) at various outdoor temperatures and wind speeds compared to the measured data.

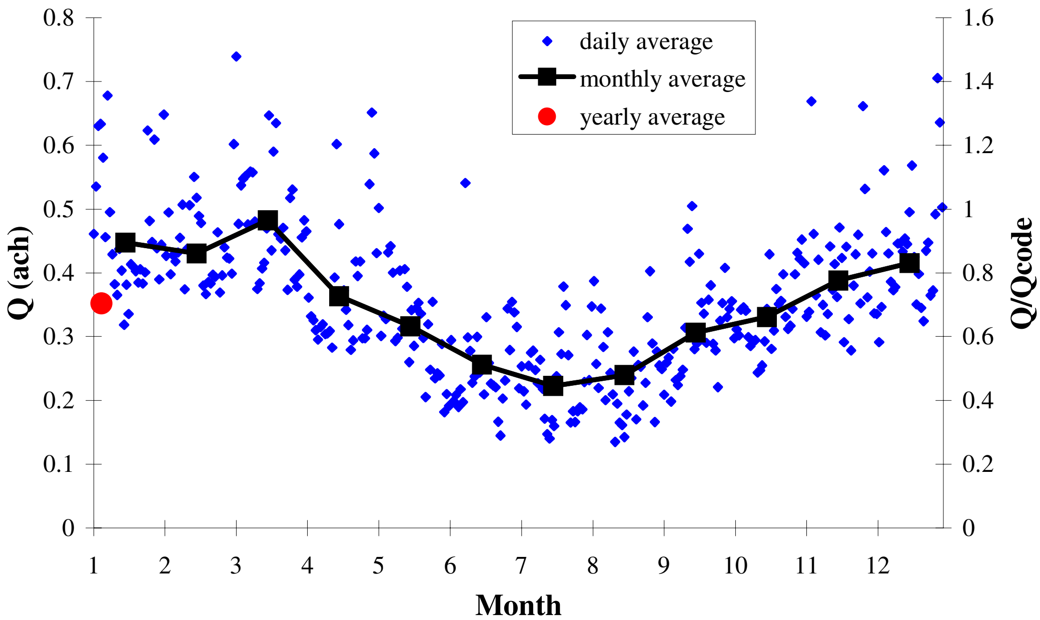


Figure 9. Expected ventilation rate and fraction of the building code ventilation rate (Q/Q_{code}) for the test house using the Helsinki (1979) weather data, reducing the wind speed by 25% to account for local wind shielding and assuming all windows are closed.

Figure 9 shows that in the winter (November to March) the daily average ventilation rate varies between 0.3 and 0.7 ach, whereas the monthly average ventilation rate varies between 0.4 and 0.5 ach (80% to 100% of the required value). In the summer (June to August), the ventilation rate often is below 0.25 ach (or 50% of the required value), but additional ventilation by opening windows is possible at this time. Using the assumption of a constant wind speed of 3 m/s, the ventilation rate at the yearly average temperature of 4.3°C is calculated to be 0.35 ach, which is 70% of the required ventilation rate.

5.0 SUMMARY

The air flow rate through the envelope of the wood frame house studied in this paper was measured to be 3 ach at an underpressure of 50 Pa, which is quite airtight considering that the house has no plastic vapour retarder. The performance of the natural ventilation system was analysed by measuring the exhaust flow rates during different conditions, measuring the concentration of CO_2 during occupation and developing an equation to predict the ventilation rate as a function of outdoor temperature and wind speed. The results indicate that the outdoor ventilation rate per person is usually above the requirement of 4 L/(s·person), but below the required air change rate for the house of 0.5 ach. The measured CO_2 concentrations, on the other hand, were generally satisfactory (i.e., below 1000 ppm) when the bedroom doors were open. The peak concentrations of CO_2 in the bedrooms were between 1400 and 1800 ppm when the bedroom doors were closed and 800 and 1000 ppm when the bedroom doors were open. The CO_2 concentration outside the bedrooms was usually less than 800 ppm. At the average yearly temperature in Helsinki (~5°C) and a wind speed of 3 m/s, the ventilation rate of the house is expected to be 30% below the design value of 0.5 ach when the windows are closed. Since the occupants often keep the windows open in the summer, which increases the ventilation rate, the measured indoor concentration of CO_2 in the summer and winter are quite similar, even though the average ventilation rate through the natural ventilation system is expected to be 0.25 ach in the summer and 0.45 ach in the winter.

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