Review of low-energy construction, air tightness, ventilation strategies and indoor radon: results from Finnish houses and apartments

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Abstract

Low-energy and passive house construction practices are characterized by increased insulation, high air tightness of the building shell and controlled mechanical ventilation with heat recovery. As a result of the interaction of mechanical ventilation and high air tightness, the pressure difference in a building can be markedly enhanced. This may lead to elevated indoor radon levels. Minor leakages in the foundation can affect the radon concentration, even in the case where such leaks do not markedly reduce the total air tightness. The potential for high pressures to affect indoor radon concentrations markedly increases when the air tightness ACH_{50}, i.e. the air change per hour induced by a pressure difference of 50 Pa, is below 1.0 h^{-1}.

Pressure differences in Finnish low-rise residential houses having mechanical supply and exhaust ventilation with heat recovery (MSEV) are typically 2–3 Pa, clearly lower than the values of 5–9 Pa in houses with only mechanical exhaust ventilation (MEV). In MSEV houses, radon concentrations are typically 30% lower than in MEV houses. In new MSEV houses with an ACH50 of 0.6 h^{-1}, the limit for passive construction, the analytical estimates predict an increase of 100% in the radon concentration compared with older houses with an ACH50 of 4.0 h^{-1}. This poses a challenge for efficient radon prevention in new construction. Radon concentrations are typically 30% lower in houses with two storeys compared with only one storey. The introduction of an MSEV ventilation strategy in typically very airtight apartments has markedly reduced pressure differences and radon concentrations.

1 INTRODUCTION

Elevated radon concentrations in indoor air are normally caused by the convective flow of radon-bearing soil air. Due to the high radon concentration in soil air, typically 20 000–50 000 Bq/m^3, even very low leakage air flows of 0.1–1 m^3/h (0.03–0.3 l/s) can raise indoor radon concentrations above the action levels of 200–400 Bq/m^3.

Convective leakage flows are created by the indoor–outdoor pressure difference. Soil air flows into indoor spaces through gaps, cracks and openings in the base floor. Two mechanisms create the pressure difference: first, natural forces such as the indoor–outdoor temperature difference and wind, and second, forced mechanical ventilation. Typical pressure differences created by the indoor–outdoor temperature difference range from 0–3 Pa (pascal). Those created by mechanical ventilation are typically 2–10 Pa, but pressures of up to several tens of pascals are possible.

The new practices of low-energy construction require improved thermal insulation, airtight house structures and the implementation of mechanical supply and exhaust ventilation with heat recovery (MSEV). Consequently, these practices also affect the pressure conditions and potential leakage air flows from soil into living spaces. This report has two aims. First, it reviews the physics of the indoor–outdoor pressure difference. Second, it explores the consequences of air tightness and pressure differences for the indoor radon concentration in houses with different ventilation strategies through calculations, modelling and experimental studies.

This study arose from the RADPAR project subtask WP6, which aimed at the assessment of radon control technologies, including the conflict between energy conservation in buildings and the reduction of radon exposure[1, 2].

2 LOW-ENERGY CONSTRUCTION AND REGULATION

Low-energy and passive house practices have arisen from the need to save energy and are characterized by increased insulation, high air tightness of the building shell and controlled mechanical ventilation with heat recovery or, for instance, preheating in soil.

Multiple and varying terms are used to refer to strategies for low-energy houses, such as low energy, zero energy and passive houses. An overview of the terms and definitions is provided by Erhorn et al.[3]. The European Union (EU) set the goal for new construction in 2002 within the Energy Performance of Buildings Directive (EPBD)[4], which is one of the directives aiming at the reduction of energy use. The EPBD has already been implemented in many EU member countries.

The requirements of the EPBD should take into account possible negative effects such as inadequate ventilation and reduced indoor air quality. The indoor radon concentration is affected by the air tightness of the building shell, air exchange and pressure conditions. As a result of the interaction of mechanical ventilation and high air tightness, the pressure differences in buildings can be markedly enhanced. In cases where there are leakage paths in the foundation, this leads to increased air leakage from soil and consequently to increased indoor radon levels. Defective planning or implementation of new construction may, in unfavourable conditions, result in enhanced radon concentrations.

Due to the demands for energy conservation, the implementation of MSEV has become an increasing practice in EU countries. In Finland, practically all new construction is presently provided with mechanical supply and exhaust ventilation with heat recovery. Experience from these practices has been utilized in this study.

Table 1 summarizes air tightness requirements for new dwellings.

3 AIR INFILTRATION, AIR TIGHTNESS AND PRESSURE CONDITIONS

The radon concentration in indoor air can be expressed by the following simplified equation:

$$C_{Rn} = S / (\mathrm{ACH}\ V), \qquad (1)$$

where S is the radon entry rate (Bq/h), ACH is the air exchange rate (h^{-1}) and V is the volume of the house (m^3). The air exchange rate is generally the quotient of the air flow rate (m^3/h) and the house volume V (m^3). ACH is also referred to as “air changes per hour” and is a measure of how many times the air within a space is replaced in a one-hour period.

The air exchange in a building comprises infiltration and forced ventilation. The concept of infiltration is used for the unintentional flow of outside air into a building, whereas in forced ventilation, exhaust and/or supply fans are used. In houses with designed natural ventilation, both unintentional flow and flow through intentional ducts is utilized.

The pressure difference driving both the air infiltration of the building and the flow of radon-bearing soil air is caused by three major effects. First, stack effect pressures are created by differences in air density within the building and in the outdoor air. Second, mechanical ventilation creates pressure differences. Third, wind forces typically create positive pressures on the windward face and negative (suction) pressures on the opposite side of the building. Figure 1 illustrates the typical pressure differences created by the stack effect and mechanical ventilation.

The pressure difference due to the natural stack effect, ΔP_{nat}, is calculated using the following equation:

$$\Delta P_{nat} = g\ h_n\ (\rho_{out} - \rho_{in}) \approx 0.043\ (T_{in} - T_{out})\ h_n\ \ \text{(Pa)}, \qquad (2)$$

where $\rho_{out} - \rho_{in}$ is the difference between outdoor and indoor air densities and g is the gravity constant, 9.8 m/s^2. T_{in} and T_{out} are indoor and outdoor temperatures and h_n is the height of the neutral level (m). In a house with a height of 5 m and a neutral level at a height of 2.5 m, the pressure difference is 1.1 Pa when the temperature difference is 10 °C. Because the foundation backfill materials are permeable, the pressure difference at floor level also determines the soil air flow through the gaps in the foundation structures (Fig. 1).

When estimating the pressure difference caused by mechanical ventilation, the air tightness of the building shell is an important factor. The effective leakage area (ELA) is a standard measure of building tightness, which is measured by pressurizing a building with a fan. ELA is defined by assuming that in the pressure range characteristic of natural infiltration (-10 to +10 Pa), the flow versus pressure behaviour of a building more closely resembles square root (turbulent) than viscous (laminar) flow. The flow of air, Q_f ($m^3\ s^{-1}$), through an orifice at a specific applied pressure P_f (Pa) can be related to these parameters as follows[11]:

$$Q_f = \text{ELA}\,(2\,\rho^{-1}\,P_f)^{0.5} \qquad (3)$$

$$P_f = Q_f^2\,\rho\,/\,(2\,\text{ELA}^2) \qquad (4)$$

ELA — Effective leakage area of the building envelope (m^2)
ρ — Density of indoor air, 1.2 kg m^{-3}
Q_f — Volume flow rate created by the test fan at a given pressure difference, m^3/s
P_f — Pressure difference across the building shell Pa ($kg/(m\ s^2)$)

In real dwellings, viscous flows also contribute to airflow resistance. In this case, Eq. (3) no longer holds over a large range of pressure differences. However, this equation is useful when estimating the effective leakage area. Single-family dwellings in the USA typically have an ELA at the reference pressure of 4 Pa in the range of 0.04 m^2 (tight) to 0.3 m^2 (leaky) (12).

'Blower Door' is the popular name for a device that is capable of pressurizing or depressurizing a building and measuring the resultant air flow and pressure(12). The test measures the air flow rate needed to pressurize the building to various indoor–outdoor pressure differences.

Multipoint measurements of a blower door test provide a set of measured flow rates, Q_f, and pressure differences, P_f. Normally, high pressure differences of up to 50 Pa are used in order to avoid measurement errors. ELA depends on the pressure difference. Therefore, an empirical power-law relationship is widely used.

$$Q_f = k\ P_f^{\,n}, \qquad (5)$$

where k and n are the leakage coefficient (or flow coefficient) and the flow exponent, respectively. These parameters can be determined from the multipoint blower door measurement. The exponent n is typically 2/3 and is observed to vary generally between 0.6 and 0.8. Theoretically, it can be anywhere from 0.5 to 1. The results of a blower door test are normally expressed in air changes per hour at the reference pressure, commonly at 50 Pa. The resulting air exchange rate induced by 50 Pa pressure (flow rate at 50 Pa divided by the house volume, Q_{50} / V) is commonly referred to as ACH_{50} (or n_{50} in Europe). ACH_{50} has become a widely used measure of the air tightness of a building.

On the basis of Eq. 5, the air exchange rate at pressure differences P_1 below 50 Pa can be estimated as follows:

$$ACH_{50}/ACH_{P1} = (50\ \text{Pa}/P_1)^n \qquad (6)$$

The seasonal amount of natural air exchange can be related to ACH_{50} using equation 7 as a "rule of thumb" (12):

$$ACH_{nat} = ACH_{50}\ /\ 20 \qquad (7)$$

The factor of 20 used in Eq. 7 is a rough estimate and varies according to the climate and housing. The extensive studies in Finland(14) have given average annual natural infiltration rates ACH_{nat} of $ACH_{50}/39$ and $ACH_{50}/24$ for one- and two-storey houses with MSEV.

4 TERMINOLOGY

The following terms and abbreviations for ventilation strategies have been used.

NAV
Natural ventilation. Air exchange occurs through gaps, cracks and other unadventitious openings and intentional ducts and vents. The driving force is the pressure difference due to wind and the indoor–outdoor temperature difference.

MEV
Mechanical Exhaust Ventilation. A fan is used to extract indoor air from a house, typically from washing rooms. Fresh air infiltrates through leaks in the building shell and through intentional, passive vents.

MSEV
Mechanical Supply and Exhaust Ventilation with Heat Recovery. This is also called balanced ventilation in the case where the supply and exhaust air flow rates are in balance. Typically, the system supplies fresh air to bedrooms and living rooms where people spend the most time and exhausts air from the kitchen and washing rooms. In cold climates the system is provided with heat recovery. In Finnish MSEV practice, the design basis for air flows is not a full balance system. The exhaust air flow is normally adjusted to be 10% higher than the supply air flow rate. This is intended to prevent long-term moisture problems in house structures. In reality, a slight positive or negative pressure can be created in living spaces when using balanced ventilation due to inaccuracies and variation in air flow adjustments. Filter clogging may also cause imbalance.

5 EXPERIMENTAL MATERIALS AND METHODS

The studies carried out at Tampere University of Technology and Aalto University in Espoo[7, 8, 13, 14] and the Technical Research Centre of Finland[15, 16] included measurement of the pressure difference across the building envelope, temperature, air exchange rate and ACH_{50} measurements. Standard blower door procedures were used in ACH_{50} measurements.

The following study data of the Finnish Radiation and Nuclear Safety Authority (STUK) have been used:

1) Radon concentration in 2267 low-rise residential buildings and in 599 apartments, on the basis of a national random sample survey conducted in 2006[17].
2) Indoor radon concentrations in Finnish apartments for different construction year categories. This data set is based on the extensive indoor radon database of STUK, including results from 100 000 low-rise residential buildings and 9000 apartments[18].
3) Pressure difference measurements in Finnish low-rise residential buildings in 2001 in the Tuusula Building Fair area[19]. The measurements in 30 dwellings with different ventilation strategies provide a good sample of the contemporary situation.
4) Pressure difference measurements in 18 apartments on the lowest floor with MEV[20] and in 8 new apartments with MSEV.
5) Pressure difference measurements in 4 recently built low-rise residential buildings and in one apartment with a passive construction.

Indoor–outdoor pressure difference measurement was carried out using a micromanometer with auto-zeroing technology and a resolution below 0.01 Pa. The measurement was performed using a copper tube with a diameter of 3 mm, which was installed through the sealing of an opening window.

The impact of ventilation strategies on the indoor radon concentration (section 6.4) was theoretically assessed through an analysis that took into account the height and volume of the house, the natural pressure difference and infiltration and the mechanical ventilation rate observed in Finland, as well as the observed ACH_{50} values and the resulting pressure differences in houses with NAV, MEV and MSEV. The effect of ventilation strategies was also estimated using indoor radon measurements by applying regression analysis in which radon concentrations in different ventilation categories were compared with the local reference values[(21)].

6 RESULTS

Pressure difference and air tightness calculations

Figure 2 presents the calculated pressure differences over a wide range of ACH_{50} for a standard house with typical net exhaust air flows and with MSEV or MEV. Equation 5 and the average flow exponent of 0.72 observed in the extensive Finnish study[(14)] were used. The air flow rates of 9, 19 and 38 m^3/h represent 5%, 10% and 20% lower supply air flows compared with balanced ventilation of 187 m^3/h in a house with MSEV. This, in turn, represents an air exchange rate of 0.5 h^{-1} in a house with a volume of 375 m^3. The line for the flow rate of 187 m^3/h in Figure 2 represents the total air flow rate in a similar house with MEV.

The results indicate that in an airtight MSEV house with an ACH_{50} of 1 h^{-1} or lower, pressure differences from 1–10 Pa may occur. An ACH_{50} of 1 h^{-1} corresponds to an ELA of 0.01 m^2 in the chosen standard house. In unfavourable cases, pressure differences of up to 10–50 Pa may occur. When the typical natural pressure differences due to the indoor–outdoor temperature difference are 1–3 Pa, these additional pressure differences created by the ventilation system and air tightness markedly increase the flow of radon-bearing soil air into living spaces.

Table 2 characterizes the relationship between ACH_{50}, the corresponding natural air exchange and the pressure differences recommended for ventilation in buildings of leakage classes A–H[(12)]. Classes P1 to P3 are included in this study, as well as the estimated ELA and pressure differences. The MSEV system works best in classes P1 to B. In houses with lower air tightness, the role of uncontrolled air flows increases and the benefits from heat recovery are lower. In classes C to F, MEV ensures a good air exchange, but without the benefits of heat recovery. In leakage classes G or worse, natural ventilation is rather good and mechanical ventilation is no longer needed. However, in order to save energy costs the buildings should be airtight.

Air tightness of Finnish dwellings and international comparison

Figure 3 illustrates the distribution of air exchange rates at a pressure difference of 50 Pa, ACH_{50}, in newly built (1995–2003) Finnish wooden-frame houses measured in 2005. The average ACH_{50} was 3.9 h^{-1}. Apartment buildings normally have concrete structures and are clearly more airtight, the average air exchange at 50 Pa being 1.1 h^{-1}.

Table 3 presents the results of Finnish air tightness studies for houses varying in the year of construction. The energy crisis in 1973 did not alter the practices towards more airtight buildings. However, the crisis started the still ongoing development towards better thermal insulation. Since 1980 there has been a clear trend towards more airtight structures. The air tightness ACH_{50} has been reduced from above 7 h^{-1} before the 1980s to less than 4 h^{-1} in the 2000s. In the present decade the energy requirements have been tightened and the trend has continued. Recent measurements(6) indicate that in new construction, typical ACH_{50} values are already less than 2 h^{-1}, the average being close to 1.0 h^{-1}.

Air exchange and pressure difference measurements in houses with different ventilation strategies

A summary of the surveys of air exchange rates in Finnish low-rise residential buildings is presented in Table 4. Both air flow measurements in vents and the tracer gas technique have been utilized in these studies. The results reveal that the mean air exchange rates vary in the range of 0.3–0.42 h^{-1} and are highest in MSEV houses and lowest for NAV. A previous extensive study in 162 low-rise houses carried out in the metropolitan area of Helsinki yielded similar results, the geometric means for NAV, MEV and MSEV being 0.36 h^{-1}, 0.42 h^{-1} and 0.42 h^{-1}, respectively(22).

The measurements carried out in the Tuusula Building Fair area(19) provide a good sample of houses constructed in 2000. The houses with MEV were provided with 2–10 fresh air vents. The normal practice in adjusting MSEV systems with heat recovery was to have a 10% higher exhaust air flow compared with the total supply air flow. The average radon concentration in the area (60 dwellings) was 200 Bq/m^3. Due to varying foundation structures, the effect of ventilation strategies on indoor radon was not estimated. The typical negative pressure difference was 5–9 Pa in MEV houses and considerably lower in MSEV houses, being only 2–3 Pa.

The Tampere results in Table 4 provide a good sample of houses in southern Finland constructed in 1995–2003(7). The results are in line with the Tuusula results when taking into account that the measurements were conducted in summer, when the pressure differences were at a minimum. Pressure differences in MSEV houses are clearly lower than in MEV houses, typically being 1–3 Pa. The number of measurements in passive houses is low but demonstrates the potential for elevated pressure differences, the highest results being -15 Pa. The ACH_{50} values in the houses were less than 0.6 h^{-1}, the lowest being below 0.2 h^{-1}. The introduction of MSEV to apartments has markedly reduced the pressure difference in these dwellings.

Assessment of the effect of ventilation strategies on the indoor radon concentration

The radon concentration in indoor air can be expressed by the simplified Equation 1. Variation in the radon concentration is created by variations in the source strength, room volume and air exchange rate. A higher house implies a larger house volume and lower radon concentration. On the other hand, house height increases the pressure difference driving both radon entry and the air exchange rate. A low air exchange rate increases the radon concentration. As the basis of the following simplified estimation, radon entry is proportional to the pressure difference driving soil air into living spaces and to the length of the perimeter of the floor slab, i.e. of the gap between the foundation wall and floor slab (Figure 1).

The effect of ventilation strategies on the indoor radon concentration can be roughly estimated using the air exchange, air tightness and pressure difference considerations in the previous sections of this article. Table 5 summarises the results for typical Finnish one- and two-storey houses. The radon entry rate is proposed to be proportional to the perimeter length of the floor slab. Both the natural pressure differences created by the indoor–outdoor temperature difference and the pressure difference created by the mechanical ventilation affect the total air exchange rate in the house. The superposition of the air flows due to these pressure differences can be estimated in different ways. The power law used in the summing in this study is called Variable Flow Exponent (VFE) superposition[11] and has been described in the explanations for Table 5.

These simplified analytical estimates in houses with different ventilation strategies reveal that radon concentrations in MEV houses are close to those in houses with natural ventilation (NAV). In MSEV houses, the radon concentrations are 20–47% lower, depending on the house height. The difference is highest in one-storey houses due to the qualified air exchange rate, which is roughly twice as high as in houses with natural ventilation, and due to the low pressure difference created by MSEV.

In new houses with airtight structures fulfilling the requirements of passive construction, this simplified analysis demonstrates that radon concentrations are elevated compared with older houses with MSEV and an average ACH_{50} of 3.9 h^{-1}. At the air tightness level ACH_{50} of 0.6 h^{-1} required in passive construction, the increase is close to 100%, and at an ACH_{50} of 0.2 h^{-1} it is already close to 400%. These results were calculated for a 10% imbalance in supply and exhaust air flows. This potential elevation of radon concentrations in airtight houses poses a challenge for efficient radon prevention in new construction.

In houses with two storeys, the estimated radon concentration is 20% to 30% lower compared with one-storey houses in the case of NAV and MEV. This is due to the lower perimeter-to-volume ratio and also due to the lower air tightness and higher natural ventilation in two-storey houses. In houses with MSEV, the effect of the number of floors is lower. This is due to the controlled air exchange rate, where mechanical ventilation dominates over natural ventilation, thereby reducing the effect of house height.

Radon measurements in houses with different ventilation strategies

Based on the questionnaire data of the national random sample radon study in 2006[17], natural ventilation was the prevailing ventilation strategy up to the mid-1980s (Figure 4). The overall prevalence of MEV was at a maximum of 30% in the mid-1990s. Mechanical supply and exhaust ventilation with heat recovery (MSEV) began a strong rise in the mid-1970s. Presently, it is the most prevalent (>95%) ventilation strategy in new construction. MSEV finally superseded MEV following the revision of energy regulations in 2004.

Both the national random sample survey in 2009 and the national radon database were utilized in assessing the effect of the ventilation strategy, and Table 6 presents the results. The indoor radon concentration is affected by multiple factors that are cross-correlated. In houses constructed before the 1970s, the relative number of basement houses and crawl-space foundations was still high. In these categories, the radon concentration is markedly lower than in houses with a slab on ground, which has been the most prevalent type of foundation from the 1970s onwards[17]. Practices regarding sub-slab earthworks have also changed. Instead of the previously used gravel, there has been a strong trend towards thicker filling layers and crushed stone materials. One of the reasons for this trend has been the preservation of the declining natural gravel deposits. Since the energy crisis of the 1970s, construction practices aiming at higher air tightness have gradually been developed. Due to all these trends, and in order to obtain a homogeneous set of study data, the effect of ventilation strategies was examined using the database material of houses constructed in 1985–1994. Figure 4 shows that in this period the prevalence of all three strategies was considerable. In the case of the random sample survey in 2006, the sample period of 1975–1994 was selected in order to obtain a higher number of houses for which ventilation strategy information was provided in the questionnaire.

Spatial variation in the radon concentration and air movements in a building

The internal air flows in houses are affected by many factors, such as the pressure differences created by temperature differences or mechanical exhaust ventilation and the opening of doors between different spaces in the house. Air infiltration is dominated by the flow of fresh air through the lower parts below the neutral level of the building (Figure 1). The overall trend in air flows is the movement of air from the lower level to upper levels. The simplified analysis of Table 5 above considers a house as a single compartment in which radon is evenly distributed. The analysis in Table 6 utilizes first floor measurements, which must be taken into account in the interpretation of the results. In order to explore the effect of spatial variation within a house, the ratio of the radon concentration between the second and first floor was determined using simultaneous measurements from the ground floor and first floor in houses with slab on ground and different ventilation strategies (Table 7). In comparison, results for room-to-room variation in single-storey houses and the first floor-to-basement ratio for semi-basement houses are also given.

Variation between two rooms on the first floor is caused by room-to-room variation in convective air flows from beneath the floor slab and in air exchange. In houses with NAV, variation may be increased by the opening of fresh air vents, or on the other hand by having rooms with very low air exchange. The GSD values for NAV (n = 1045), MEV (n = 409) and MSEV (n = 787) were surprisingly all in the range of 1.36–1.39. In Finnish MEV houses, the exhaust vents are normally located in other spaces than the living room or bedroom, typically in washing rooms. Therefore, the equality with NAV is expected. In MSEV houses, field measurements have revealed, for instance, a bedroom with only a fresh air supply vent and a radon concentration of 60 Bq/m^3. Simultaneously, behind the normally closed door in the living room the radon concentration was 600 Bq/m^3. When this door was open, high radon concentrations were also observed in the bedroom. This example illustrates that although MSEV offers better and more uniform room-specific air exchange, pressure differences and internal air flows in the dwelling sustain a degree of variation comparable with NAV and MEV.

The first- to ground-floor radon concentration ratio of 0.84 in slab-on-ground houses illustrates the air flows between the storeys and the dilution of the radon concentration when the ground floor air mixes with the upstairs air volume. Due to vents, flows of outdoor air and variations in source strength, the radon concentration may be also higher upstairs. In the upper 5% of the houses, the ratio was in the range of 1.5–5.6. Direct air flow to the first floor through pipe penetrations and the intermediate floor may also increase first-floor radon concentrations.

In semi-basement houses the walls in contact with soil increase the radon concentration in first floor rooms, especially when doors to the staircase space are closed. The gmean of the ratio was lower (0.67) than with slab-on-ground houses. Due to additional room-specific radon sources, the variation also increases to a GSD of 1.85.

The air exchange between the basement and first floor recorded in the Minnesota basement houses is lower than that in Finnish semi-basement houses. Therefore, the first floor–basement ratio is lower, being 0.54.

Pressure difference and radon in Finnish apartments

Finnish apartments are normally built using very airtight concrete element technology. Indoor radon measurements in apartments therefore provide excellent data on the effect of air tightness on pressure conditions and indoor radon. The building code for the energy performance of apartment buildings was revised in 2004. Due to the new requirements, the previously used mechanical exhaust ventilation systems (MEV) have been replaced by mechanical supply and exhaust systems with heat recovery (MSEV). As presented in previous chapters, the pressure difference created by MSEV is markedly lower than with MEV.

Measurements in apartments carried out by both the Technical Research Centre of Finland(16) and STUK(20) have demonstrated that the negative pressure differences in MEV apartments are high, typically 8–14 Pa, and that these differences have been markedly reduced in MSEV apartments, typically being 2–6 Pa. The MSEV results represent new construction since 2004, with supply and exhaust ventilation with heat recovery in each dwelling or centralized in the service room of the building.

The previous study by STUK revealed that the indoor radon concentration in lowest floor apartments has markedly declined, by roughly 50%, since 2000(18). Both radon prevention in new construction and the introduction of MSEV were expected to be the main reasons for the reduction. Radon concentrations in the dwellings of the upper floor remained concurrently unaltered. This is because in both MEV and MSEV apartments the air exchange has been dimensioned in a similar way, with 0.5 air changes per hour, and because building materials form the main source of radon in these upper floor dwellings.

A new comparison was carried out between 289 ground contact apartments completed in 2001–2006 and 101 apartments with MSEV completed in 2007–2012. For this data set, the median for the ratio of the measured radon concentration and median of the local radon concentration of detached houses was calculated: This normalized data set yielded a decrease of 35% for new MSEV apartments. However, this is an underestimate, because a marked proportion of apartments completed in 2001–2006 were already provided with MSEV instead of MEV.

The pressure difference results for the new MSEV apartments of this study demonstrate that the reduced pressure level is a significant source of the observed reduction in the indoor radon concentration of the lowest floor apartments. Further case studies are needed to quantify the effects of pressure difference reduction and radon prevention.

Pressure difference measurements in passive construction

Pressure difference measurements were carried out in three recently built passive single-family or semi-detached houses in 2011–2013. The number of houses with passive construction in Finland is still limited but increasing. However, these few measurements provide a first sample of the contemporary situation. The negative pressure difference measured in these four houses was 15 Pa, 4.2 Pa, 5.7 Pa and 2.2 Pa. The corresponding ACH_{50} values were 0.2 h^{-1} and 0.48 h^{-1} in the two first cases. In the third and fourth case, the air tightness was also below 0.6 h^{-1}. These few measurements indicate that airtight constructions fulfilling the requirements of passive houses may also create negative pressure differences exceeding 10 Pa. The situation sets special requirements for the control of pressure differentials, and further measurements are needed.

7 CONCLUSIONS

Low-energy and passive house construction practices are characterized by increased insulation, high air tightness of the building shell and controlled mechanical ventilation with heat recovery. The key issue regarding radon is the prevention of air leakages in the foundation. The aims towards high air tightness of the base floor and foundation constructions in contact with soil are synergetic for radon prevention and low energy construction.

All measures that reduce the air exchange in buildings increase the indoor radon concentration. Therefore, in countries where the natural air exchange rate is excessive from the point of view of energy conservation, the trend towards low energy construction tends to increase radon concentrations. On the other hand, in the case of air-tight structures and low air exchange rates, from the point of view of healthy indoor air, measures increasing air exchange tend to reduce the radon concentration.

In the case of airtight buildings, pressure differences caused by mechanical ventilation have an important role, in addition to the air exchange rate. Due to the interaction of mechanical ventilation and high air tightness, the pressure difference in buildings can be markedly enhanced. This may lead to elevated indoor radon levels. Minor leakages in the foundation can affect the radon concentration, even in cases where the leaks do not markedly reduce the total air tightness. The potential for high negative pressures to affect indoor radon concentrations considerably increases when the air tightness ACH_{50} is below 1.0 h^{-1}.

Compared with mechanical exhaust ventilation, MSEV makes it possible to control the pressure difference. Due to risks of moisture loads in structures, the exhaust air flows in Finnish MSEV systems are adjusted to a slightly higher level than supply air flows. In practice, in countries where fully balanced ventilation is recommended, slight positive or negative pressures exist in living spaces due to inaccuracies and variation in air flow adjustments.

Pressure differences in Finnish low-rise residential houses having mechanical supply and exhaust ventilation with heat recovery (MSEV) are typically 2–3 Pa, which is clearly lower than the values of 5–9 Pa in houses with only mechanical exhaust ventilation (MEV). The typical air tightness ACH_{50} in these buildings is 2–7 h^{-1} and the average air-exchange rate is 0.4 h^{-1}. Simplified analytical estimates and comparison of the radon concentration in houses with different ventilation strategies revealed that radon levels in MEV houses are close to those in houses with natural ventilation (NAV). In MSEV houses, radon concentrations are lower, the difference being 30% in measurement statistics. In new MSEV houses with an ACH_{50} of 0.6 h^{-1}, the analytical estimates predict an increase of 100% in the radon concentration compared with older houses with an ACH_{50} of 4.0 h^{-1}. This is a challenge for efficient radon prevention in new construction. Guidelines for ventilation adjustment in MSEV houses may also need revision.

The results demonstrate that in typical Finnish houses with two storeys with NAV and MEV, radon concentrations are 30% lower than in houses with only one storey. In houses with MSEV, the effect of the number of floors is lower. These effects arise from the interaction of house geometry, volume, pressure differences and air exchange. Due to the internal air flows in houses, the geometric mean of the first floor to ground floor radon concentration ratio in non-basement houses was 0.84. In semi-basement houses, the first floor to basement ratio was 0.67.

Finnish apartments are normally built using very airtight concrete elements. Indoor radon measurements in apartments therefore provide excellent data on the effect of air tightness on pressure conditions and indoor radon. Radon concentrations measured in Finnish apartment buildings provide strong evidence for the importance of air pressure differences. The concrete structures of these apartments are very airtight. Typical air leakage rates at 50 Pa are less than 1.0 h^{-1}. Typical pressure levels in apartments with mechanical exhaust ventilation range from 8–14 Pa, the average being 13 Pa. Since 2004, new energy requirements have forced constructors to implement supply and exhaust ventilation with heat recovery. This has resulted in markedly lower air pressure differences, typically 2–6 Pa, and in reductions of several tens of percent in radon concentrations.

8 REFERENCES

1. Bartzis J, Arvela H, Bochicchio F, Collignan B, Fojtikova I, Gray A, Grosche B, Holmgren O, Hulka J, Jiranek M, Kalimeri K, Kephalopoulos S, Klerkx J, Kreuzer M, Mc Laughlin J, Mueller S, Olsen B, Reina V, Ringer W, Rovenska K, Schlesinger D, Standring W, Strand T, Venoso G, Zeeb H . RADPAR Final Scientific Report. Radon Prevention and Remediation. University of Western Macedonia, Dep. of mechanical engineering, Kozani, Greece., 2012. http://web.jrc.ec.europa.eu/radpar/.

2. Arvela H, Holmgren O, Reisbacka H. WP 6: Assessment of radon control technologies Deliverable 13/6: Review of Low Energy Construction, Pressure Conditions and Indoor Radon in Finnish Residential Buildings. RADPAR, Radon Prevention and Remediation. April 2012. http://web.jrc.ec.europa.eu/radpar/.

3. Erhorn-Kluttig H. and Erhorn H. Terms and definitions used in the EU Member States for High Performance Buildings (2009). Information Paper available on the EU portal BUILD UP www.buildup.eu.

4. EPBD: Directive 2010/31/EU of the European Parliament and the Council of 19 May 2010 on the energy performance of buildings (recast). http://eurlex.europa.eu/JOHtml.do?uri=OJ%3AL%3A2010%3A153%3ASM%3AEN%3AHTML

5. Erhorn-Kluttig, H, Erhorn, H, Lahmidi H and Anderson R. Airtightness requirements for high performance building envelopes. 2012. www.asiepi.eu.

6. Kauppinen T, Paloniitty S, Vinha J, Aaltonen A, Manelius E and Korpi M. Philosophy and approaches for airtightness requirements in Finland. TightVent international Workshop, Brussels 28-29.3.2012. Achieving relevant and durable airtightness levels: status, options and progress needed. www.tightvent.eu.

7. Vinha J, Korpi M, Kalamees T, Eskola, L, Palonen J, Kurnitski J, Valovirta I, Mikkilä A, Jokisalo J. Moisture and temperature conditions, air excahnge and air-tightness in Finnish detached houses with wooden frame. Research Report 131. Tampere Universitry of Technology. Tampere 2005. (in Finnish).

8. Vinha J, Korpi, M, Kalamees T. Jokisalo J, Eskola L, Palonen J, Kurnitski J, Aho, H Salminen M, Salminen K, Keto, M. . Asuinrakennusten ilmanpitävyys, sisäilmasto ja energiatalous. (Air tightness, indoor climate and energy economy of detached houses and apartments). Research Report 140. Tampere University of Technology. Department of Civil Engineering. Structural Engineering. Tampere 2009. 148 pp. + 19 app. (Abstract in English)

9. Stephen R.K. (2000) Airtightness in UK Dwellings. BRE Information Paper IP 1/00. Building Research Establishment. Garston, Watford.

10. Sherman M, Walker I. Philosophy and approaches for airtightness requirements in the USA. Proceedings of International Airtightness Workshop, Brussels, Belgium, March 2012. Report LBNL-5713E. Lawrence Berkeley National Laboratory, Berkeley, California.

11. Sherman M H. Superposition in Infiltration Modeling. Indoor Air, 2, pp. 101-114, 1992. LBL-29116, Lawrence Berkeley Laboratory, University of California.

12. Sherman M. The Use of Blower-Door Data. LBL-35173. Lawrence Berkeley Laboratory, University of California, 1998.

13. Kalamees T, Kurnitski J, Jokisalo J, Eskola L, Jokiranta K and Vinha J. Measured and simulated air pressure conditions in Finnish residential buildings. Building Services Engineering Research and Technology 2010 31:177. http://bse.sagepub.com/content/31/2/177.

14. Jokisalo J, Kurnitski J, Korpi M, Kalamees T and Vinha J. Building leakage, infiltration and energy performance analyses for Finnish detached houses. Building and Environment 44 (2009), 377-387.

15. Polvinen M, Kauppi A, Saarimaa J, Haalahti P and Laurikainen M. Airtightness of the building envelope. Technical Research Center of Finland- VTT. Research report 215. Espoo 1983. (abstract in English)

16. Metiäinen P, Saarimaa J, Saarnio P, Salomaa H, Tulla K and Viitanen H. Haalahti P and Laurikainen M. Constancy of air-tightness in buildings. Technical Research Center of Finland- VTT. Research report 422. Espoo 1986. (abstract in English)

17. Mäkeläinen I, Valmari T, Reisbacka H, Kinnunen T, Arvela H. Radon in Finnish dwellings –Sample survey 2006. STUK-A242. Helsinki 2009. 45 pp. +App. 23 pp. (Abstract in English)

18. Valmari T, Arvela H, H. Reisbacka H. Radon in Finnish apartment buildings Radiation Protection Dosimetry Vol. 152, No. 1–3, pp. 146–149 (2012).

19. Airaksinen M, Arvela H and Jokiranta K. Air exchange and radon studies in the Tuusula Building Fair area. Report B73. Helsinki University of Technology, Laboratory of Heating Ventilation and Air Conditioning. Espoo 2002 (abstract in English).

20. Arvela H, Reisbacka H. Asuntojen radonkorjaaminen (Indoor radon mitigation). STUK-A252. Radiation and Nuclear Safety Authority, Helsinki 2012, 138 pp. + appendices 3 pp. (Abstract in English)

21. Arvela H, Holmgren O, Reisbacka H. Radon prevention in new construction in Finland: a nationwide sample survey in 2009. Radiat Prot Dosimetry 2012.

22. Ruotsalainen R, Ronnberg R, Säteri J, Majanen A, Seppänen O, Jaakkola J.J.K. Indoor Climate and the Performance of Ventilation in Finnish Residences. Indoor Air, 2,137-145 (1992).

23. Steck D J. Spatial and temporal indoor radon variations. Health Phys. 62, 351-355 (1992).

Table1 Air tightness requirements for new dwellings. Typical air tightness n_{50} (Europe) or ACH_{50} (USA) for current housing. Source: Ernhorn-Klutig(5) or otherwise indicated in the table.

Country	Air tightness requirement at 50 Pa pressure, n_{50} (ACH_{50})		Air tightness of the housing stock, n_{50} or ACH_{50}
	Natural ventilation	Mechanical ventilation	
Czech Republic	4.5 h^{-1}	With heat recovery 1.0 h^{-1}	
Germany	3.0 h^{-1}	1.5 h^{-1}	
Denmark	1.5 l/s per m^2 floor area (n_{50} 2.2 h^{-1}) 1)		
Finland(6)	2008 base value for calculations 4.0 h^{-1} 2012 building envelope 4 m^3/(h m^2) (n_{50} 4.8 h^{-1})		Houses: mean 3.9 h^{-1}; apartments: mean 1.6 h^{-1}, Vinha et al. (7, 8)
Norway	3.0 h^{-1}		
The Netherlands	200 l/s (10 Pa) (n_{10} = 2.9 h^{-1}) 1)		
UK	10 m^3/m^2 h (n_{50} 8 h^{-1}) 1)		Typically 5–25 h^{-1}, mean 13 h^{-1}, Stephen(9)
USA(10)	Codes and regulations at state level. Voluntary programmes IECC 2012 and Energy Star V, 5.0 or 6.0 for climate zone 1 and 3.0 for zone 8 (northern)		New buildings typically 3–5 ACH_{50}, which is three times tighter than in the existing stock

1) Estimated n_{50} or n_{10} has been calculated for a house with a volume of 250 m^3, floor area of 100 m^2 and house envelope area of 200 m^2.

Table 2 Characterization of building leakage using ACH_{50}, air exchange at a pressure difference of 50 Pa. Leakage classes A–J and the recommended ventilation strategy are according to Sherman[(12)]. Classes P1 to P3 for low energy construction, the estimated equivalent leakage area (ELA) and typical pressures differences due to mechanical ventilation have been estimated in this study for a one-storey house with a volume of 375 m^3.

Leakage class	ACH_{50} h^{-1}	ACH natural h^{-1}	Estimated ELA 1) m^2	Typical pressure difference 2)		Recommended ventilation strategy
				MSEV Pa	MEV Pa	
P1	0.1	0.004	0.0008	19	466	Balanced only
P2	0.2	0.008	0.0016	7.3	178	Balanced only
P3	0.6	0.024	0.005	1.6	39	Balanced only
A	1	0.04	0.008	0.78	19	Balanced only
B	2	0.08	0.016	0.30	7.3	Balanced
C	3	0.13	0.024	0.17	4.1	Either
D	5	0.2	0.041	0.08	2.0	Either
E	7	0.28	0.057	0.05	1.3	Unbalanced
F	10	0.4	0.081	0.03	0.8	Unbal. only
G	14	0.56	0.11	0.02	0.5	Unbal. only
H	20	0.8	0.16	0.01	0.3	None
I	27	1.1	0.22	0.08	0.2	Build. too leaky, should be tightened
J	>27	>1.1	> 0.22	<0.08	<0.2	

1) ELA has been calculated for the standard pressure difference of 4 Pa[10] for the corresponding ACH_{50} using Equations 6 and 3.
2) The pressure difference for MSEV has been calculated for an air flow rate of 19 m^3/h, which represents a 10% lower supply air flow compared with balanced ventilation of 187 m^3/h in a house with a volume of 375 m^3. For an MEV house, an air flow of 187 m^3/h has been used. The highest pressure differences (>100 Pa) are theoretical, because the fan is not capable of creating such pressure differences. Equation 6 has used in the calculations of the natural air exchange rate.

Table 3 Air tightness measurements in Finnish detached houses with a wooden frame and in apartments with concrete structures.

House type, year of construction	Air tightness ACH_{50}, h^{-1}		
	N	Mean	Range
Detached houses			
1950–1980, Polvinen et al. 1983[(15)]	61	7.0	2.2–17.8
1978–1982, Polvinen et al. 1983[(15)] 1)	28	3.5	1.0–7.5
1979–1982, Metiäinen et al. 1986[(16)] 1)	32	2.7	1.1–6.0
1979–1984, Vinha et al. 2005[(7)]	7	5.2	2.1–7.3
1985–1999, Vinha et al. 2005[(7)]	40	4.1	0.5–8.9
2000–2003, Vinha et al. 2005[(7)]	55	3.6	0.6–7.2
2005–2011, Kauppinen et al. 2012[(6)]	12	1.2	0.9–3.2
Multi-storey apartments			
1997–2005, Vinha 2009[(8)]	40	1.1	0.3–5

1) Special emphasis was given to air tightness during construction.

Table 4 Pressure differences and air exchange rates in Finnish low-rise residential houses with natural ventilation (NAV), mechanical exhaust ventilation (MEV) and mechanical supply/exhaust ventilation with heat recovery (MSEV). The results are from heating season measurements in the Tuusula Building Fair area in 2001(19) and from summer measurements in the Tampere survey in 2005(8). Positive pressure means overpressure indoors compared with outdoors.

		Pressure difference, Pa			Air exchange, h^{-1}
Housing type, ventilation strategy, reference	Num -ber	Mean	Range	Typical, 25% – 75% quartiles	Mean (range)
Houses, NAV					
Vinha et al. 2005(7)					0.30 (0.10–0.50)
Houses, MEV					
Airaksinen et al. 2002(19)	8	-7.4	-2 to -11	-5 to -9	
Vinha et al. 2005(8) 1)	30	-3.0	+2.0 to -8.8	-1.6 to -4.3	0.36 (0.1–0.6)
Houses, MSEV					
Airaksinen et al. 2002(19)	11	- 2.9	-1 to -6	-2 to -3	
Vinha et al. (7) 1)	61	-1.8	+1 to -12	-0.9 to -2.0	0.40 (0.15–0.80)
This study, newly built passive houses 2)	4	-6.8	-2.2 to -15		
Apartments, MEV					
Metiäinen et al. 1986(16)	21	-15.0	-7 to -25	-12 to -19	
Arvela et al. 2012(20)	18	-13	-6 to -40	-8 to -14	
Apartments, MSEV, newly built					
This study	8	-4	+4 to -11	-2 to -6	

1) Summer and spring measurements. The pressure difference values represent the lowest annual values. The indoor–outdoor temperature difference was at the minimum. In houses with MEV, fresh air vents were typically open, reducing the pressure difference.
2) Observations -2.2, -4.2, -5.7 and -15 Pa

Table 5 Simplified estimation of the relative radon concentration in Finnish houses with natural ventilation (NAV), mechanical exhaust ventilation (MEV) or mechanical supply and exhaust ventilation with heat recovery (MSEV) and varying in air tightness and the number of storeys.

House category Typical year of construction	Number of storeys Per/Vol 1/m^2 1)	Air exchange, total Nat & forced h^{-1} 2)	Air tightness ACH_{50} 3)	Pressure difference, ΔP_{tot} $\Delta P_{nat} + \Delta P_{for}$ Pa 4)	Radon concentration, relative 5)	Ratio between two/one storey houses
Older housing stock						
NAV 1951–1978	1 0.147	0.23	7.0	1.46 + 0	1.00	
	2 0.097	0.41	7.7	2.75 + 0	0.70	0.70
MEV 1988, 1979–1995	1 0.147	0.44 0.16 & 0.36	4.7	2.87 1.46 + 1.41	1.03	
	2 0.097	0.53 0.28 & 0.36	5.2	3.97 2.75 + 1.22	0.78	0.76
MSEV 1993, 1988–2001	1 0.147	0.46 0.13 & 0.40	3.9	1.55 1.46 + 0.09	0.53	
	2 0.097	0.53 0.23 & 0.40	4.3	2.83 2.75 + 0.08	0.56	1.05
New single family houses						
MEV 2000–2005	1 0.147	0.39 0.08 & 0.36	2.5	4.84 1.46 + 3.38	1.96	
MEV 2010	1 0.147	0.37 0.03 & 0.36	1.0	8.72 1.46 + 7.26	3.71	
MSEV passive, 2010	1 0.147	0.40 0.02 & 0.40	0.6	2.62 1.46 + 1.16	1.03	
	1 0.147	0.40 0.01 & 0.40	0.2	6.80 1.46 + 5.34	2.69	

Explanations for Table 5

1) Per/Vol: Perimeter per volume. One storey: floor area 10*12 m^2, perimeter 44 m, room height 2.5 m, volume 300 m^3, Per/Vol = 0.147 1/m^2. Two-storey: floor area 7*10 m^2, perimeter 34 m, room height 2 x 2.5 m, volume 350 m^3, Per/Vol = 0.097 1/m^2. House statistics from a STUK questionnaire(17).

2) The natural air exchange rate is calculated using the equation: $ACH_{nat} = ACH_{50}/C_{inf}$. C_{inf} for one-storey houses is 30.2 and for two-storey houses 18.9, based on extensive Finnish measurements(14). The forced air exchange rate ACH_{for} is based on the measured results presented in Table 4. The superposition of these, ACH_{tot}, is based on the summing of ACH_{nat} and ACH_{for} using the following power law(11):

$$ACH_{tot}^{1/n} = ACH_{nat}^{1/n} + ACH_{for}^{1/n}, \qquad (8)$$

where the exponent of 0.72 based on Finnish studies has been used.

3) For one-storey houses, air tightness was estimated based on the national surveys reported in Table 3. In two-storey houses, ACH_{50} is 10% higher compared with one-storey houses based on the measurements in the Tampere survey.

4) The pressure difference due to the natural stack effect, ΔP_{nat}, is calculated using Equation 2. An indoor–outdoor temperature difference of 20 °C has been used. In this example case, the neutral level for the one-storey house is 1.70 m and for the two-storey case 3.23 m. The calculation takes into account the relative leakage in the walls, ceiling and floor[11].

   The forced pressure difference, ΔP_{for}, is calculated using Equation 6 for the forced air exchange rate ACH_{for}. In the case of supply and exhaust ventilation, an air flow of 0.1 x ACH_{for} has been used, because only the net imbalance of supply and exhaust air flows causes the pressure difference. The total pressure difference at floor level, ΔP_{tot}, is the sum of ΔP_{nat} and ΔP_{for}.

   In the airtight MEV 2010 house (ACH_{50} = 1.0), the air tightness necessitates the use of fresh air vents. An estimated reduction of 40% in ΔP_{for} has been taken into account.

5) Using Equation 1, the relative radon concentration for one- and two-storey houses has been calculated as ΔP_{tot} (Per/Vol) / ACH_{tot}. The one-storey house with NAV has been taken as the reference.

Table 6. Effect of the ventilation strategy on the indoor radon concentration of detached houses with slab on ground based on 438 houses from a random sample survey 2006 and 5312 houses in the national radon database.

Study material, year of construction and feature	Ventilation strategy			
	Natural	Mechanical exhaust	Mechanical supply and exhaust	Total TO BE ADDED
Radon database, One storey				
Number of houses (1985–1994)	1538	1438	2336	
Radon concentration, average Bq/m^3	348	332	256	
Radon concentration, median Bq/m^3	237	233	178	
Radon concentration, local reference value, median, Bq/m^3, 1)	138	153	154	
Ratio of radon concentration to local reference value, median	1.76 (gmean 1.76)	1.64 (gmean 1.65)	1.30 (gmean 1.30)	
Regression factor 2)	2.38 +-0.05	2.20 +-0.05	1.70 +- 0.05	
Relative radon concentration compared with natural ventilation, 95% confidence limits 3)	1.00	0.92 +-0.14 (0.94)	0.71 +- 0.14 (0.74)	
Random sample survey 2006, One storey				
Number of houses (1975-1994)	196	89	153	
Radon concentration, median	94.8	113	82.5	
Local reference value, median	91.6	95.3	99.4	
Ratio to local reference	1.14	1.16	0.97	
Regression factor	1.36 +-0.06	1.18 +-0.10	0.976 +-0.051	
Relative radon concentration	1.00	0.87 +- 0.23	0.72 +- 0.16	
Two storeys Radon database				
Regression factor	1.92 +- 0.05	1.70 +-0.05	1.66 +- 0.05	
Relative radon concentration	1.00	0.89	0.86	
Ratio, two to one storeys	0.81	0.77	0.98	

1) Median of the measurements carried out in the postal code area, from the STUK database. If the number of measurements was below 10, the municipal median was used.
2) Coefficient from linear regression analysis. Ratio of the measured radon concentration to the local reference value. The intercept term is set to zero.
3) Relative radon concentration has been calculated as the ratio of the regression coefficient to the coefficient of the "Natural" class. The confidence limits have been calculated by summing the 2 STD errors in quadrature with the "Natural" class.

Table 7 Summary of spatial variation in one- and two-storey houses with slab on ground and houses with a semi-basement. COV is the mean coefficient of variation calculated for the measurement pairs. All other statistics have been calculated for the ratio of the two measurements. Comparison with Upper Midwest USA results[23].

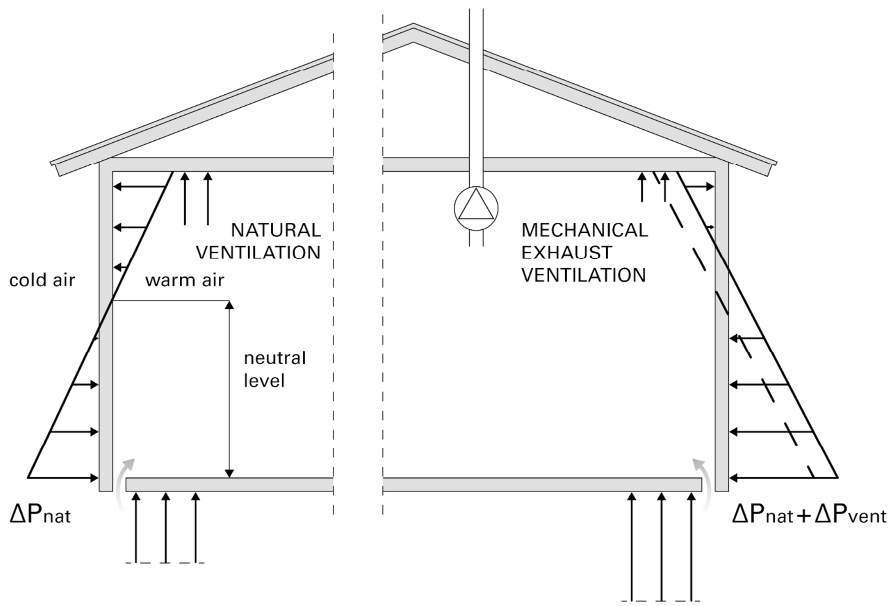
House type Storeys Comparison type	*N*	Mean	Gmean	Gsd	Percentiles.		Range		COV %
					5%	95%	Min	Max	
Finland									
Slab-on-ground, 1 storey Room 1/ Room 2	2241	1.04	0.99	1.38	0.63	1.55	0.05	11.2	14.4
Slab-on-ground, 2 storey First floor/ground floor	421	0.91	0.84	1.54	0.45	1.47	0.04	5.6	19.8
Semi-basement 1 storey above basement First floor/basement	249	0.82	0.67	1.85	0.22	1.58	0.08	11.6	34.0
USA									
First floor/basement	208		0.54	1.78					

Figure 1 Pressure differences created by the stack effect ΔP_{nat} and forced exhaust ventilation ΔP_{vent}. The arrows describe the pressure difference and direction of air flow. The curved arrows indicate the flow of radon-bearing soil air.

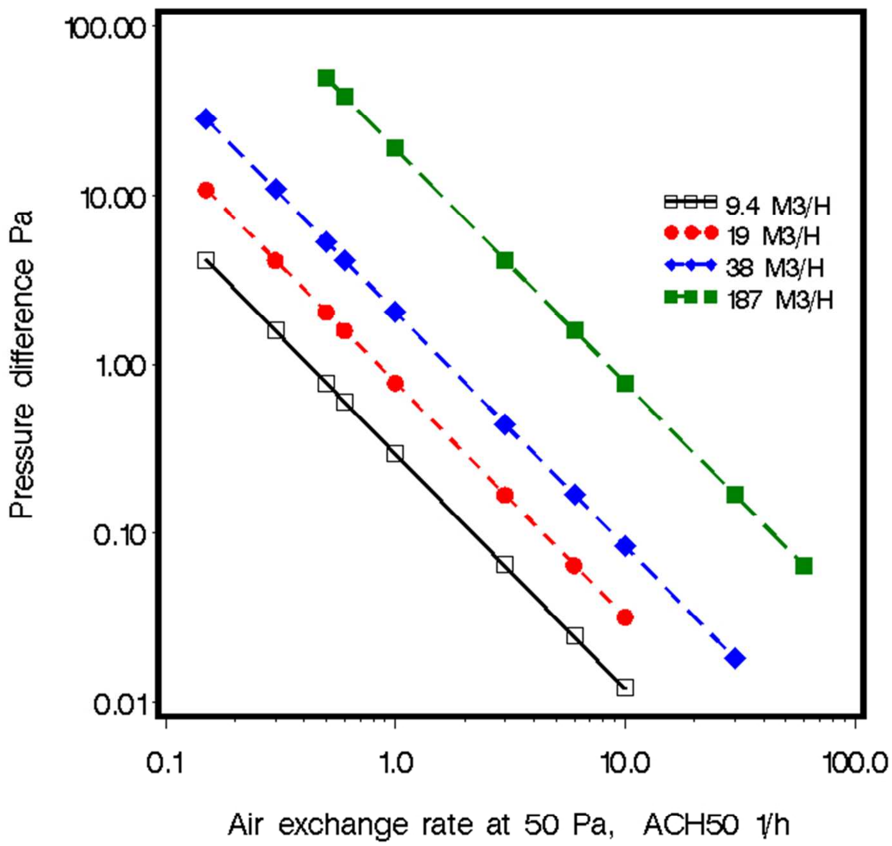
Figure 2 Pressure difference vs. air tightness expressed as ACH_{50}, the air exchange rate at a pressure difference of 50 Pa. The air flow rates of 9.4, 19 and 38 m^3/h represent 5%, 10% and 20% lower supply air flows compared with an exhaust air flow of 187 m^3/h in a house with a volume of 375 m^3 and mechanical supply and exhaust ventilation. The flow rate of 187 m^3/h represents a similar house with exhaust ventilation. Calculations were performed for a standard house with a height of 2.5 m and a floor area of 150 m^2.

Figure 3 Distribution of the ACH_{50} leakage factor in newly built wooden-frame detached houses (1995–2005, n = 79) and apartments with concrete structures (2001–2003, n = 40) [7, 8]. The upper limit of the ACH_{50} categories is presented.

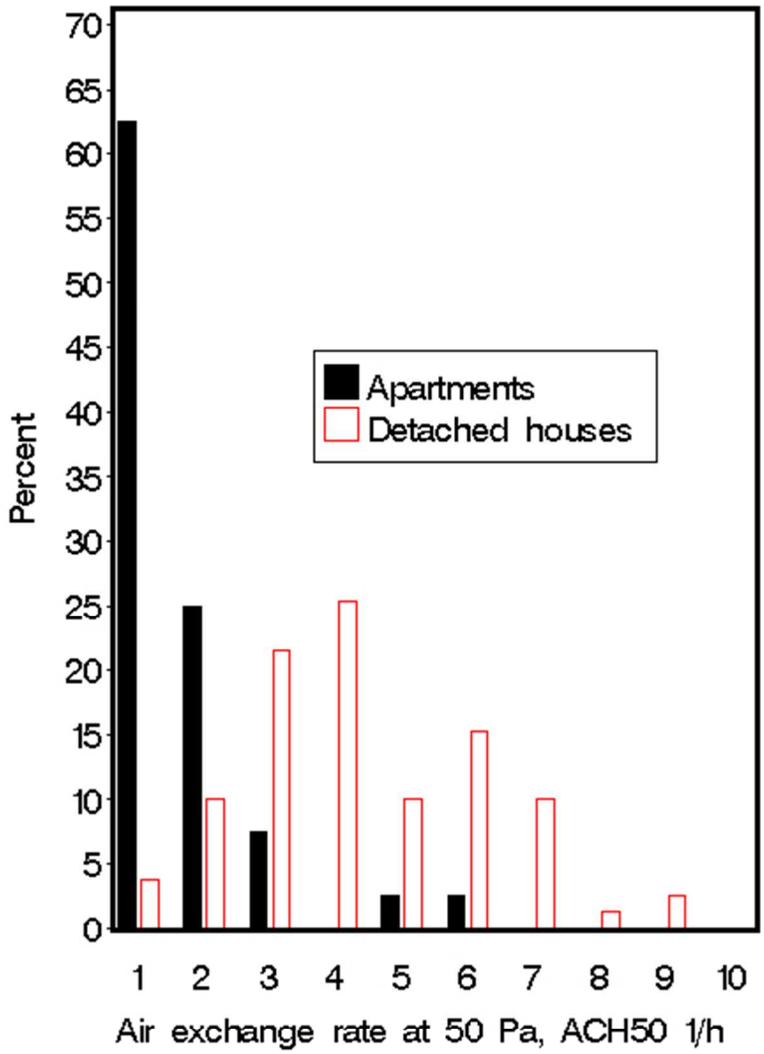
Figure 4 Prevalence of ventilation strategies in Finnish low-rise residential buildings. Source: National random sample surveys[17, 21].



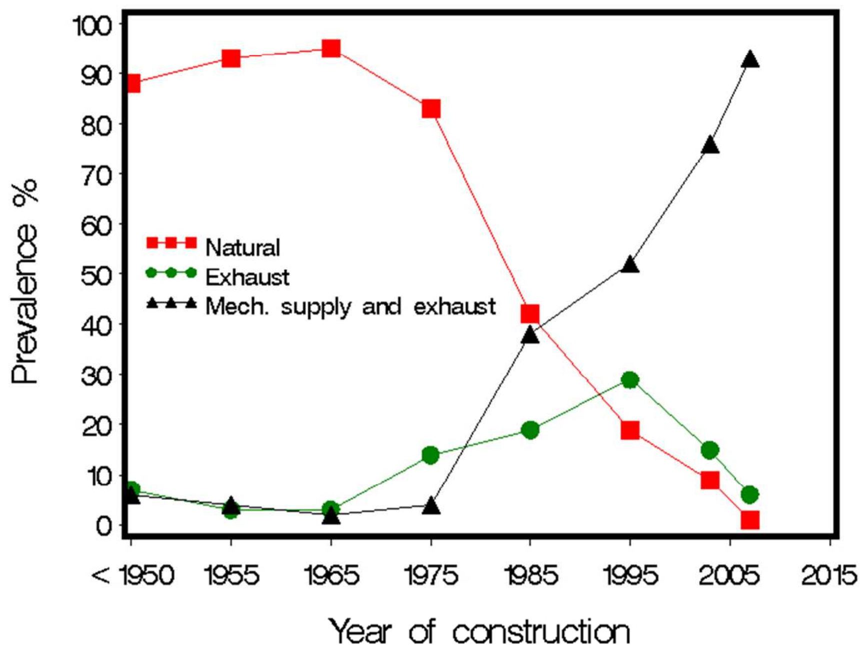
Pressure differences created by the stack effect ΔP_{nat} and forced exhaust ventilation ΔP_{vent}. The arrows describe the pressure difference and direction of air flow. The curved arrows indicate the flow of radon-bearing soil air.
185x121mm (300 x 300 DPI)



Pressure difference vs. air tightness expressed as ACH^{50}, the air exchange rate at a pressure difference of 50 Pa. The air flow rates of 9.4, 19 and 38 m^3/h represent 5%, 10% and 20% lower supply air flows compared with an exhaust air flow of 187 m^3/h in a house with a volume of 375 m^3 and mechanical supply and exhaust ventilation. The flow rate of 187 m^3/h represents a similar house with exhaust ventilation. Calculations were performed for a standard house with a height of 2.5 m and a floor area of 150 m^2.
266x266mm (72 x 72 DPI)



Distribution of the ACH_{50} leakage factor in newly built wooden-frame detached houses (1995–2005, n = 79) and apartments with concrete structures (2001–2003, n = 40)[7, 8]. The upper limit of the ACH_{50} categories is presented.
200x226mm (72 x 72 DPI)



Prevalence of ventilation strategies in Finnish low-rise residential buildings. Source: National random sample surveys(17, 21).
282x211mm (72 x 72 DPI)