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The performance of ventilation systems and indoor climate in residences

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THE PERFORMANCE OF VENTILATION SYSTEMS AND INDOOR CLIMATE IN RESIDENCES

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1 Background

The ventilation in residendial buildings has a significant effect on the health and comfort of the people and on the energy consumption of residences. The importance of adequate ventilation is recognized by medical doctors. On the other hand, ventilation is responsible for approximately 40 % of the total energy consumption in Finnish buildings. Very little is, however,known about the actual magnitude of ventilation in buildings. Ventilation systems are often criticized for their poor performance. Natural ventilation has been said to give too low and unsteady ventilation rates. Mechanical ventilation has been accused of introducing draught, noise and dust, just to mention a few disadvantages, to the occupancy zone. The criticism has usually been based on several stray remarks rather than on scientific research. The objective of this research was to gather information about the actual ventilation and indoor air quality in Finnish residences. The performance of various ventilation systems was studied. The latest field monitoring techniques were used to gain this information.

2 Field measurement techniques

2.1 Measuring the ventilation parameters

The ventilation parameters in buildings were measured using two tracer gas techniques. The tracer decay technique was used to measure the instantaneous air-exchange efficiency and the nominal time constant. The passive perfluorocarbon technique (PFT-technique) was used to measure the average turn over time of contaminants over a two week period. The measurement principles and procedures are discussed in the following.

Measuring the air-exchange efficiency. The instantaneous air-exchange efficiencies were measured using a tracer decay technique. Refridgerant 12 (CCl_2F_2) was used as the tracer gas and the analysis was made in situ with an infrared analyzer. In the beginning of the measurement the tracer gas was spread over the dwelling. Mixing fans were used to achieve complete mixing. The concentration of the tracer gas was measured at 11 points in the dwelling. One channel was used to monitor the outdoor air concentration in order to allow for the drift of the analyzer. The ventilation system was operated at the same power as that normally used. All windows were closed during the 2-4 hour measurement period. The air-exchange efficiencies and nominal time constants were calculated from the measurements. The instantaneous nominal time constant measured in this manner is in most cases close to the minimum ventilation value .

Measuring the average ventilation over a two-week period. The average turn over time of contaminants was measured using the PFT- technique. The PFT-technique is an integrating constant tracer flow technique. Miniature permeation tubes are used to create the constant injection of up to three different perfluorocarbon tracer gases. An integrating adsorption sampler measures the average concentration of each tracer. The samplers are analysed in a laboratory using an ECD gaschromatograph. A more detailed description of the PFT-technique is presented in references (1) and (2). The quantity that describes the performance of the ventilation system with temporally varying air flows is the age of contaminants in the exhaust, the turn over time (3). The turn over time is directly related to the human respiratory exposure to indoor air pollutants and can thus be used in examining the effects of ventilation on the health of the people living in the house. If the air flow rates are constant with time and there is uniform and instantaneous internal mixing in the system, the turn over time is equal to the nominal time–constant (1).

2.2 Measuring the temperature and humidity

The temperature and humidity of the indoor air were measured and recorded by the occupants. Calibrated instruments were given to each dwelling. A standard thermometer, which had a scale from 0^oC to 40^oC at 1^oC intervals, was used. The relative humidity was measured with a hair hygrometer, scale from 0% to 100 % relative humidity at 1% intervals. The instruments were placed in the master bedroom. The measurements were made twice a day, in the morning and in the evening.

2.3 Measuring the contaminants

Measuring the contaminants included the measurement of dust and radon concentrations. The measurement period was the same two weeks as for the ventilation, temperature and humidity measurements. The field measurement instruments are shown in figure 1.

Measuring the dust concentration. Dust concentrations in the dwellings were measured using the deposition method. In the deposition method a sample is collected passively as the airborne dust particles settle on the greasy surface of the collector. This technique measures dust particles of all sizes . The dust collector was placed horizontally in the master bedroom, approximately 1.4 m from the floor. Dust concentrations equivalent of 100 hour exposition were calculated.

Measuring the radon concentration. Radon concentrations in the dwellings were measured using passive integrating solid state nuclear track detectors. Two detectors were placed in the dwelling, one in the master bedroom and one in the living room.

3 The residences studied

3.1 Field measurements during the 1987-1988 heating season

The field measurements were made in 49 typical Finnish residences during the 1987-1988 heating season. The house types and ventilation systems of the dwellings studied are presented in table 1. The following measurements were carried out in these

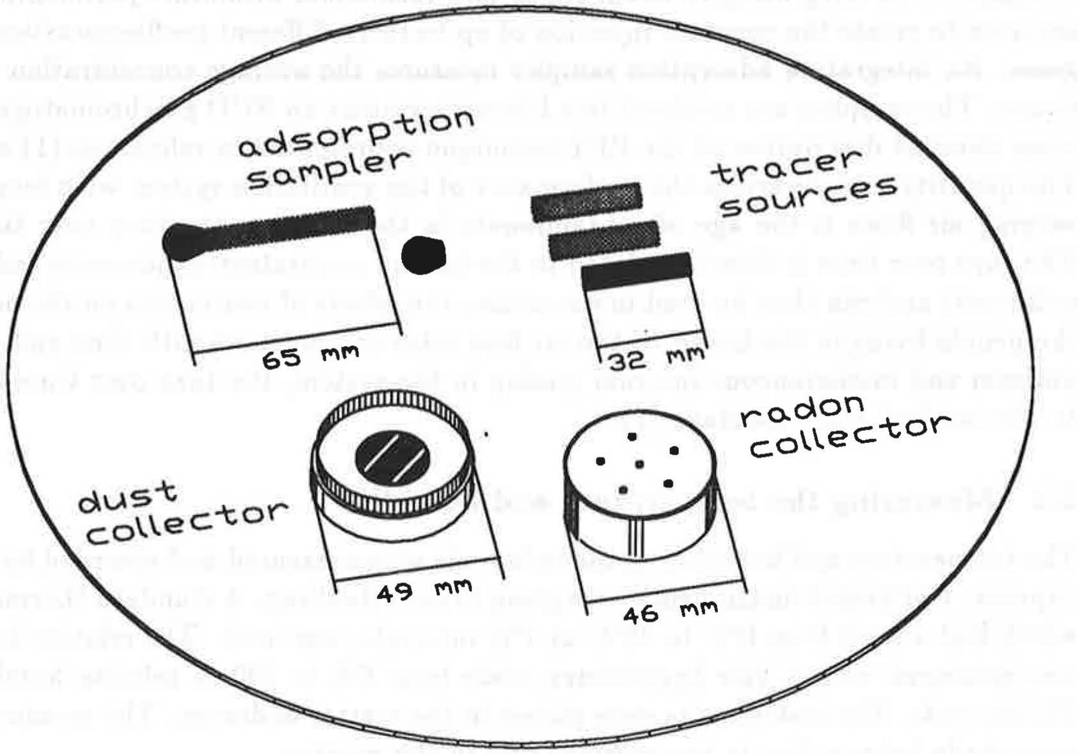

Fig. 1: Field measurement instruments.

Table 1: The residences studied during 1987-1988 heating season

	natural ventilation	mechanical exhaust	balanced ventilation	total
single family	8	9	10	29
block of flats	7	8	7	22
total	15	18	17	49

Table 2: The residences studied during 1988-1989

	natural ventilation	mechanical exhaust	balanced ventilation	total
single family	58	61	43	162
block of flats	20	47	22	89
total	78	108	65	251

dwellings:

- The temperature and humidity of the bedroom (two-week follow-up in November, January and April).
- The dust concentration (simultaneously with temperature and humidity measurements).
- The air exchange efficiency (one day between November and May)
- The average turn over time with the PFT-technique (simultaneously with the follow-up measurements in January and April)

In the PFT-measurements the dwellings were divided into zones according to the following principles:

- different floors are different zones
- the sauna section, the door of which is closed most of the time, is one zone
- the master bedroom, the door of which is closed during the night, is one zone

The instructions given by Brookhaven National Laboratory (4) were applied in the placement of sources and samplers.

3.2 Field measurements during the 1988-1989 heating season

The field measurements were made in 251 typical Finnish residences during the 1988-1989 heating season. The house types and ventilation systems of the studied dwellings are presented in table 2. The following measurements were carried out in these dwellings:

- The temperature and humidity of the bedroom (a measurement period of two weeks between November and April).
- The dust and radon concentration (simultaneously with temperature and humidity measurements).
- The average turn over time with the PFT-technique (simultaneously with the other measurements)

In the PFT-measurements the dwellings were divided into zones according to the same principles as during 1987-1988.

Table 3: The air-exchange efficiencies in the 49 homes measured during the 1987-1988 heating season

	natural ventilation	mechanical exhaust	balanced ventilation
Interval (%)	35–53	33–53	41–53
Avarage (%)	45	43	48
Std. (%)	5	6	4

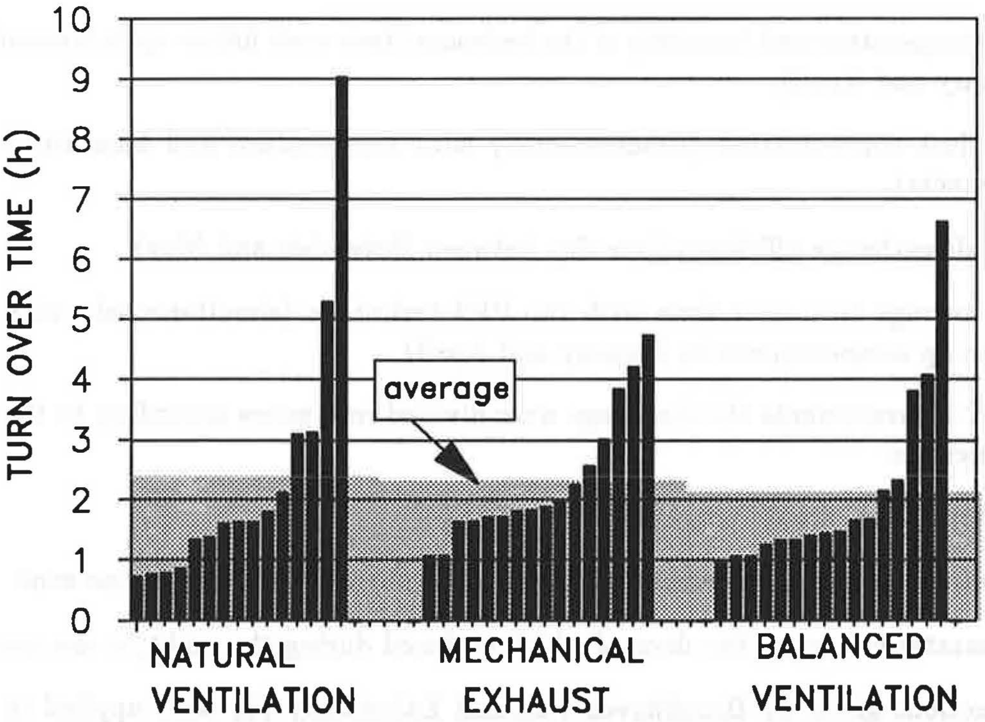

Fig. 2: The average turn over times in 49 dwellings, April 1988.

4 Results

4.1 Performance of the ventilation systems

The air-exchange efficiency. The air-exchange efficiencies were measured in 49 homes during the 1987-1988 heating season. The results of the measurements are presented in table 3.

All the systems were mixing systems. For balanced ventilation systems the air exchange efficiencies were close on 50%, but some short circuiting cases existed. Lower air exchange efficiencies were more common in the natural ventilation and mechanical exhaust systems. These figures are in good agreement with earlier measurements in Finnish homes (5).

Average turn over times. The measured average turn over times are presented in tables 4-5 and figures 2-3.

It can be seen from the results that the average turn over time in block of flats is close to the recommended value 2.0 *h* (actually this value is the inverse of the air

Table 4: The average turn over times and their relative standard deviations

		Natural ventilation	Mechanical exhaust	Balanced ventilation
49 dwellings, 4/88	Avg. (h)	2.35	2.32	2.11
	Rsd. (h)	2.13	1.05	1.46
242 dwell.,11/88–4/89	Avg. (h)	3.21	2.53	2.55
	Rsd. (h)	2.48	1.64	1.66

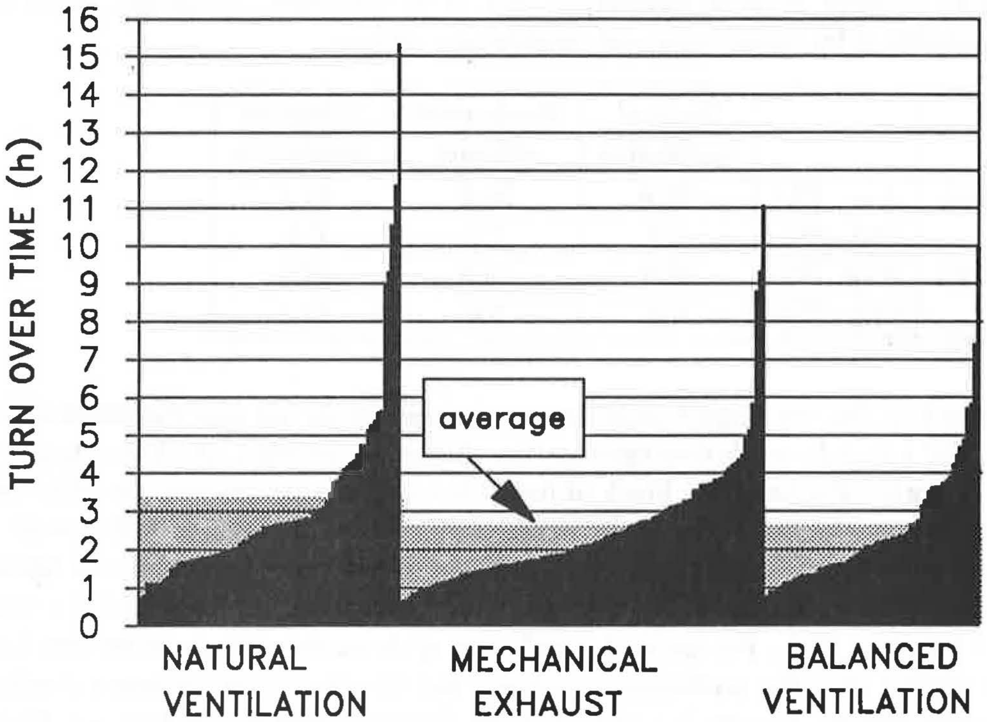

Fig. 3: The average turn over times in 242 dwellings,November 1988-April 1989.

Table 5: The average turn over times and their standard deviations in 49+242 dwellings, tabulated by house type and ventilation system.

		Natural ventilation	Mechanical exhaust	Balanced ventilation	All systems
single family	Avg. (h)	3.39	2.84	2.78	3.02
	Std. (h)	2.52	1.67	1.81	2.06
block of flats	Avg. (h)	2.31	2.09	1.86	2.09
	Std. (h)	2.09	1.36	0.96	1.51
All dwellings	Avg. (h)	3.07	2.51	2.46	2.67
	Std. (h)	2.45	1.58	1.63	1.93

Table 6: The average temperatures and their standard deviations in 49+251 dwellings, tabulated by house type and ventilation system.

		Natural ventilation	Mechanical exhaust	Balanced ventilation
single family	Avg. (°C)	21.8	21.7	21.4
	Std. (°C)	1.3	1.5	1.4
block of flats	Avg. (°C)	22.3	22.2	22.6
	Std. (°C)	1.7	1.2	1.1

Table 7: The average relative humidities and their standard deviations in 49+251 dwellings, tabulated by house type and ventilation system.

		Natural ventilation	Mechanical exhaust	Balanced ventilation
single family	Avg. (%)	37.9	36.8	35.5
	Std. (%)	6.7	7.2	6.9
block of flats	Avg. (%)	32.7	35.8	34.6
	Std. (%)	5.9	6.4	13.1

exchange rate $0.5\,1/h$). In single family homes the ages of the air and the contaminants are higher. For natural ventilation systems the difference between the house types can be caused by higher stacks in the block of flats. For mechanical systems the differences are probably due to irregular use of the ventilation system in single family homes.

Comparison of the different ventilation systems shows that the deviations between dwellings are lowest for balanced ventilation. The differences from mechanical exhaust systems are not very high. For natural ventilation systems the average turn over times are slightly higher than for mechanical systems, but the deviations between dwellings are significantly higher. Figures 2-3 show, that the lowest ventilation values (the highest turn over times) appear in natural ventilation systems. On the other hand,there were also some very low turn over times among the natural ventilation systems.

4.2 The indoor climate in residences

Temperature and relative humidity. The average temperatures and their standard deviations are presented in table 6. The variations are quite small within various ventilation systems. The temperatures are slightly higher in the block of flats than in single family homes. On average the temperature in the bedroom was approximately 22 $°C$. The variations in the indoor temperature were small.

The average relative humidities and their standard deviations are presented in table 7. The winter-time humidities are on average approximately 35 %, which is a quite satisfactory level. The variations between the ventilation systems were low.

Dust concentration. The average dust concentrations and their standard deviations are presented in table 8. The average dust concentrations were approximately 16 μg, but the standard deviations were quite high. Figure 4 shows that the average

Table 8: The average dust concentrations and their standard deviations in 49+229 dwellings, tabulated by house type and ventilation system.

		Natural ventilation	Mechanical exhaust	Balanced ventilation
single family	Avg. (μg)	16.0	16.9	19.9
	Rsd. (μg)	11.9	11.2	14.5
block of flats	Avg. (μg)	13.7	16.5	22.7
	Rsd. (μg)	8.3	13.3	11.7

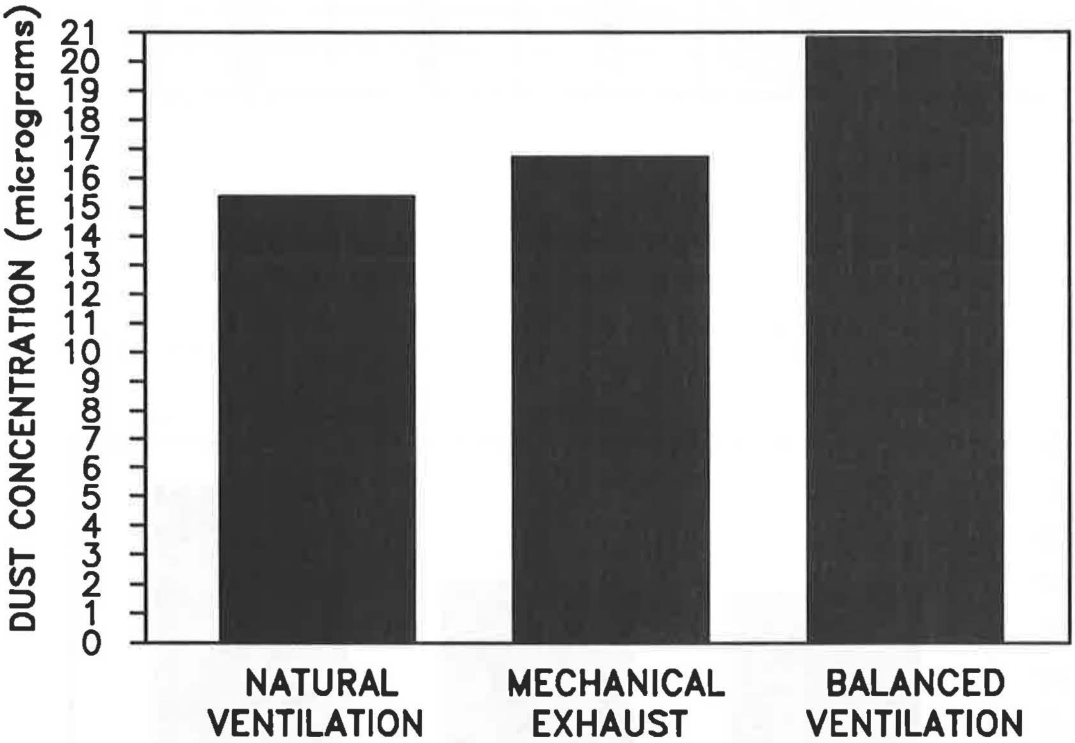

Fig. 4: Dust concentrations in various ventilation systems

dust concentrations in balanced ventilation systems were higher than in other systems. This may be due to the fact that supply jets induce settled dust from surfaces to the air.

Radon concentration. The radon concentrations in various ventilation systems are presented in table 9 and figure 5. On average the radon concentrations are low, approximately 105 Bq/m^3, which is well below the Finnish action level of 800 Bq/m^3 for old dwellings. Only few houses exceeded the action level, maximum value being 866 Bq/m^3. The mean indoor radon concentration in the Helsinki area is lower than the mean level in Finnish houses. The concentrations in single family dwellings were higher than in block of flats. This, as well as the differences between various ventilation systems, can be explained by variations in the radon influx from the ground, the radon diffused from building materials and the operation of the ventilation system. The analysis of these factors is currently going on at the Finnish Centre for Radiation and Nuclear Safety.

Table 9: The average radon concentrations and their standard deviations in 251 dwellings, tabulated by house type and ventilation system.

		Natural ventilation	Mechanical exhaust	Balanced ventilation
single family	Avg. (Bq/m^3)	115	128	153
	Std. (Bq/m^3)	140	99	170
block of flats	Avg. (Bq/m^3)	62	66	64
	Std. (Bq/m^3)	47	41	29

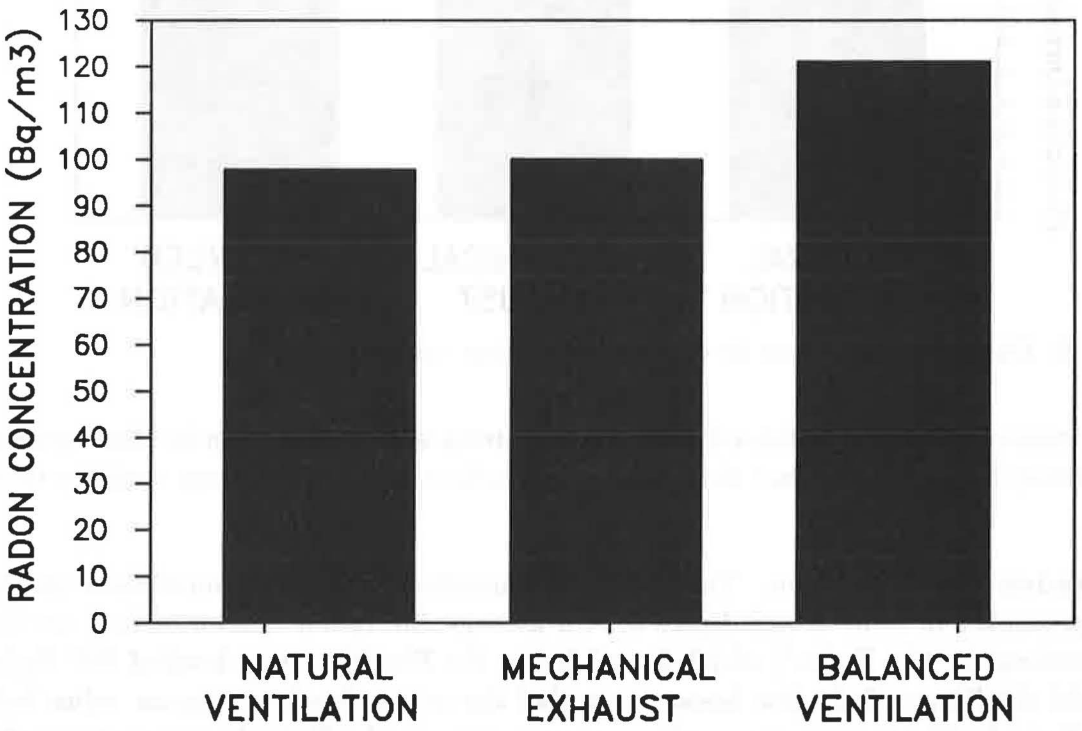

Fig. 5: Radon concentrations in various ventilation systems

5 Discussion

The average turn over time in the block of flats was close to the recommended value of 2.0 h. In single family homes the ages of the air and the contaminants were higher. Comparison of the different ventilation systems showed that the deviations between dwellings were lowest for balanced ventilation. For natural ventilation systems the average turn over times were slightly higher than for mechanical systems, but the deviations between dwellings were significantly higher. The lowest ventilation values appeared in natural ventilation systems. On the other hand,there were also some very low turn over times among the natural ventilation systems.

On average the temperature in the bedroom was approximately 22 ^oC. The variations in the indoor temperature were small. The temperatures were slightly higher in the block of flats than in single family homes. The winter-time humidities were on average approximately 35 %. The variations between ventilation systems were low.

The average dust concentrations were approximately 16 μg, but the standard deviations were quite high. The average dust concentrations in the balanced ventilation systems were higher than in other systems. On average the radon concentrations were low, approximately 105 Bq/m^3, which is well below the Finnish norm value of 800 Bq/m^3 for old dwellings.

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Summary

The ventilation in residendial buildings has a significant effect on the health and comfort of the people and on the energy consumption of residences. Very little is known about the actual magnitude of ventilation in buildings. On the other hand, ventilation systems are often criticized for their poor performance. The objective of this research was to gather information about the actual ventilation and indoor air quality in Finnish residences. The performance of various ventilation systems was also studied.

It was found out that the average turn over time in the block of flats was close to the recommedation value of 2.0 *h*. In single family homes the ages of the air and the contaminants were higher. Comparison of the different ventilation system showed that the deviations between dwellings were lowest for balanced ventilation. For natural ventilation systems the average turn over times were slightly higher than for mechanical systems, but the deviations between dwellings were significantly higher. On average the temperature in the bedroom was approximately 22 ^oC. The winter-time humidities were on average approximately 35 %. The average dust concentrations were approximately 16 μg, but the standard deviations were quite high. The average dust concentrations in the balanced ventilation systems were higher than in other systems. On average the radon concentrations were low, approximately 105 Bq/m^3, which is well below the Finnish norm value of 800 Bq/m^3 for old dwellings.

APPENDIX A

MEASURING THE AIR-EXCHANGE EFFICIENCY.

The air-exchange efficiency

The air-exchange efficiency (ε_a) is defined as follows:

$$\varepsilon_a = \frac{\tau_n}{2* < \tau >} \tag{1}$$

where τ_n is the nominal time constant and $< \tau >$ is the mean age of air. In a house with multiple exhausts the nominal time constant is calculated by weighing the local ages of air in the exhausts (τ_p) with the air flows:

$$\tau_n = \frac{\sum_1^k Q_k * \tau_{pk}}{\sum_1^k Q_k} \tag{2}$$

The mean age of air is the average of local ages of air:

$$< \tau >= \frac{\sum_1^k \tau_{pk}}{k} \tag{3}$$

The local age of air in each measurement point (room or exhaust) was calculated from the area under the concentration decay curve:

$$\tau_p = \frac{\int_0^\infty C_p dt}{C(0)} \tag{4}$$

where C_p is the concentration at point p and $C(0)$ is the initial concentration.

The principle of the measurement

Refridgerant 12 (CCl_2F_2) was used as the tracer gas and the analysis was made in situ with an infrared analyzer. In the beginning of the measurement the tracer gas was spread over the dwelling in order to achieve initial concentration $C(0)$. Two mixing fans were used to achieve complete mixing. The concentration of the tracer gas was measured at 11 points in the dwelling. A channel was used for each exhaust. The local age of air in each exhaust was calculated from these measurements. One channel was used to monitor the outdoor air concentration in order to allow for the drift of the analyzer. The rest of the channels were placed in the middle of the rooms. The local age of air in each room was calculated from these measurements. The ventilation system was operated at the same power as that normally used. All windows were closed during the 2-4 hour measurement period. The air flows in the exhausts were measured using a calibrated thermoanemometer.