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Improved Ventilation Combined with Energy Efficiency in Naturally Ventilated Houses.

A. Blomsterberg

Swedish National Testing and Research Institute,
Box 857, S-501 15 Borås, Sweden.

SYNOPSIS

Modern one-family houses in Scandinavia built before 1980 are often naturally ventilated and heated by electric baseboard heaters. The overall supply of fresh air is often inadequate during the heating season in many of these houses. Long periods of time individual rooms might get too little fresh air. The performance of a natural ventilation system is very much dependant upon the overall airtightness and the distribution of the airtightness of the building and the weather.

This paper examines the performance of six modern one-family houses before and after the ventilation system was improved. Different means of improving ventilation are described. The constant concentration tracer gas technique was used to examine the supply of fresh air. Fan pressurization combined with infrared photography were employed to characterize the air leakage of the building. A simplified theoretical model was used to further evaluate the measurements.

It is obvious from the tested houses that the overall ventilation and the ventilation of individual rooms were improved. The ventilation losses were increased and therefore energy conserving measures had to be taken. The overall costs were high compared with the energy savings obtained.

LIST OF SYMBOLS

ach = air changes per hour

1. INTRODUCTION

In Sweden there are close to 500000 one-family houses heated by electric baseboard heaters. Of them 90 % were built before 1980. In this group the most common ventilation system is natural ventilation. Half of all houses with electric baseboard heaters were built between 1971 and 1980.

The Swedish Council for Building Research has been asked by the Swedish government to carry out a program concerning the efficient use of electricity in buildings. Consequently one-family houses with electric baseboard heaters and with a high consumption of electricity are an area where research and development and demonstration projects are needed.

Making the use of electricity efficient in one-family houses with electric heating includes measures to reduce the consumption and to reduce the power demand. In one project, which is carried out in four different cities (Umeå, Stockholm, Göteborg and Lund), 37 one-family houses have been investigated.

The object of the project is to show how electrically heated one-family houses can use electricty more efficiently employing existing techniques. The indoor climate is to be kept at the same level or improved. An important aspect of indoor climate is ventilation, which was an important part of the investigation in Lund. This paper deals with the investigation in Lund, which included six houses .

2. THE HOUSES TESTED

Two types of houses were studied, a 1½ storey detached one-family house and a one storey detached one-family house. Both types are very common in Sweden. The 1½ storey house is part of a group of 100 identical houses built in 1974. The houses are 140 m^2, with a kitchen, laundry, bathroom, living room, bedroom downstairs and three bedrooms and a bathroom upstairs. A detached non-heated storage also belongs to the house. The one storey house is part of a group of 120 identical houses built in 1974. The houses are 121 m^2, with a kitchen, laundry, bathroom, living room and 3 - 4 bedrooms.

The 1½ and the one storey houses are built on a slab on grade. Space heating is provided by electric baseboard heaters and an electric heating cable (1 kW) inside the slab along the perimeter of the house. The exterior walls are of traditional wood frame construction with 120 mm of mineral wool. The attic insulation consists of 150 mm of mineral wool. The windows have double panes. The window area is large, 28 % of the floor area. The houses are naturally ventilated with vertical shafts from bathrooms, kitchen and laundry. There are no supply vents for outdoor air.

3. TEST METHODS

3.1 AIRTIGHTNESS

The standard method for finding the leakage function of a building is fan pressurization. The estimated inaccuracy in the measured air leakage is ± 10 %. According to the Swedish standard for fan pressurization all openings in the exterior envelope intended for ventilation purposes must be sealed before the test is performed. Other openings are kept closed. For the purpose of modelling air infiltration and exfiltration it is advantageous to also make a test with open supply vents part of an exhaust fan ventilation system and with open vertical shafts part of a natural ventilation system.

3.2 VENTILATION

The most straightforward method of measuring the total ventilation rate i.e. the combined effect of mechanical ventilation and natural ventilation is to measure it directly (Blomsterberg 1990). In a mechanical ventilation system the air flow in the ducts can be measured with different techniques for volume and mass flow rate measurements. There are many ways of measuring total ventilation, and almost all of them involve a tracer gas, which permits the indoor air to be labelled so that the outdoor air ventilation can be traced.

The tracer gas is injected into and mixed with the indoor air and its concentration is monitored. The mixing is assumed to be complete, which is probably the largest single source of error in tracer gas measurements. There are three different schemes; decay, constant concentration, and constant flow of a tracer gas. All measurements are governed by the continuity equation. The single-chamber continuity equation is given here:

$$V\, dC/dt + Q\, C = F$$

where V is the effective volume, m^3
dC/dt is the time rate of change of concentration
Q is the outdoor air ventilation rate, m^3/s
C is the concentration and
F is the effective injected tracer gas flow rate, m^3/s

In the two houses tested a constant concentration of tracer gas was maintained in order to measure the ventilation rate. One of the principle advantages with this technique is that it eliminates the problem of estimating the effective volume as the effective volume is eliminated from the continuity equation (dC/dt = 0). The outdoor air ventilation is obtained directly. The field of application for the constant concentration technique is to continuously monitor the supply of outdoor air to several individual rooms simultaneously, i.e. outdoor air which enters an individual room directly instead of first passing through an adjacent room. The estimated inaccuracy in the measured outdoor air ventilation rate is ± 10 %.

4. RESULTS AND DISCUSSION - BEFORE RECONSTRUCTION

In all six houses the airtightness has been tested before reconstruction. When these houses were built there was no official requirement on airtightness. All houses were pressurized and depressurized with open and closed vertical shafts (see table 1).

Table 1. Measured airtightness at 50 Pa, ach.

House	closed shafts	open shafts
# 1, 1 storey	2,5	4,4
# 2, 1 storey	2,9	5,3
# 3, 1 storey	2,9	4,5
# 4, 1½ storey	4,1	5,4
# 5, 1½ storey	3,7	5,3
# 6, 1½ storey	4,7	5,8

All houses have a good level of airtightness, the one-storey houses even meet today´s requirement. The 1½ storey houses are leakier, generally due to the fact that it is difficult to achieve a good airtightness in the joints between ceiling and wall upstairs and the joint between the intermediate floor and exterior walls. This is in particular valid for a house without a continuous plastic air/vapour barrier.

Tracer gas measurements using the constant concentration technique were performed in two houses, # 1 and # 4. House # 1 had a total outdoor air ventilation rate of 48 m^3/h (0.16 ach) during a measuring period of 6 hours (see table 2 for individual rooms).

Table 2. Measured outdoor air ventilation for individual rooms in house # 1, m³/h. The wind speed at a height of 10 m was 0.7 m/s and the outdoor air temperature was 6 °C.

Bedroom 1	7
Bedroom 2	26
Bedroom 3	3
Kitchen/living room	1
Study	1
Bathroom	10
Laundry	0
Hallway	0
Total	48

House # 4 had a total outdoor air ventilation rate of 71 m³/h (0.21 ach) during a measuring period of 3 hours (see table 3 for individual rooms).

Table 3. Measured outdoor air ventilation for individual rooms in house # 4, m³/h. The wind speed at a height of 10 m was 1.4 m/s and the outdoor air temperature was 9 °C.

Laundry	46
Kitchen	13
Bedroom	2
Living room	6
Bedroom upstairs	0
Bedroom upstairs	0
Living room upstairs	0
Bedroom upstairs	0
Bathroom upstairs	4
Total	71

Both tested houses have an inadequate ventilation. Some individual rooms hardly receive any outdoor air at all. The outdoor air ventilation will probably be higher if it is windier. The wind direction decides which rooms will receive outdoor air in a leaky house. The outdoor air ventilation rate will also be higher if the outdoor air temperature is lower than during the measurements i.e. more representative for a winter.

Low ventilation rates have been reported from many dwellings. Measurements of ventilation rates have been carried out in connection with energy analysis of buildings and with analysis of sick buildings. The Swedish Institue for Building Research has recorded measurements of ventilation rates in 900 dwellings (see table 4) (Lyberg 1989). The houses were not randomly sampled. The results are not statistically relevant. All values are from short term measurements and are not valid for an entire year. Most of the measurements were made with the tracer decay technique and can therefore have an inaccuracy of ± 30 %.

The ventilation rate in naturally ventilated one-family houses tend to be lower the newer the house is. One-family houses built after 1972 have an average ventilation rate of 0.26 ach, which is half of the stipulated value of 0.5 ach. Houses with mechanic ventilation have a satisfying average ventilation. The variation between individual houses is, however, considerable.

Table 4. Measured ventilation rates in 900 dwellings (recorded by the Swedish Institue for Building Research).

Type of dwelling	Ventilation system	ach
Mechanical ventilation		
Apartment	Exhaust fan	0.63 ±0.23
One-family house	Exhaust fan	0.48 ±0.18
Mixed	Balanced	0.64 ±0.17
Natural ventilation		
Apartments		
built before 1940		0.62 ±0.22
built 1940-1960		0.55 ±0.27
built after 1960		0.33 ±0.13
One-family house		
built before 1960		0.45 ±0.29
built 1960-1971		0.38 ±0.20
built after 1971		0.26 ±0.14

Previous investigations carried out by the Swedish National Testing and Research Institute show that the ventilation rate can be low not only for entire one-family houses, but even lower for individual rooms. This is especially true for naturally ventilated houses, but also true for exhaust fan ventilated houses.

In order to determine the ventilation rate during the heating season calculations were made using the LBL-modell (Blomsterberg 1990). The calculations were first made for the tracer gas measuring periods (see table 5). The agreement between modell and measurement is reasonable for a winter day with mild weather.

Table 5. Calculated (LBL-modell) ventilation rates vs measured ventilation rates.

	House # 1	House # 4
Ceiling leakage arera, cm^2	80	200
Floor leakage area, cm^2	0	0
Total leakage area, cm^2	170	400
Vertical shaft leakage area, cm^2	80	30
Wind speed, m/s	0.7	1.4
Outdoor temperature, °C	6	9
Calculated ventilation, m^3/h (ach)	38 (0.12)	80 (0.23)
Measured ventilation, m^3/h (ach)	48 (0.16)	71 (0.21)

Estimates for a heating season during a reference year give a ventilation rate of 57 m^3/h (0.19 ach) for house # 1 and 126 m^3/h (0.37 ach) for house # 4.

The houses are not airtight enough for a balanced ventilation system. The installed exhaust air heat pump delivers heat to domestic hot water and to two centrally located radiators.

The main improvement to the building envelope was new windows. The old double-pane windows (U = 2.5 W/ m² °C) were exchanged for new quadruple-pane windows (U = 1.0 W/ m² °C).

6. RESULTS AND DISCUSSION - AFTER RECONSTRUCTION

After reconstruction all houses were pressurized and depressurized again. This time it was done with open and closed supply vents (see table 6).

Table 6. Measured airtightness at 50 Pa, ach, before and after reconstruction.

House	closed vents		open vents	
	before	after	before	after
# 1, 1 storey	2,5	2,1	4,4	2,9
# 2, 1 storey	2,9	2,4	5,3	3,0
# 3, 1 storey	2,9	2,4	4,5	3,1
# 4, 1½ storey	4,1	5,9	5,4	6,7
# 5, 1½ storey	3,7	3,8	5,3	4,6
# 6, 1½ storey	4,7	4,6	5,8	5,4

The 1-storey houses met today´s requirement before and have become even airtighter, mainly due to new windows. Two of the 1½-storey houses have unchanged airtightness and the third has become leakier. The window areas have become airtighter for the same reason as for the 1-storey houses, but more new penetrations for heating and ventilation have worked against this improvement.

Tracer gas measurements using the constant concentration technique were performed in two houses, # 1 and # 4. House # 1 had a total outdoor air ventilation rate of 52 m³/h (0.17 ach) before and 151 m³/h (0.50 ach) after reconstruction (see table 7 for individual rooms).

Table 7. Measured outdoor air ventilation for individual rooms in house # 1 before and after reconstruction, m³/h.

	Before	After
Outdoor temperature, °C	6	6
Wind speed, m/s	0.7	4
Bedroom 1	7	20
Bedroom 2	26	12
Bedroom 3	3	10
Kitchen/living room	1	42
Study	1	25
Bathroom	10	9
Laundry	0	26
Hallway	0	7
Total	48	151

5. DIFFERENT MEANS OF IMPROVING NATURAL VENTILATION

The aim is to improve the air exhange in individual rooms and the whole house. A ventilation system should be able to provide outdoor air to the whole house.

Swedish one-family houses built during the seventies with natural ventilation are often reasonably airtight, although they usually do not meet the Swedish Building Code requirement for 3.0 ach at 50 Pa. This means that the ventilation rate (excl. airing) most of the time is too low i.e. below 0,5 ach. Individual rooms, especially with doors closed, can have a very low ventilation rate. One improvement would be to to install temperature controlled supply vents in the exterior walls. The maximum opening area of these vents has to be large enough compared with the leakage area of the building envelope. The advantages would be a less varying ventilation rate and a better distribution of outdoor air between individual rooms. The disadvantages would be sligthly raised overall ventilation energy losses due to somewhat increased ventilation and no possibility for heat recovery.

Another alternative of improving natural ventilation is to install supply vents in the exterior walls and a temperature controlled fan in the vertical shafts . When it is cold outside the fan will not run and the ventilation will be all natural. During warm and mild periods, when the stack effect is insufficient, the fan will increase the ventilation rate. The advantages would be a raised and more constant ventilation rate and a better distribution of outdoor air between individual rooms. The disadvantages would be raised ventilation energy losses due to increased ventilation and no possibility for heat recovery.

Sofar the suggestions have meant improving on the existing systems for natural ventilation. Another option is to install a completely new ventilation system i.e. mechanical balanced ventilation or exhaust only. A balanced ventilation system should only be installed in a very tight building (Blomsterberg 1990). The advantages would be a raised and constant ventilation rate, a controlled distribution of outdoor air between individual rooms and the possibility to install a heat recovery system e.g. an air-to-air heat exchanger. The main disadvantage would be high costs. New ductwork for supplying and exhausting air has to be installed.

If an exhaust fan ventilation system with supply vents is to be installed the house does not have to be as airtight as for the balanced ventilation system. The recommendation is 3.0 ach at 50 Pa (incl. open supply vents) (Blomsterberg 1991). The advantages would be a raised and constant ventilation rate, a fairly well controlled distribution of outdoor air between individual rooms and the possibility to install a heat recovery system e.g. an exhaust air heat pump. The main disadvantage would be high costs. Using an exhaust air heat pump more heat can be recovered then by an air-to-air heat exchanger. The vertical shafts can to some extent be used for the installation of exhaust air ducts.

For the tested houses the last alternative was chosen. The reason for the choice was that the aim of the project was to make the use of electricity more efficient at the same time as the indoor climate is maintained at the same level or improved.

House # 4 had a total outdoor air ventilation rate of 71 m³/h (0.21 ach) before and 141 m³/h (0.41 ach) after reconstruction (see table 8 for individual rooms).

Table 8. Measured outdoor air ventilation for individual rooms in house # 4 before and after reconstruction, m³/h.

	Before	After
Outdoor temperature, °C	9	4
Wind speed, m/s	1.4	3
Laundry	46	32
Kitchen	13	21
Bedroom	2	24
Living room	6	25
Bedroom upstairs	0	1
Bedroom upstairs	0	5
Living room upstairs	0	10
Bedroom upstairs	0	13
Bathroom upstairs	4	10
Total	71	141

In both houses the overall ventilation and the ventilation of individual rooms have been improved after the reconstruction. The new ventilation system will of course have the problem that the colder the weather the lower the outdoor air and the overall ventilation of the bedrooms and the living room upstairs will be. The stack effect is then more powerful than the exhaust fan. To counteract this effect the building envelope has to be airtighter (Blomsterberg 1991).

In order to determine the ventilation rate during the heating season calculations were made using the LBL-modell (Blomsterberg 1990). The calculations were first made for the tracer gas measuring periods (see table 9). The modell overestimates the ventilation for house # 4. According to the measurements the exfiltration is very low. For colder weather there will most likely be some exfiltration.

Table 9. Calculated (LBL-modell) ventilation rates vs measured ventilation rates.

	House # 1	House # 4
Ceiling leakage arera, cm²	70	325
Floor leakage area, cm²	0	0
Total leakage area, cm²	145	525
Wind speed, m/s	4	3
Outdoor temperature, °C	6	4
Calculated ventilation, m³/h (ach)	155 (0.51)	192 (0.56)
Measured ventilation, m³/h (ach)	151 (0.50)	141 (0.41)
Measured exhaust air flow, m³/h	150	140

Estimates for a heating season during a reference year using the LBL-modell give a ventilation rate of 155 m³/h (0.51 ach) for house # 1 and 205 m³/h (0.64 ach) for house # 4. A reasonable assumption for house # 1 is 0.51 ach as calculated and for house # 4 0.5 ach instead of as calculated 0.64 ach .

A comparison of ventilation heat losses for an entire year show increased and reduced ventilation energy losses (see table 10). The calculated heat losses after reconstruction are based on measured exhaust air temperatures. Degree day values were used.

Table 10. Calculated ventilation heat losses before and after reconstruction, kWh, for the reference year of 1971 from Stockholm.

House	Before	After (actual)	After (feasible)
# 1	2200	3900	450
# 4	4800	4900	950

7. CONCLUSIONS AND RECOMMENDATIONS

Modern one-family houses in Scandinavia built before 1980 are often naturally ventilated and heated by electric baseboard heaters. The overall supply of fresh air is often inadequate during the heating season in many of these houses, and often individual rooms are poorly ventilated. The performance of a natural ventilation system is very much dependant upon the overall airtighness and the distribution of the airtightness of the building and the weather.

Six modern one-family houses were examined before and after the ventilation system was improved. The system for natural ventilation was exchanged for an exhaust fan ventilation system incorporating an exhaust air heat pump. It is obvious from the tested houses that the overall ventilation and the ventilation of individual rooms were improved. The ventilation losses were increased and therefore energy conserving measures had to be taken. The overall costs for the new system were high compared with the energy savings obtained.

For mechanical ventilation with heat recovery to really make sense the house has to have a good level of airtightness. Older houses with natural ventilation are often not airtight enough. There are also practical problems in installing new ventilation systems in existing houses.

8. REFERENCES

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