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The Development of an Occupancy-Controlled Exhaust Air Ventilation System

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Synopsis

Many dwellings with natural or gravity ventilation systems suffer from poor airchange rates. In Sweden, especially houses built in the 1960-ies and 1970-ies heated with electric resistance heating and thus without chimneys, are at risk. Improving the airchange rate in these houses is to some extent performed to decrease Radon gas concentrations where appropriate. For comfort, most homeowners learn to live with low airchange rates, accepting e.g. odours or window condensation and trying to compensate this with increased airing. They are often reluctant to install mechanical ventilation systems.

This paper describes a new concept for an occupancy-controlled exhaust air ventilation system. The system features bedroom night-time ventilation, wet-room day-time ventilation and variable total air flow at a low installation cost.

The system has since autumn 1994 been successfully installed in four houses and evaluated by air flow measurements, tracer gas tests, multizone airchange calculations etc. The homeowners are very pleased with the performance of the systems and the improved airchange rates.

1. Introduction

During the 1950-ies and 60-ies electric resistance heating systems were introduced in a large scale in Sweden which meant that houses could be built without chimneys for combustion gasses. Separate ventilation ducts for gravity-driven air flows was drawn from "wet rooms". A separate cooker-hood with fan was mounted above the stove.

At the end of the 70-ies, more strict requirements on thermal insulation and building airtightness of building envelopes were introduced. In spite of that sealing measures were performed both in new production and in older houses, no requirements to ensure an adequate airchange rate was given. Natural gravity ventilation systems was for a period allowed for single-family houses even though the required air flow, 0,35 l/sm^2, not could be guaranteed for all seasons. In practice, almost all new permanently occupied houses in Sweden since the end of the 70-ies have mechanical ventilation systems installed.

More effective weather-stripping and other sealing measures in houses with natural gravity ventilation restricts the supply air flow but the large area of the ducts still remains. The relatively small pressure differences that drives the air flow becomes insufficient and the system becomes unstable. Starting the cooker-hood fan will then cause the air flow to change direction in one or more ducts. If these ducts are cooled down there is a risk that a more stable condition takes place in that e.g. the duct in the bathroom becomes supply instead of exhaust at the same time as the total air flow is greatly increased.

Unevenly distributed air leakage can cause parts of houses to be poorly ventilated, especially at exhaust or gravity systems. Air leakage also includes open vents and windows etc.

The present Building Code (BBR 94, in effect from 950101) stipulates a supply air flow to bedrooms of 4 l/s and person as supplement to the requirement on overall airchange rates. Also, recirculating air is not allowed to bedrooms anymore.

In a large investigation performed by KTH, Dept. of Built Environment, 737 single-family houses in 60 Swedish communities built before 1988-89 were investigated by interviews and measurements. The investigation involved, among other things, potential moisture problems and measurements of airchange rates. In the following, some relevant results of the investigation are reviewed. The reference list contains some of the reports (in Swedish) that are relevant for this paper's topic.

From the total number of single-family houses in Sweden built by 1990, 1,7 million, 1,35 million houses have natural gravity ventilation systems installed. Most of them are built before 1976. About 500 000 houses with natural gravity ventilation systems are built 1961-1988 of which about 1/3 are heated with electric resistance systems. Of these, only about 10 % have chimneys.

Window condensation occurs to a relatively large extent. More in the houses built before 1975 (30%) than in the newer (13%). Differences in glazing and airchange rates explains the difference. Moisture problems in wet rooms occurs in about 15 % of the houses, relatively independent of house age. This indicates that even in new houses with mechanical ventilation systems there are difficulties to manage the moisture load from showers, laundry etc. that exist today.

Performed measurements in the houses show low airchange rates compared to the present Swedish Building Code requirement, 0,35 $l/s{\cdot}m^2$. About 80 % of the single-family houses do not meet this requirement and the measured airchange rates was lowest for the houses ventilated with natural gravity system even though the measurements were performed in winter. Table 1 gives measured ventilation air flows for houses with different ventilation systems. Average values for houses with gravity ventilation systems built after 1961 show even lower values, about 0,17 $l/s{\cdot}m^2$, with some variation between different parts of the country.

Table 1. Measured ventilation air flows in Swedish single-family houses as result of the ELIB investigation which can be compared with the code requirement: 0,35 $l/s{\cdot}m^2$.

Type of ventilation system	Ventilation air flow, $l/s{\cdot}m^2$
Gravity	0,23
Exhaust	0,24
Supply and exhaust	0,29

Risk group

In conclusion, a potential risk group could be identified as:

- Houses with gravity ventilation systems built after about 1961
- House that don't have chimneys and own boiler or changed to direct electric or district heating.
- One-story houses with low roof pitch.
- House where supply air devices are missing or where air sealing measures have been performed.

The size of this risk group can roughly be estimated to between 200 000 and 250 000 houses in Sweden.

2. Scope

Draw-backs with installing ventilation systems constructed according to present codes are that they either are very expensive to install, or increase energy use requiring full continuous ventilation, or don't guarantee the airchange rates in all rooms, e.g. in bedrooms at night.

The scope of this project was to find a relatively cheap ventilation system that in a simple way guarantees proper airchange rates in single family houses. The primary target was houses with natural gravity ventilation systems as indicated in the risk group defined previously.

The following criteria was considered important in the development process:

occupancy control,
secure bedroom night-time ventilation,
secure bathroom daytime ventilation,
easy maintenance and service.

Kitchen ventilation obtained low priority because most houses have cooker-hood fans installed that are used intermittently. Living and dining rooms were also considered less important. The thought behind occupancy control is that the occupants can direct air flows to where they are most needed i.e. bring the ventilation with them. In this way, the total air flow from the house could be reduced without a reduction in comfort and the ventilation energy losses are decreased compared to Swedish standard systems. This idea was penetrated by Stig Jahnsson already in 1979 and has since 1988 been tested and developed in a series of full scale test houses. The earlier tests included the use of small, 15 W, fans that were installed in bedrooms, bathrooms and living rooms in different concepts. The fans were tested both in supply and exhaust modes. For several reasons, this concept was abandoned *(Levin and Isaksson 1991).*

The occupancy-controlled exhaust air system

In principle, the system is an extended exhaust fan ventilation system. The differences from a regular system are that ducts are drawn to bedrooms and that no ventilation outlets in kitchen or closets are installed. For older houses, existing ductwork are used as much as possible. An exhaust fan is connected and placed for easy access for cleaning and service. A schematic drawing of the system principle is shown in Figure 1.

Occupancy control is achieved by the exhaust air devices that are opened when needed, e.g. in bedrooms at bedtime. The bathroom air flows then reduces. The speed control of the fan (5 speeds) allows the occupants both to reduce the total air flow when the house is empty and increase the air flow in the summer or when many people are present. The capacity is also enough to fulfil the Building Code requirement, 0,35 l/sm^2 of continuous air flow when that is desired.

The objective of easy cleaning and service has been met by using a very serviceable fan type with removable fan blade. The exhaust air outlet has partly been developed within this project. Adjustment and locking is simple and it contains a filter where cleaning does not spoil the adjustment. It could be used in bedrooms, where the air flow is maximised, or in bathrooms where the air flow is minimised. Thus could the bathroom air flow be increased when needed. Air flow measurements could be done with standard measurements. Special measurement lids has also been manufactured in order to facilitate air flow measurements, where pressure difference measurements are used together with a calibration diagram.

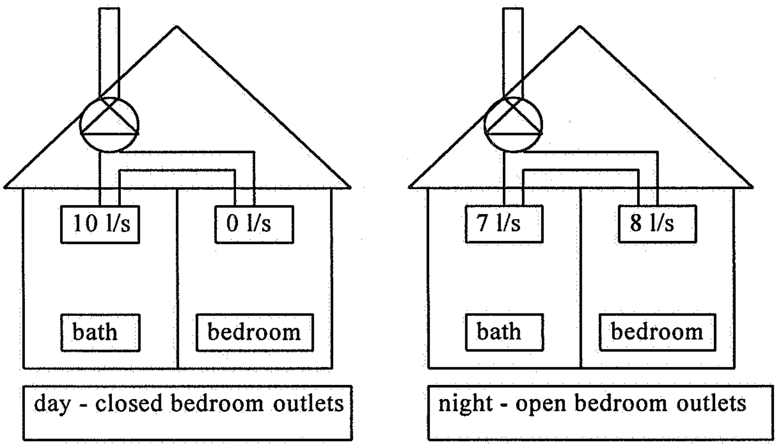

Figure 1. The principle for the occupancy-controlled exhaust air ventilation system with examples of obtained air flows for day and night operation in a bathroom and a master bedroom. The fan is placed to obtain easy access and low noise disturbance.

3. Full-scale test houses

Four houses in different Swedish cities were chosen as full-scale test objects. The main purpose was to see installation time, potential problems and cost, ease of adjustment and performance. The four houses all had natural gravity ventilation systems before measures. The reasons for needing improved ventilation were different, Radon gas from building material, unevenly distributed air leakage between floors or different parts of a house or just low airchange rates. An example of a floor plan for one of the test houses is given in Figure 2.

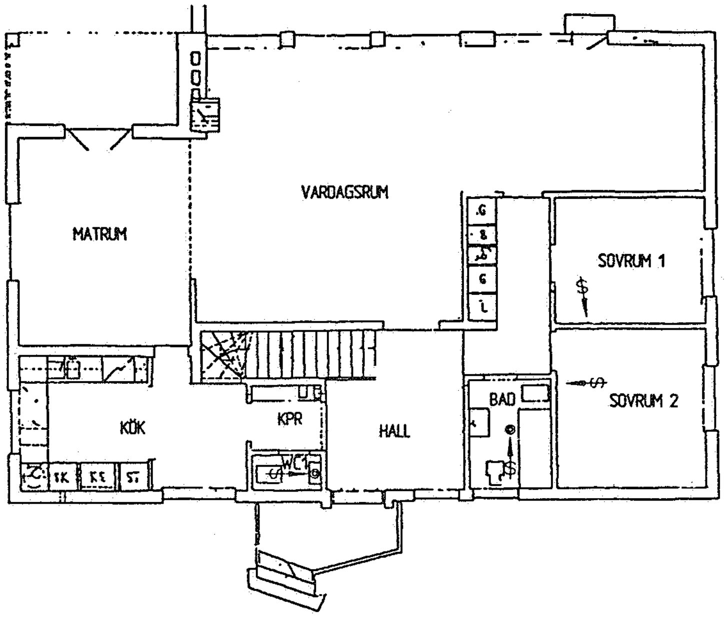

Figure 2. First floor plan with exhaust air points for one of the test houses. This 1 1/2-story house was built 1960 and the floor area is 133 m^2 *for this floor.*

Commissioning

Air flows were adjusted for day and night operating mode, where the target was to achieve air flows according to the building code in bathrooms at daytime and in bedrooms at night (4 l/s and person). In guest toilets that are not frequently used, air flows were adjusted lower than the Building Code requirement of 10 l/s. This means the total exhaust air flow from the house is much smaller than the air flow according to the Code. An example of adjusted air flows for the test house shown in Figure 2 at different operating modes is given in Table 2.

Table 2. Example of air flows at different operating modes for the 1 1/2-story house of about 180 m^2 *at different fan speeds. The outlet devices have an adjustment scale marked 0 to 10. The adjusted flows for fan speed 2 were a little low, why normal operation is on fan speed 3.*

Room	Fan speed 2				Fan speed 5 (all open max.)	
	"Day"		"Night"		"Summer"	
	Adj.	l/s	Adj.	l/s	Adj.	l/s
Bath	3,0	10		5,6	10	15
WC	1,0	3,6		1,9	10	12,5
WC (upstairs)	1,2	5,0		2,2	10	12,5
Bedroom 1	closed	0	5,0	4,2	5,0	5,8
Bedroom 2	closed	0	10	6,4	10	9,4
Bedroom 3 (upstairs)	closed	0	3,0	3,9	3,0	6,7
Bedroom 4 (upstairs)	closed	0	2,4	3,3	2,4	4,4
Total exhaust air flow		18,6		27,5		66,3

4. Evaluation

In addition to the measurements of exhaust air flows, air change rates have been measured in bedrooms with tracer gas decay and complete mixing. These measurements were made with closed doors at both night and day operating modes. Measurements of pressure differences, noise levels and Radon gas concentrations have complemented the evaluation when relevant. The occupants were also interviewed of how they perceived the changes from the conditions before measures. A sensitivity analysis was performed with a multizone air exchange calculation model.

Airchange rates

Measured airchange rates in bedrooms were in general very close to the exhaust air flows in the rooms. One concern was whether extra supply vents had to be installed in the bedrooms. In spite of that none of the houses had supply vents, no large pressure drops were measured across the building envelopes which would indicate the need for supply vents or to remove a part of the weather-stripping. What the tracer gas measurements did not show was whether the air to the bedrooms comes from the outside or from other parts of the building. In one case, the air change rate in a bedroom was higher because of air flow to a nearby bathroom. Additional air flow because of very strong winds was also seen in one case.

Energy costs

The energy use could be expected to increase by the measures, both from the increased airchange rate and electricity use for the fan. In continuous use at middle fan speed (135 V) an electric use of about 315 kWh per year could be expected for operating the fan.

A energy comparison between the occupancy-controlled system and a standard exhaust-supply system with an air-to-air heat exchanger have been made for the test houses. For the occupancy-controlled system, the lowest fan speed was assumed be used 40 hours per week and night ventilation mode was used 70 hours per week. At the exhaust-supply system, a temperature efficiency of 60 % was assumed on the heat exchanger. The weekly average effective air flow for the shown test house then becomes 21,9 l/s for the occupancy-controlled system and 25,3 l/s for the exhaust-supply system with heat recovery. In the Stockholm area, this roughly corresponds to an energy use of about 400 kWh/year more for the latter system. To this, electric use for the supply fan, maybe 350 kWh/year, should be added. Further, the effects of air infiltration and exfiltration has not been considered in this comparison.

Practical experiences

The man-hours for installing the systems have varied greatly because of ease to connect to existing ductwork and how the ducts to the bedrooms could be placed and insulated (outside the envelope). In total, up to 24 man hours of installation work was required for one house. The commissioning of the systems was very easy to perform, especially when using the flow-pressure diagrams and a simple manometer. The air flow adjustment procedure should not take more than an hour for a normal single-family house.

All the occupants in the four test houses are very satisfied with the system and claims better indoor air quality in bedrooms. For some, it is hard to remember to close the bedroom outlets in the morning. No complaints on noise levels have occurred and ventilation noise were in most cases hard to notice.

Computer calculations

For a simple sensitivity analysis of the system, the IDA Multizone Air Exchange simulation module was used. The computer program was developed from the MOVECOMP code *(Sahlin and Bring, 1995)*.

The previously shown test house was chosen to form the input data. The floor plan of the first floor was simplified into five zones for the analysis. WC, bath and bedroom 1 faced the windward side, the smaller bedroom 2 the gable side and the rest of the floor faced the leeward side. A block diagram over the zones and connecting air leakage paths is shown in Figure 3.

Two levels of airtightness were considered. One according to the present Swedish Building Code, that requires a maximum air leakage of 0,8 l/sm^2 at 50 Pa, where the area relates to exterior building envelope area. The air leakage level is about the same as was first introduced in 1978. This level might be considered as too airtight for older houses, but is relevant for the risk group as defined in the beginning of this paper. Also, sealing measures as replacing weather-strips, caulking, etc. have often been performed. The other air leakage level was chosen to 1,5 times the present code value, thus 1,2 l/sm^2 at 50 Pa.

Only effects of different air leakage paths and wind speed were considered in this study. Buoyancy-driven air flows were thus not modelled. Other simplifications included one-way air flow through open doors, constant exhaust air flows, no air leakage through floor and ceiling and interior air leakage paths dominated by door leakage. Closed doors were assumed to have a 1 mm gap around the perimeter.

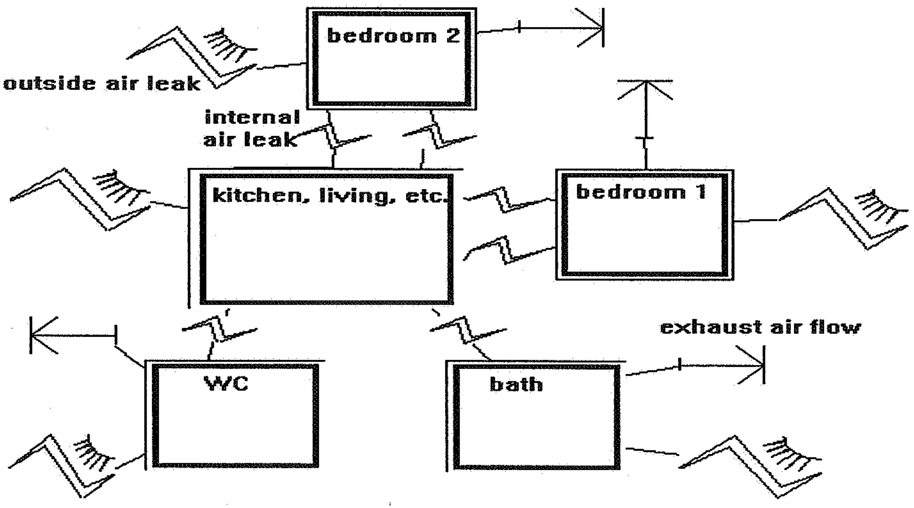

Figure 3. Simplified zone model with air leakage paths as used in the calculations.

The most important operating mode to study was night-time and air change rates in bedrooms with closed doors. Opening the bedroom exhaust outlets increased the air change rates to the setting of the mechanically controlled air flows, several times more than without exhaust. For the tighter case, about half of the air leakage came through the closed interior door and half through infiltration. Adding an outside vent in a bedroom caused the major part of the supply air to the room to enter through the vent.

With the doors closed, pressure differences up to 20 Pa occured between the small wet rooms and the house, which indicate that the air leakage between the rooms are underestimated or the need for slot vents in interior partitions to the wet rooms. When opening the interior doors, pressure differences between rooms reduces to very small numbers, less than 0,1 Pa. These two cases form the range of pressure differences, and the reality is likely to be in between. The calculations showed that door opening does not have a major effect on the air flows between rooms in the tighter test case except in combination with an open outside vent and 6 m/s wind speed.

The small bedroom 2 with side wind obtained more air from the house at increasing wind speed. The size of the air leakage in combination with the exhaust air flows made the air exfiltration through the envelope very small if no outside vents were installed.

5. Conclusions

Installing and commissioning the occupancy-controlled exhaust air ventilation systems in the four test houses were performed as intended. Sometimes, extra man-hours were needed e.g. to properly connect to the old ductwork, which could be of non-standard shapes and sizes. Adjustment of design air flow was a relatively reliable and easy procedure using the special exhaust air outlets.

Tracer gas measurements have shown substantial increases in airchange rates for bedrooms with exhaust air, which also was verified with multizone airchange calculations. The amount of air that comes directly from the outside depends on the air leakage paths and their distribution in the house. At air leakage levels according to the Swedish Building Code, an outside air vent should be installed in bedrooms to avoid excessive pressure drops across the building envelope. However, adding more outside vents (which are large air leaks) will increase the risk of air exfiltration through the building envelope because of wind pressures and thereby contribute to uncontrolled increase in airchange rates. The buoyancy-driven air flows should be considered for two-story buildings.

The increase in energy use for heating ventilation air could be regarded as small if the occupants use the features of the system as intended. A comparison with an exhaust and supply air system with an air-to-air heat exchanger as commonly used for new houses, show that the occupancy-controlled system in most cases will have lower ventilation energy losses. The installation cost in an older house is about one third for the occupancy-controlled system compared to the exhaust and supply air system with an air-to-air heat exchanger.

6. Acknowledgements

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