PROGRESS AND TRENDS IN AIR INFILTRATION
AND VENTILATION RESEARCH

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Paper 16

VENTILATION AND AIRTIGHTNESS IN ENERGY BALANCE ANALYSES

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SYNOPSIS

The air exfiltration part of ventilation is often difficult to determine and its part of the energy balance is therefore usually determined as a remainder or given a constant value.

This paper examines ventilation systems in six different modern houses. The constant concentration tracer gas technique tended to underestimate the total ventilation. A simplified theoretical one-zone model made accurate estimations of the air exfiltration. For detailed information on air flows a multi-zone network model was useful.

Different levels of airtightness should be required depending upon the ventilation system. It is recommended to couple predictions with tracer gas measurements. Determining the energy balance, e.g. using a constant air change rate for the mechanical and/or natural ventilation is in most cases inaccurate, unless the house is very tight.

1. INTRODUCTION

Ventilation in buildings occurs as a consequence of natural ventilation and through the use of purpose provided ventilation. The air exfiltration part of ventilation is often difficult to determine for different boundary conditions. The influence of ventilation on the energy balance of a residential building is therefore usually determined as a remainder together with internal gains from people and the sun or given a constant value.

This paper summarizes a report (Blomsterberg) on one-family houses, examining:
- the influence of ventilation and airtightness on the energy balance
- methods of separating out the ventilation heat losses from the energy balance
- the performance of different ventilation systems.

The results are based on performance monitoring and evaluation during two years of six modern one-family houses with different ventilation systems. Two of the houses are equipped with mechanical exhaust-supply ventilation and three with mechanical exhaust ventilation. The ventilation systems were studied during several one-week periods using the constant concentration tracer gas technique. The airtightness of the houses was examined using the fan pressurization technique. The ventilation was predicted with a simplified theoretical one-zone model (the LBL-model) and a multi-zone network model (MOVECOMP).

2. TEST METHODS

2.1 Airtightness

The standard method for finding the leakage function of a building is fan pressurization. According to the Swedish standard for fan pressurization (SS 02 15 51) all openings in the exterior envelope intended for ventilation purposes must be sealed before the test is performed. For the purpose of modelling air infiltration a test was also made with open supply vents part of an exhaust fan ventilation system and with open vertical shafts part of an unpowered ventilation system.

A door-leaf is replaced by a sheet of plywood. An air flow generating and metering system is connected through the sheet, and a sensing tube from the micromanometer continues through the sheet to the outside. The air flow rate is recorded at a number of pressure differences, positive and negative, and the test results presented in a diagram with pressure difference and air flow/air change rate on the axes. The requirement of the Swedish Building Code of 1985 is 3.0 air changes per hour at 50 Pa, for a detached house.

2.2 Ventilation

The most straightforward method of measuring total ventilation rate i.e. the combined effect of purpose provided ventilation and natural ventilation is to measure it directly. 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 air movement can be traced. If the purpose provided ventilation is mechanical with ducts, then the air flow in the ducts can be measured with different techniques for volume and mass flow rate measurements, without a tracer gas.

The tracer gas is injected into and mixed with the indoor air and its concentration is monitored. 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 (i.e. ventilated) volume, m3
dC/dt is the time rate of change of concentration,
Q is the infiltration, m3/s
C is the concentration and
F is the effective injected tracer gas flow rate, m3/s.

In all houses, examined in this paper, the constant concentration technique was employed, where a constant concentration of a tracer gas is maintained in the test space. 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:

$$Q\,C = F$$

The field of application is to continuously monitor the supply of fresh air to individual rooms i.e. fresh air which enters an individual room directly instead of first passing through an adjacent room.

An automated air infiltration monitoring system (developed by the National Testing Institute) based on this principle was used. The system is capable of handling nine rooms simultaneously. Tracer gas is injected into each room and the concentration is measured in each room. After each measurement the tracer gas flow is updated. The same constant concentration is maintained in all rooms being tested. Air flows between rooms shouldn't affect the measurements i.e. air flows between rooms will never be measured, as all air flows between rooms contain the same tracer gas concentration. Other techniques have to be used to study the air flows between rooms.

3. MODELS

3.1 Multi-zone Network Approach

The multi-zone approach is recommended when the internal partitioning in a building presents a resistance to the movement of air and/or when information as to the supply of fresh air to individual rooms and air flows between rooms is wanted.

A multi-zone model, which has been developed at the Royal Institute of Technology in Stockholm (Bring), was used as a tool for further evaluating the measurements performed for this paper. In the program (MOVECOMP) the building and its ventilation system is modelled. The model consists of pressure nodes connected to each other with flow paths. The nodes are different zones and duct components, while the flow paths are different leakage openings and ducts. The air flows are calculated by seeking a flow balance in each node. Mass balance has to be achieved.

The natural driving forces (i.e. wind and temperature) are determined by the pressure distribution on the building envelope and the pressure gradients within different rooms and inside the duct system. The stack effect is caused by differences in air density. In the model the pressure gradients are assumed to be linear, i.e. the gradients within a certain volume are calculated as if the density was constant. The wind pressure is related to the dynamic pressure of the free wind with a pressure coefficient.

The mass flow through leakage openings and ducts/ducts components, which is a function of the pressure difference, is throughout the model approximated with a power function. The flow through a leakage opening is calculated using the same flow exponent throughout the entire flow intervall. The Reynholds number correction of the air flow coefficient is done for the actual condition. Ducts/duct components are simulated in a conventional manner with the flow as a function of the squareroot of the pressure difference. The air flow coefficient is determined for the actual

Reynholds number.

The system of simultaneous equations describing the flow balance is solved with a modified Newton-Raphson method. The method avoids in most cases otherwise common problems with convergence. As a result of a simulation natural and mechanical ventilation air flows in a building between rooms, through a building envelope and in a ventilation system are given. The pressure conditions within the simulated building are also given. Almost any kind of combination of zones and leakage openings can be simulated.

3.2 Simplified Theoretical Approach

A number of "simplified" methods have been developed in order to reduce the computational effort of theoretical techniques. As of yet they are only applicable to single zone structures and only provide estimates of the total ventilation. The model, which is used in this paper, was originally developed at Lawrence Berkeley Laboratory (Sherman). The primary input to the model is the air leakage of the entire building envelope, which is given as an effective leakage area.

The forces that drive infiltration are pressure differences across the building envelope caused by wind forces and by indoor-outdoor temperature differences. The stack-induced infiltration and the wind-induced infiltration are calculated separately. The air flow resulting from the two driving forces must be combined to arrive at the total infiltration. If the expression for wind-induced and stack-induced infiltration are interpreted as effective pressure differences across the leakage area of the structure, the total infiltration can be determined by adding these two pressures. If the flow is proportional to the squareroot of the pressure, then two flows acting independently must add as the squareroot of the sum of the squared flows.

The ventilation through vertical shafts is combined with the the above flows using superposition. The same technique should apply if there is an exhaust fan. A balanced ventilation system should not affect the pressure drop across the envelope caused by the natural driving forces. The fan flow should therefore simply be added to the natural ventilation.

4. BUILDINGS

A number of experimental houses has been performance monitored and evaluated by the National Testing Institute with the author as project leader. All of them except one are energy efficient designs. Common features are a very high standard of the thermal insulation and a system for mechanical ventilation (see table 1). The energy inefficient house is an older conventional house, which was included in the study for the purpose of comparison.

Skultorp (Skul): Two experimental one-storey houses were built in 1982 in Skultorp, in southern Sweden. Both houses are very well insulated modern wood frame structures, employing boxbeams made of wood and masonite throughout the structure. Each house is 110 m2. Space heating is provided for by a warm air heating system. The warm air is blown into the individual rooms from inlets located in the partitions up by the ceiling.

Täby: A conventional 1.5-storey house was built in 1982 in Täby 30 km north of Stockholm in Sweden. The house is 146 m2 and was designed according to Sweden's National Building Code for energy conservation, but with windows with a better U-value than what's required. Space heating is provided for by a warm air heating system. The warm air is blown into the individual rooms from inlets located in the partitions up by the ceiling.

Table 1 Technical description. SBN80 = Swedish Building Code of 1980. ELAK = Building Code for houses with electric heating.

Project	Skul	Täby	L85	Karl	Svan
SBN80-insulation	-	x	-	-	-
ELAK-insulation	x	-	x	x	-
"Superinsulation"	x	-	x	x	-
Balanced ventilation	x	x	-	-	-
Extract ventilation	-	-	x	x	-
Unpowered vents	-	-	-	-	x
Warm air heating	x	x	-	-	-
Electric baseboard heaters	-	-	x	-	-
Hydronic heating	-	-	-	x	x
Heat recovery	x	x	-	-	-

Lättbygg 85 (L85): A group of 18 identical 1.5-storey well-insulated experimental houses in Täby 30 km north of Stockholm, utilizing simple construction techniques, was built during 1984. All houses are modern wood frame constructions employing I-beams made of wood and masonite throughout the construction. Wall, ceiling, roof, and floor elements are prefabricated. Space heating is provided for with electric baseboards heaters. The houses are 119 m2.

The houses have an exhaust fan ventilation system, with special vents, in the exterior walls, for supplying fresh air. The ventilation rate can be controlled by the user by adjusting a conveniently located three-way switch: no one at home = 0.1 air changes per hour, at home = 0.3 air changes per hour, maximum = 0.5 air changes per hour.

Karlstad (Karl): Sixteen well-insulated townhouses, utilizing passive solar energy and attached sunspaces, were built in 1984 in Karlstad. There are two types of townhouses, a one-storey townhouse with a floor area of 90 m2 and a two-storey with 116 m2. All townhouses have a sunspace facing south. The three monitored townhouses are 116 m2.

The townhouses are modern wood frame constructions with structural elements of concrete. They are heated by an hydronic heating system incorporating only two radiators on the first floor and a towel-dryer on the second floor. There are fans in the intermediate floors in order to circulate the heated air within the apartment.

Svaneholm (Svan): A conventional house was built in 1972 in Svaneholm 15 km south of Boras in Sweden. The house is 135 m2. It is a one-storey building with full basement. The house was designed according to Sweden's standard for energy conservation of 1968. Space heating is provided for by a hydronic heating system. The heat is delivered by an oil fired boiler. The house is ventilated by unpowered vents i.e. vertical shafts where the air is mainly driven by the stack effect.

5. RESULTS AND DISCUSSION

5.1 Predictions of Ventilation

All measurements of ventilation rates using tracer gas are valid for the range of weather conditions, which prevailed during the measurements. The question is what happens if the weather conditions are changed, the building moved to another location or even the building itself modified. If we want to calculate the influence of ventilation on the energy balance we need to know the ventilation rate throughout the year, not only for certain weather conditions. For a house with mechcanical ventilation we need to know the air exfiltration part of the total ventilation as well. Heat can't easily be recovered from that part. To answer some of these questions the buildings were modelled using two different models:
- the LBL-model (single-zone simplified theoretical model)
- MOVECOMP-PC (multi-zone network model)

The first step for both models was to examine how accurately they predict ventilation rates during the actual tracer gas measurements. As inputs were used:
- the results from the fan pressurization tests
- the distribution of leakage openings according to infrared photography scans
- the actual local shielding conditions
- the building height
- the measured indoor and outdoor temperatures (hourly averages)
- the on site measured wind speed (hourly averages)
- the terrain roughness

- the measured mechanical ventilation rates (air flows in the ducts), which were assumed to be constant.

The following inputs only apply to MOVECOMP-PC:

- the on site measured wind direction (hourly averages)
- wind pressure coefficients from windtunnel studies
- the measured geometry of door openings, which was converted to a leakage function
- each room was a separate zone.

The second step was to make predictions for an entire heating season. Weather data was taken from the reference year 1971 of Stockholm. Using the LBL-model hourly calculations were performed. Predictions with MOVECOMP for one combination of wind speed and temperature difference i.e. for one hour requires half a minute of time on a PC. To simplify the calculations the reference year was condensed to relative frequencies of simultaneous values of outdoor temperature and wind speed. This way MOVECOMP could be used for estimating the ventilation rate for an entire heating season.

5.2 Predictions using the LBL-model

Predictions were made for all the houses and compared with tracer gas measurements. The main inputs for the modelled houses are presented in table 2.

Table 2 Inputs to the LBL-model. L = effective leakage area, cm2. Q = fan flow, m3/h. n = number of air changes per hour at 50 Pa (fan pressurization). Exhaust = the difference between the total exhaust and the supply.

Project	Skul	Täby	L85(3)	L85(14)	Karl	Svan
Lceiling	30	40	40	56	42	100
Lfloor	30	0	20	28	0	0
Ltotal (n)	89 (1.1)	130 (2.0)	132 (1.3)	185 (2.2)	125 (2.0)	250 (5.0)
Qexhaust	33	9	80	70,90	140	0
Qsupply	109	160	0	0	0	0

Skultorp: The LBL-model overpredicts the ventilation rate with 10 % for a 21 hour measuring period (see table 3). The weather was rather typical for a inland winter day in southern Sweden, the wind speed varied between 0 and 5 m/s and the temperature between 0 C and - 2 C.

The measured total ventilation rate (135 m3/h) is even lower than the measured mechanical ventilation rate (142 m3/h). The inaccuracy in both measurements is however 5 to 10 %. The model predicts the relative variation in total ventilation fairly well for the measuring period. According to the prediction the average air exfiltration for the 21 hours is 7.5 m3/h, which is a reasonable number.

The predictions for an entire heating season show an average total ventilation rate of 151 m3/h. The average air exfiltration is 9 m3/h, while the maximum is 33 m3/h and the minimum 1 m3/h. Only 5 % of the total ventilation is "uncontrolled" i.e. doesn't pass through the mechanical ventilation system. There is no need to make the house tighter.

Täby: The predictions show similar results to the Skultorp house. This time the LBL-model overpredicts with 12 % for a 85 hour and a 23 hour period (see table 3). The weather was rather cold with an average value of - 6.5 C (85-hour period) and -3.4 C (23-hour period), while the wind speed was very low with an average value of .3 m/s (85-hour period) and .6 m/s (23-hour period). The lowest temperature was -13 C and the highest - 1 C. The wind speed didn't change very much, this is also a very well shielded house located inland and is therefore not likely to ever experience high wind speeds.

According to the measurements the air exfiltration is only 6 m3/h, but as mentioned before both measurements are experiencing inaccuracies in the order of 10 %. The LBL-model gives an air exfiltration of 27 m3/h. The truth must be somewhere in between.

The average total ventilation rate during the heating season will be 191 m3/h according to the LBL-model. This corresponds to an average air exfiltration rate of 22 m3/h with a maximum of 47 m3/h and a minimum of 6 m3/h. Approximately 12 % of the total ventilation doesn't pass through the mechanical ventilation system and isn't quite controlled. Although the envelope of the house meets the requirements in the Swedish Building Code it should preferably be tighter.

Lättbygg 85: The discrepancy between the LBL-model and the tracergas measurements is large. For house # 14 the model overpredicts with 60 % for a 108 hour period (see table 3). The overprediction for house # 3 is more reasonable with a value of 23 % for a 17 hour period. For house # 14 there was probably background leakage of tracer gas, which accounts for part of the large discrepancy between prediction and measurement. The air exfiltration is 7 m3/h in house #3 and between 14 m3/h and 19 m3/h in house # 14 according to the LBL-model for the measuring periods. The LBL-model tracks the variation in ventilation fairly well, but overstimates the air exfiltration rate.

The weather was rather cold during the 108-hour period with an average outdoor temperature of - 14 C. The wind speed was very low approximately 0.5 m/s. For the other periods the average outdoor temperature was close to the freezing point.

The total ventilation rate during the heating season in house # 3 varies between 82 m3/h and 100 m3/h, while the average value is 88 m3/h. The air flow through the exhaust fan was assumed to be at a constant rate of 80 m3/h, which is equal to the average measured rate. The average air exfiltration rate is then 8 m3/h. The maximum rate is 20 m3/h and the minimum rate 2 m3/h. Approximately 10 % of the ventilation rate isn't quite "controlled" i.e. doesn't pass through the intended ventilation system.

An estimation for an entire heating season was also made for house # 14. The result was an average total ventilation rate of 95 m3/h and air exfiltration rate of 15 m3/h. The maximum exfiltration rate was 36 m3/h and the minimum rate 3 m3/h. The "uncontrolled" air flow is thus 15 % of the total ventilation rate. The variation in this flow is also rather large. Although the house meets the requirement for airtightness of the Swedish Building Code, it isn't tight enough.

Karlstad: This is the only house that isn't a detached house, it is a two-storey townhouse with an attached sunspace. The LBL-model was primarily developed for detached houses. In spite of this fact the results from using the model on one of the townhouses in Karlstad (apartment B4), gave reasonable results. The overprediction was 10 % for a 24-hour winter period (see table 3). The air exfiltration is, according to the prediction, very low.

The Karlstad apartment has an average total ventilation rate of 146 m3/h during the heating season i.e. the air exfiltration is very low, 6 m3/h or 4 % of the total rate. The variation in air exfiltration is also very small. The maximum value is 16 m3/h and the minimum value 1 m3/h. There is obviously no need to make the house tighter.

Svaneholm: The LBL-model tracks the total ventilation rate fairly well, but with an average overprediction of 10 % for a 43-hour period (see table 3). The average wind speed was 2 m/s and the average outdoor temperature was 1 C.

The predicted average ventilation rate during the heating season for the Svaneholm house is 75 m3/h, which is only 0.23 air changes per hour. The maximum ventilation rate for the same period is 0.35 air changes per hour. The minimum is 0.10 air changes. The ventilation is always below the required rate of 0.5 air changes per hour, unless the house is made leakier or the occupants open windows. Even if the house was made leaky enough to obtain a correct average ventilation rate, there would be long periods when the ventilation would be inadequate and long periods when the ventilation rate might be uncomfortably high.

5.3 Predictions using MOVECOMP

All the predictions were performed using average weather conditions for the measuring periods (see previous chapter). If the weather conditions change over time the air infiltration prediction can then be in error. For all the measuring periods predictions were therefore made using the relative frequency of simultaneous values of outdoor temperature and wind speed.

Skultorp: The predicted total ventilation rate is very similar to the LBL-prediction i.e. the average predicted total ventilation rate is approximately 10 % higher than the tracer gas measurements (see table 3). The variation in total ventilation rate is similar for the prediction and the measurement.

The average air exfiltration rate during the heating season is 10 m3/h according to MOVECOMP. This value is very similar to the LBL-prediction (9 m3/h). The variation in air exfiltration rate during the heating season is according to MOVECOMP large, the maximum value being 42 m3/h and the minimum 1 m3/h. The spread according to the LBL-model is 33 m3/h to 1 m3/h.

Täby: The predictions of the total ventilation rate is very similar to the predictions using the LBL-model (see table 3). What this prediction also shows is that the fresh air supplied directly to the bathroom, the WC and the closet probably wasn't covered by the tracer gas measurement. This makes up for the discrepancy between measurement and prediction.

Lättbygg 85: The prediction of the total ventilation rate for house # 3 is closer to the tracer gas measurement than the LBL-prediction (see tabel 3). There is no air exfiltration according to MOVECOMP.

During the heating season the variation in air exfiltration rate is very large according to MOVECOMP. The maximum rate is 67 m3/h and the minimum rate 1 m3/h. The average rate is however very low, 4 m3/h. According to the LBL-model the average rate is higher, 8 m3/h, and the variation smaller, between 20 m3/h and 1 m3/h.

Predictions were also made for house #14. This house is identical to # 3 with a few exceptions, it is leakier, and the weather during the measuring period was much colder. There is a large discrepancy between prediction and measurement. The overprediction is close to 70 % (see table 3). This can partly be explained by the fact that there was presumably a constant background leakage of tracer gas from the equipment during the tracer gas measurements. This would mean that the measured ventilation rate would be too low with almost a constant factor, as the total ventilation rate is dominated by the exhaust air flow, which can be assumed to be constant over time.

The total measured and predicted ventilation rate varies almost to the same extent over time. During the 108-hour period the predicted rate varies between 116 and 155 m3/h, while the measured rate varies between 60 and 73 m3/h. As can be calculated from the prediction there is an air exfiltration rate of between 26 and 65 m3/h in house # 14, while there was no air exfiltration in house # 3. This can partly be explained by the fact that house # 3 is tighter and was subject to a milder climate.

The variation in air exfiltration rate during the heating season is larger for house # 14 than for house # 3. The main reason is that house # 14 is leakier. The maximum air exfiltration rate is almost two times higher, 117 m3/h compared with 67 m3/h. The average rate is four times higher, 18 m3/h vs. 4 m3/h. The average air exfiltration rate is 20 % higher than the LBL-prediction, and the maximum rate is 3 times higher than the LBL-prediction. The maximum values occur at high wind speeds and are therefore uncertain, as high wind speeds never occured during the tracer gas measurenments.

Karlstad: The overprediction of the total ventilation is very small for apartment B4 (see table 3). The discrepancy would be negligible if we take into account that the predicted air infiltration to the WC probably wasn't covered by the tracer gas measurements. Both prediction and measurement indicate that there is no air exfiltration during the measuring period. The prediction also shows that the total flow of air from the sunspace to the house is 34 m3/h, which is 1/4 of the total ventilation. The same result was obtained from a separate tracer gas measurement, where the same concentration was kept in the sunspace as in the house itself. According to the design principles all air should have entered the house through the sunspace.

The average predicted air exfiltration rate during the heating season is reasonable. The rate is 9 m3/h, which is higher than the LBL-prediction of 6 m3/h. The maximum rate is too high, 110 m3/h (compare with Lättbygg 85). The result of the LBL-prediction is 25 % of that value 26 m3/h.

Svaneholm: The prediction overestimates the ventilation rate with 40 % (see table 3), which is not surprising taking into consideration the assumptions which had to be made in order to create the necessary inputs.

Table 3 Measured and predicted ventilation rates, m3/h.

Project	Skul	Täby	L85(3)	L85(14)	Karl	Svan
Measured, mechanical	142	169	80	90	140	-
total	135	174	71	69	131	71
Predicted, total LBL-model	149	196	87	109	144	78
MOVECOMP	152	198	80	118	140	101

5.4 Energy balance

For most houses the ventilation heat loss make up an important part of the energy balance. It may constitute between 20 and 50 % of the total energy loss. For all tested houses the ventilation heat losses were calculated using weather data from the heating season of the reference year 1971 of Stockholm (see table 4). The calculations are based on the average predicted ventilation rates, i.e. the average of the LBL-prediction and the MOVECOMP-prediction.

In the original energy balance the calculation of the air exfiltration heat loss was based on an estimation of the air exfiltration rate. For all houses (except Svaneholm) the rate was estimated to be 0.05 ach throughout the heating season. This gives a "correct" exfiltration heat loss for only one house, the L85(14). For the tight houses, the Skultorp house,

Table 4 Calculated ventilation heat losses for the heating season of the reference year 1971 of Stockholm, kWh. For the purpose of this calculation it was assumed that no heat recovery was installed.

Project	Skul	Täby	L85(3)	L85(14)	Karl	Svan
Total ventil. (MOVECOMP, LBL)	5100	6450	2900	3250	4950	2550
Exfiltr. (MOVECOMP, LBL)	300	700	200	550	250	2550
Exfiltr. (0.05 ach)	450	600	550	550	450	-

the L85(3) house and the Karlstad, the heat loss due to air exfiltration is overestimated using the simple approach. None of the above used averaging techniques shows directly the energy consumption for space heating due to air exfiltration. In the real building the air exfiltration will vary over time. There can then be periods when the space heating due to exfiltration is reduced by internal gains in a low energy house i.e. it is important to know when the air exfiltration occurs.

6. CONCLUSIONS

Six different modern Swedish one-family house with different ventilation systems were examined in this report. There is only one house that isn't quite modern and can't be considered a low energy house. If doors and windows are closed in this house, with unpowered vents and vertical stacks, it will be inadequately ventilated all year around. The house wasn't even as tight as is required by the Swedish Building Code. The ventilation rate can of course be increased by airing. Whether relying on airing or unpowered vents and vertical stacks or both of them, it is very difficult to recover any heat from the air leaving the structure.

The three houses with exhaust fan ventilation systems were all adequately ventilated. For two of them the air exfiltration rates were fairly low i.e. there is no need to make the houses tighter in order to better control the energy loss due to air exfiltration or to improve the total ventilation. All of them met the airtightness requirement of the Swedish Building Code. One of the ideas behind the ventilation system was that the occupants should be able to control were the outdoor air entered the house. Vents which can easily be closed and opened were incorporated in the building envelope. Measurements and calculations show for these three houses that approximately 1/3 of the air enters through the vents if all of them are open. The remainder of the outdoor air enters through whatever cracks or openings there are.

Two houses were equipped with a balanced mechanical ventilation system. One of the two houses (2.0 air changes per hour at 50 Pa) should preferably have had a tighter building envelope. This would have reduced the air exfiltration heat loss substantially. The other house had a very low air exfiltration rate, due to the fact that the house is very tight (1.1 air changes per hour at 50 Pa).

The following conclusions are valid for the examined houses. The constant concentration tracer gas technique tended to underestimate the total ventilation. All air flows were probably not measured. A simplified theoretical one-zone model can be useful and makes accurate estimations of the air exfiltration in tight houses with mechanical ventilation. This is also a very straightforward kind of model to employ. It is necessary to know the airtightness of the building envelope, the mechanical air flow rates and the shielding. For detailed information on air flows a multi-zone network model can be useful. There are however two problems associated with a multi-zone network model: it is time-consuming to put together all the required inputs and there isn't enough data as to wind pressure and the location of leakage openings.

Whatever model is used it is recommended to couple predictions with tracer gas measurements. Determining the energy balance, based on a simple estimation of the air flows due to mechanical and/or natural ventilation by e.g. using a constant air change rate, is in most cases inaccurate, unless the house is very tight.

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Discussion
Paper 16

Willem de Gids (TNO, Netherlands)

Did the natural ventilated houses have slot vents in the roof? Why did you come to the conclusion that natural ventilation fails? The flow rates given do not differ significantly from, for instance, mechanically exhaust systems as you showed by the model calculations.

Åke Blomsterberg (Lund Institute of Technology, Sweden)

The house with natural ventilation had five inlets (vents) which can be opened and closed. The calculations and measurements were made with all inlets open. During the heating season the average predicted ventilation rate, with all windows closed, is then 75 m^3/h, which is 0.25 ach. According to the Swedish National Building Code the required minimum ventilation rate is 0.5 ach. All the other tested houses meet this requirement.

Bjorn Kvisgaard (Bruel & Kjaer, Denmark)

One of your conclusions was that the constant concentration method underestimated the air exchange in the house. How did you come to that conclusion?

Åke Blomsterberg (Lund Institute of Technology, Sweden)

Our automated tracer gas system has nine channels. We were therefore not able to cover all rooms, i.e. in some rooms fresh air entered from the outside and used air was exhausted without being labelled with tracer gas. This we discovered in houses with mechanical ventilation. The total ventilation as measured by tracer gas was smaller than the air flows in the ventilation ducts (not measured by tracer gas). Both measurements have of course a certain inaccuracy.

Jorma Heikkinen (Technical Research Centre, Finland)

Is it acceptable, according to Swedish Building Codes, to design a ventilation system where only 1/3 of incoming air flow can be delivered into individual rooms?

Åke Blomsterberg (Lund Institute of Technology, Sweden)

I was referring to houses with exhaust fan ventilation where 1/3 of the fresh air enters through the vents if all of them are open. The remainder of the fresh air enters through whatever cracks or openings there are. The Swedish Building Code only specifies that the total ventilation should be 0.5 ach and certain minimum exhaust air flows from bathrooms and kitchen.

Willigert Raatschen (Dornier GmbH, Germany)

To get a reliable data input base for the network simulation you did blowerdoor and tracer gas measurements. Further you stated that background leakage is about 2/3 of the total leakage. How did you get around with the distribution of the background leakage into the different walls?

Åke Blomsterberg (Lund Institute of Technology, Sweden)

The air leakage sites were distributed according to the themography tests. The problem was to determine the size of the individual leakage paths. All paths were given the same flow exponent i.e. the exponent from the blower door test of the entire house. For walls the themography tests showed, in most cases, leakage sites at the lower and the upper edge and around windows. Half of the leakage for a wall was then considered to be around windows.

David Hill (Eneready Products, Canada)

Concerned by conflict of conclusions.

1. House with mechanical supply and exhaust should be tighter than 1.0 ach.
2. Houses with mechanical exhausts should be tighter than 2.5 ach.
3. Only 1/3 of the air passed through inlets.

Perhaps a good conclusion for building science/energy reasons, but 2) and 3) seem in conflict regarding ventilation effectiveness and exhaust in homes.

Åke Blomsterberg (Lund Institute of Technology, Sweden)

The required airtightess of 2.5 ach includes the air leakage through the inlets (all of them open). When only 1/3 of the fresh air enters through inlets, some rooms might not get enough fresh air. Ideally the air leakage through the building envelope is fairly evenly distributed i.e. the remainder of the fresh air (2/3). The overall aim is that the exfiltration rate should be less than 10% of the total ventilation for a home with mechanical ventilation.