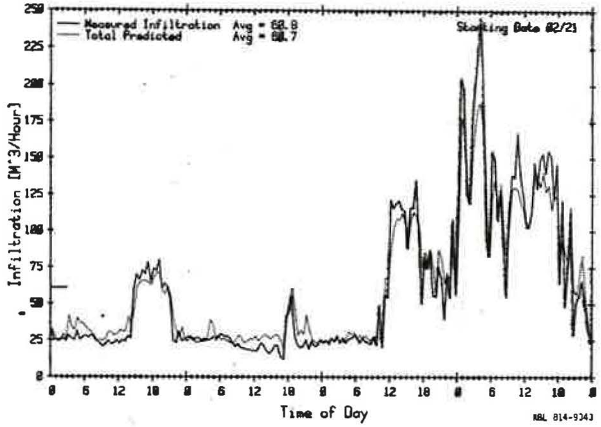

Figure 5. Plot of measured infiltration and infiltration model prediction vs. time: Four-day test in MITU.

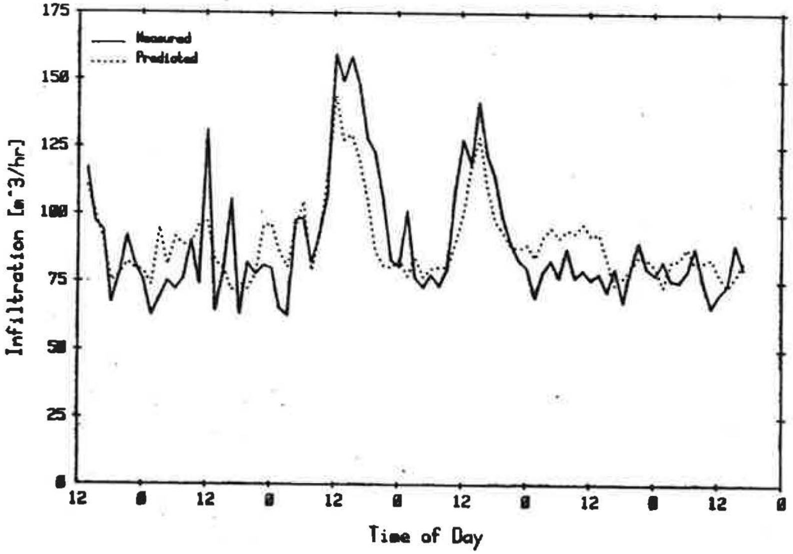

Figure 6. Measured and Predicted infiltration vs. time in Rochester Test House.

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Air Tightness vs. Air Infiltration for Swedish Homes - Measurements and Modelling

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ABSTRACT

Air infiltration, an important energy loss mechanism in buildings, has been studied in a number of homes in Sweden. Two methods for measurement have been utilized: the fan pressurization technique and the tracer gas technique. The pressurization technique is used to measure the air tightness of the building envelope, while the tracer gas technique is used to measure the air infiltration. Pressurization is used routinely for checking dwellings in Sweden. This technique does not give the air infiltration as a direct result.

A previously developed model correlating air tightness and air infiltration was used for evaluating the performance of Swedish homes. The results show that it is difficult to achieve the recommended minimum ventilation rate according to the Swedish Building Code only relying on natural air infiltration. It may work for a house with little shielding located in a windy area. Most new Swedish homes do, however, meet the stringent air tightness requirement of the Swedish Building Code. A comparison with American houses show that Swedish homes are very tight.

INTRODUCTION

Air infiltration typically accounts for a third of the energy loss in a heated building. The driving forces for natural air infiltration are weather i.e. wind and temperature. For a given combination of weather conditions the size of the air infiltration is determined by the character of the building envelope. The main property being the air tightness of the shell.

A promising technique to characterize this housing quality is air leakage measurements. An air leakage standard for new construction exists since 1975 in Sweden. Pressurization i.e. measurement of the air leakage is performed

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routinely for checking Swedish dwellings. This paper as well as a previous paper by the author (1) and a report by Max Sherman (2) support the idea that results from air leakage measurements can be used to predict the average air infiltration for an entire building. Results from tracer gas measurements and fan pressurization measurements in 45 houses are evaluated using the model developed by the author. None of the houses meet the minimum ventilation requirement recommended by most experts on ventilation, by only relying on natural ventilation.

TEST METHODS

In order to perform the measurements necessary for this paper two methods were used: the pressurization technique and the tracer gas technique (2).

The pressurization technique is used for testing air tightness of building envelopes for entire buildings. The procedure is the following: a fan is mounted into the building envelope. Using this fan the entire house is first pressurized and then depressurized (i.e. a differential pressure is established between the inside and the outside of the house). All vents are sealed off during the test. The air flow through the fan is determined using a flow meter. It is assumed that this air flow is equal to the air flow through the building envelope at the same time. Within a short period of time a pressure-flow rate profile is established for the house.

The tracer gas technique is used for measuring air infiltration for natural running conditions in a building. Tracer gas, a gas normally not present in the structure, is injected into the house to be tested and the concentration is measured; from that the air infiltration can be derived. Three methods can be used: concentration decay following periodic injections, constant concentration obtained by continuous injections, constant flow. The first method was used in all buildings presented here. Tracer gas is injected once and the resulting decay in concentration is monitored. In order to determine the air infiltration, measurements of concentration (C) from a minimum of two different times (t and t+Δt) are used. The following relation is employed to find the air change rate (hr^{-1}):

$$A = -\frac{1}{\Delta t} \ln \frac{C_t}{C_{t+\Delta t}}$$

With this technique the concentration is measured repeatedly during at least one hour.

DESCRIPTION OF THE MODEL

The model uses two primary inputs to calculate air infiltration. The first is the measurement of air leakage of the entire building envelope; the second is the pressure distribution over the building envelope caused by the wind and indoor-outdoor temperature differences (1, 3).

The leakage of the entire building shell is obtained using fan pressurization. An equation describing the air flow through a single opening is

$$Q = K\,(\Delta P)^{\alpha} \qquad (1)$$

where
- Q is the air flow (m^3/hr)
- K is the air flow coefficient (m^3/hr at 1 Pa)
- ΔP is the pressure difference across the opening (Pa) and
- α is the flow exponent ($0{,}5<\alpha<1{,}0$).

Fan pressurization measurements do not yield information about flows across individual openings but rather the integrated flow characteristic for the entire envelope. Consequently, if no information as to the leakage distribution is available, the model uses the simplifying assumption that the leakage of the entire building shell is uniform. Non-uniform leakage distributions can be taken into account by the model. This is done by estimating the neutral pressure level. Unfortunately, measurements of the neutral pressure level do not exist for any of the houses in this paper.

The flow exponent and air flow coefficient for any house is found by fitting the measured flow characteristic for the whole building to an equation having the form of eq. 1.

The pressures on the building envelope are obtained by summing the pressure due to the wind with the pressure due to the indoor-outdoor temperature differences for the entire building shell. The pressure due to the wind at location j, P_{wj}, is given by

$$P_{wj} = \frac{1}{2} C_j \rho V^2 \qquad (2)$$

where
- ρ is the density of air (kg/m^3)
- V is the wind speed at the roof ridge (m/s) and
- C_j is the shielding coefficient at location j.

The shielding coefficients are obtained from wind tunnel measurements on elementary building forms. The vaule of V is computed from wind speeds measured at 10 m weather tower on site or at a weather station using corrections for the ground plane and terrain roughness.

The pressure difference due to the inside-outside temperature difference at location j, P_{tj}, is given by

$$P_{tj} = (\rho_o - \rho_i) g h_j \qquad (3)$$

where ρ_o is the density of the outside air (kg/m^3)
ρ_i is the density of the inside air (kg/m^3)
g is the acceleration of gravity (m/s^2) and
h_j is the height of location j above a reference level (m).

When added, the pressures from the temperature difference and wind may be positive or negative relative to the interior of the house. Summing over all sites at which the surface pressures is larger than the interior pressure gives the total air flow into the structure.

$$Q_{in} = K \sum_j (P_j - P_r)^{\alpha} \qquad (4)$$

where Q_{in} is the total air flow into the structure (m^3/hr)
P_j is the weather-induced surface pressure at point j (Pa) and
P_r is the interior pressure correction (Pa). (If h_j is equal to the neutral pressure level, then P_r will be equal to the interior reference pressure.)

In a similar fashion the air flow out of the structure is given by

$$Q_{out} = K \sum_{j'} (P_r - P_{j'})^{\alpha} \qquad (5)$$

where the symbols have the same meaning as in eq. (4). The interior pressure, P_r, will adjust until the flow into the structure and the flow out are the same.

When an unoccupied attic is present the actual air infiltration will occur into or from a well-shielded attic space. An unoccupied attic space is typically open to the outside. Known wind-tunnel pressure measurements do not take this into account. Clearly, this shielding of the attic space by the roof reduces the magnitude of the wind pressures seen by the ceiling. The exact amount of shielding due to the roof is not known; calculations show that the results are insensitive to the exact value as long as the magnitude of the pressures seen by the ceiling are smaller in magnitude than 30 % of the average wind pressure experienced on the roof. This value is considered to be a reasonable assumption and is therefore used in the calculations necessary for this paper.

RESULTS

A large number of one-family houses in Sweden have been tested using the pressurization technique. About 450 of these have been compiled in a database at Lund Institute of Technology. Information as to the natural air infiltration i.e. measured air infiltration (4) is available for only 10 % of these houses. This smaller subgroup consists of a nice mixture of house types. The houses have 1 or 1 1/2 storeys. They are detached houses and town houses. The employed production technique was prefabrication of volume elements, prefabrication of surface elements, fabrication on site. The structural material was either wood or cellular concrete or concrete. The houses were naturally ventilated or mechanically ventilated. The mechanical ventilation was of balanced type or exhaust type.

The measured air change rates are shown in table 1. The houses were divided into two groups; houses built 1965-75 and houses built after 1975. The reason for this is that a new Building Code was imposed in 1975, which requires a specific level of air tightness for all new houses. A new one-family house should not leak more than 3,0 air changes per hour (ach) at a pressure difference of 50 Pa. The results are shown with one standard deviation. The weather conditions for which the air infiltration values are valid would be equal to a typical spring or fall day.

In order to get an idea as to how these houses perform during winter and summer relying only on natural ventilation, three houses were modelled using the previously described model. The first house (house A) is a detached one-storey building made of prefabricated surface elements of wood, with natural ventilation. The second house (house B) only differs in that it was built on site and has an exhaust air ventilation system, which was sealed off during the

	Built 1965-75 (6 houses)	Built after 1975 (39 houses)
Pressurization at 50 Pa, hr^{-1}	5,5 ± 3,0	3,8 ± 1,9
Natural air infiltration, hr^{-1}	0,23 ± 0,08	0,16 ± 0,10
Temperature difference, °C	11,0 ± 4,0	12,3 ± 6,5
Wind speed at house, m/s	5,0 ± 2,5	3,5 ± 2,0

(The wind speed was measured 10 m in front of the house and at a height of 2 m)

Table 1. Air Change Rates for One-family Houses in Sweden.

test. The third house (house C) is very similar to house B. It is however somewhat bigger. The area of the living-space is 90 m^2 for house A, 90 m^2 for house B and 136 m^2 for house C. These three houses are representative of modern Swedish construction. All of them meet the air tightness requirement in the Building Code (see fig. 1). The model was first applied to the houses for the same weather conditions as during the air infiltration measurements.

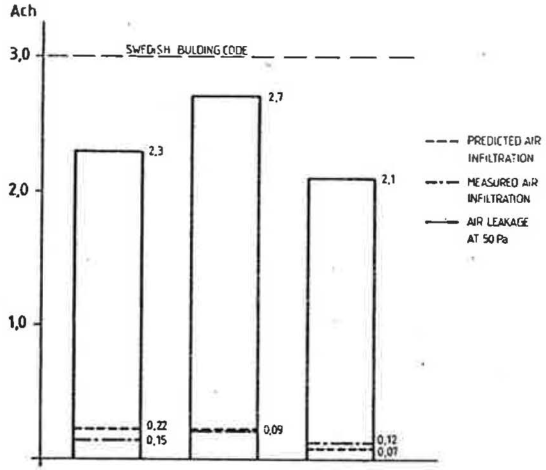

Figure 1. Air Leakage vs. Air Infiltration and Predicted vs. Measured Air Infiltration for three One-family Houses.

It should be observed that the houses are located in a terrain considered to be "country with scattered windbreaks" before looking at the predictions for typical winter and summer weather conditions. When modelling the winter and

summer air infiltration, the average weather for February and July in the south of Sweden, where these houses are located, was chosen (see table 2).

	House A	House B	House C
February			
Air changes at 5,5 m/s and -0,6 °C, hr^{-1}	0,15	0,18	0,13
July			
Air changes at 4,0 m/s and 16,6 °C, hr^{-1}	0,12	0,14	0,09

(The wind speed was measured at a weather station at a height of 10 m).

Table 2. Air Infiltration Predictions for three Houses located in South Sweden.

In order to get an idea as to how tight modern Swedish one-family houses are a comparison was made with a sample of one-family houses in the U.S. (see fig. 2). The American houses were divided into two groups: houses built to be energy efficient and conventional houses (5). All houses were built in the seventies and have the same size as Swedish houses. The houses are located in California, Minnesota and New Jersey.

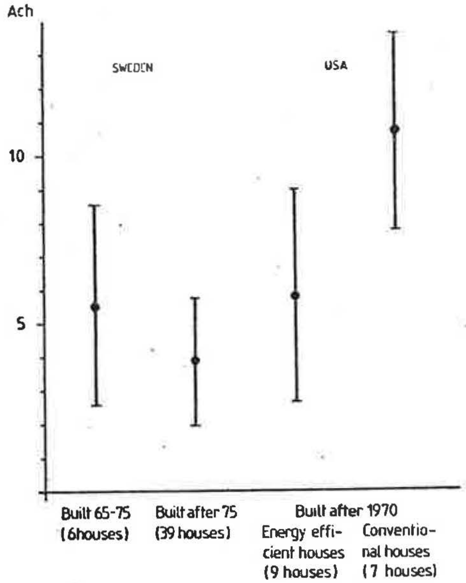

Figure 2. Air Change Rates at 50 Pa for One-family Houses in Sweden and in the U.S..

DISCUSSION AND CONCLUSIONS

The purpose of an exercise such as this is to attempt to find the ventilation rate for tight dwellings if one were to rely only on natural ventilation. A group of 45 houses built in the south of Sweden have been investigated. The average measured air infiltration for houses built between 1965-75 is 0,23 ± 0,8 ach and for houses built after 1975 0,16 ± 0,10 ach (see table 1). These numbers should be compared with what is considered to be an acceptable ventilation rate. For one-family houses the recommendation is 0,5 ach. None of the houses meet this requirement. The measurements were performed during typical spring or fall weather.

In order to see if the houses mentioned above would at least be adequately ventilated by natural means during the winter, a model was used to calculate these numbers. The model has previously been evaluated and been shown to be able to predict the air infiltration for a wide variety of very leaky one-family houses with an accuracy of ± 30 % (1). Three typical Swedish houses were chosen from the group. The predictions must be considered (see fig. 1) very good, especially taking into account the inaccuracy of low air infiltration rate measurements. The winter predictions show an increase in air infiltration for only two of the houses (see table 2). These values still fall short of the desired ventilation rate. The conclusion is obviously that unless a tight house is located in a very windy area the ventilation rate relying on only natural means will be too small during most of the year. The ventilation rate for the summer case was also calculated and shown to be very low. This is however no mayor problem as people this time of the year can be expected to open their windows to get fresh air. Airing during the rest of the year would mean an additional energy consumption, which is hard to control.

The best way of both supplying adequate ventilation and conserving energy is to make sure that the building envelope is sufficiently tight and then install a ventilation system. If this is done it will be possible to control the ventilation rate all year around and avoid excessive or too small ventilation. The system should either be of the balanced type or the exhaust air type with special vents to the outside for supplying fresh air.

In order to conserve energy the first system can be combined with a heat exchanger and the second system with a heat pump for heating domestic hot water.

The group of buildings described above have an air tightness level approximately equal to the limit imposed by the Swedish Building Code in 1975 (see fig. 2). Buildings built between 1965 and 1975 are somewhat leakier than the ones built after 1975. A comparison with American housing reveal that Swedish houses are indeed very tight (see fig. 2). Conventional American houses are three times leakier. Only the houses built to be energy efficient are close the Swedish ones, (5,8 ach compared with 3,8 ach).

Recent research has revealed that mechanically ventilated houses with an acceptable average ventilation rate, may have individual rooms with hardly any ventilation at all (6). This is an indication that attention has to be paid not only to the overall ventilation but also to the ventilation of individual rooms. As of today there is no easy way of monitoring local ventilation. A promising technique for this purpose is to further develop the tracer gas technique. A constant concentration method is being developed. The idea being to inject tracer gas continuously into each room of an apartment or a house and to maintain a constant concentration of tracer gas in the whole house. By measuring the supply of tracer gas to each room the supply of fresh air to each room will be known directly.

In this paper it was shown that it is possible to correlate fan pressurization measurements and infiltration rates. Improvements in this technique are necessary and are clearly possible. Relying on only natural ventilation for the ventilation of low leakage houses is clearly not possible. The solution is to install a ventilation system where adequate ventilation rates can be quaranteed 12 months a year and where energy losses caused by ventilation can be recovered. A ventilation system will work well only in a tight dwelling. When ventilating a house attention has to be paid to each individual room. Every room should have a supply of fresh air sufficient for its usage. This is not always the case.

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A Multiple Tracer Gas Technique for Measuring Air-flows in Houses

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ABSTRACT

A technique has been developed for measuring air-flows between internal spaces of houses using a portable gas chromatograph to monitor the concentrations of three tracer gases released in three distinct zones within the building envelope. Using the results of each measurement, which takes approximately two hours, the ventilation rate of each zone can be calculated along with the interconnecting air-flows. The paper presents the tracer decay equations involved, including their derivation and application. An account of the experimental method is included and the practical difficulties are mentioned. A programme of field work has commenced with the objective of investigating the magnitudes of air movement in a wide range of houses and conditions. The fourth section presents two of the early results which have been obtained by use of the multiple tracer gas technique.

RESUME

On a développé une technique pour mesurer les courants d'air entre les espaces internes des maisons, se servant d'une chromatographe à gaz portative à surveiller la concentration des trois gaz traceurs dans trois zones distinctes du bâtiment. Se servant des résultats de chaque mesurage, qui dure à peu près deux heures, on peut calculer le taux de ventilation de chaque zone et aussi les courants d'air communiquants. Cette étude offre les équations qui moutrent à l'égard de la réduction des gaz traceurs, leurs dérivations et leur usage. On a rapporté la méthode expérimentale et les difficultés pratiques. On a commencé un programme de travaux pratiques afin de rechercher les courants d'air dans des maisons, et des conditions, bien diverses. La quatrième partie rend des résultats préliminaires, que l'on a gagnés de l'emploi de la technique des gaz traceurs multiples.