AIR INFILTRATION - MODELLING AND PRACTICAL RESULTS

Railio Jorma M. Sc. (Eng.)
Association of Finnish manufacturers of air handling equipment

Saarnio Pekka M. Sc. (Eng.)
Technical Research Centre of Finland
Laboratory of Heating and Ventilating

Abstract

A steady state multi-cell calculation model has been developed in order to predict the interconnection between airtightness and ventilation rates. The model has been tested with measured leakage data of a detached house. It is applicable also for other types of buildings provided with natural ventilation system. The model is being used - combined with field measurements on airtightness, air flows, pressure conditions and air change rates - to help to solve various practical problems on ventilation. Some examples of calcutation results are presented. The air-tightness of various leakage paths is measured with the collector chamber method. To measure local air change rates and ventilation efficiency in various rooms, a ten-point measurement equipment with N_2O tracer gas is used. For practical purposes, methods for airtightness measurements in larger buildings have been developed. Results from measurements in residential buildings will be presented. Observed comfort or air quality problems are related to, rather than air infiltration, insufficient total or local air change rates, which occur in airtight buildings without supply air arrangements, and provided with natural ventilation or mechanical exhaust.

1. CALCULATION MODEL FOR AIRTIGHTNESS AND NATURAL VENTILATION OF BUILDINGS

1.1 Common information

A multi-cell calculation model was developed for calcutation of the interconnections between airtightness, air change rates, pressure conditions and energy consumption of ventilation. The flow equation used in model is a quadratic one. It can be used as well for a single leakage path as for a whole building envelope.

The momentary pressure fluctuations of wind are not taken into account in calculation. Steady-state flow equations are applied to each leakage path to solve the mass flow balance of the building. Outside pressure distribution is calculated by using mean values of wind pressure coefficients for each wall area and wind sector.

The local airtightness of various leakage paths of the building envelope can be given as input data for calculation to each wall.

1.2 The theoretical basis /1/

In theoretical calculation the basic element consists of a separate crack restricted as to its location and known as to its leak characteristics.

The leakage flow of a structure or its component or joint can be expressed:

- as the total leakage of construction, m^3/s
- as a leakage per surface area, m^3/m^2s
- as a leakage calculated per crack length, m^3/ms

The leakage flow for a single leakage point can be calculated using a crack flow equation, whose general form can be written as follows:

$$\dot{V} = f(\Delta p) \qquad (1)$$

where $\dot{V}$ is the leakage air flow (m^3/s, m^3/m^2s, m^3/ms),
Δp is the pressure difference across the construction, Pa.

In the model the air leakage of a single flow path is calculated using a quadratic flow equation:

$$\Delta p = a \cdot \dot{V}^2 + b \cdot \dot{V} \qquad (2)$$

Flow coefficients a and b can be calculated from measured leakage values at two pressure differencies (e.g. 10 Pa and 50 Pa).

The equation (2) is generally applicable. For the use of the equation any knowledge of the geometry of the crack is not needed.

It is accurate enough to be applied for practical pressure differences measured in buildings (-50...+50 Pa). The flow equation can also be used to describe the correlation between air flow and pressure difference for the ducts of natural ventilation and for devices of supply air intake. The leakage curve of the building envelope (measured with the pressure test) also agreed well with the quadratic flow equation., (see Fig. 1).

When the pressures in the surrounding rooms, on the outside walls and the air flows of the mechanical ventilation system are known, it is possible to calculate the flow equilibrium of the room (pressure at the medium height of the room) by using the equilibrium equation.

Applying the conservation of mass principle to the air flow mechanism of the room the flow equation under steady state wind conditions is:

$$\dot{m}_{+}(i) + \dot{m}_{n+}(i) + \dot{m}_{V+}(i) + \dot{m}_{-}(i) + \dot{m}_{n-}(i) + \dot{m}_{V-}(i) = 0 \qquad (3)$$

The sum of the air flows entering the room is equal to the sum of the escaping ones.

This simple shysical law is the basic principle at the calculation procedure studying the interconnections between airtightness and ventilation.

The different elements of the mass flow equation (3) are (see also fig. 2):

- supply air flow, $\dot{m}_{+}(i)$
- exhaust air flow, $\dot{m}_{-}(i)$
- the air leakage flows through the outside walls of the room:
  - air flow into the room, $\dot{m}_{n+}(i)$
  - air flow from the room, $\dot{m}_{n-}(i)$
- the air leakage flows through the partition walls of the room:
  - air flow into the room, $\dot{m}_{V+}(i)$
  - air flow from the room, $\dot{m}_{V-}(i)$

The total leakage flows of a room are achieved by summing up the leak flows of the separate elements. The flow equilibrium of a building exists when the flow equilibrium equations for each room are simultaneously valid.

A general flow chart of the calculation principle is presented in fig. 3. The calculation procedure can be summarized as follows:

- the air leakage of a separate crack is calculated using a crack flow equation (2) which describes accurately enough the crack flow in practical conditions.
- determination of the flow equilibrium equation (3) for a separate room.
- calculating the flow equilibrium for the building in a way

enabling a simultaneous validity of the flow equilibrium equations for the separate rooms.

In solving the equation group is used an application of Brown's method /2/. At the initial stage of the calculation, an approximate value of the internal pressure of the room occurs in the flow equation. The flow balance of the building is then solved so that the mass flow balance of various rooms occurs simultaneously in all the rooms with the accuracy used in iteration.

1.3 Examples of calculation results

a. Verification of the physical reliability of model

The physical reliability of the model was tested by comparing the results of the calculation with the results of the measurements in an actual building. The airtightness of various leakage paths of the reference house was measured with the collector chamber method /3/. The length of the collector chamber used to measure the airtightness of a single joint was one meter. Average air leakage values (at 10 Pa and 50 Pa) of various types of the joints are shown in table 1.

Table 1. Average air leakage values of the samples (at 10 Pa and 50 Pa) measured with the collector chamber method to the various types of the joints in the test house.

	Δp = 10 Pa	= 50 Pa
bottom joists joint to outside wall	31,6 cm^3/ms	133,3 cm^3/ms
roof joists joint to outside wall	13,1 cm^3/ms	38,9 cm^3/ms
vertical joints between elements	10,0 cm^3/ms	44,0 cm^3/ms
joints between ceiling boards	48,6 cm^3/ms	160,4 cm^3/ms

Example leakage curves measured to vertical joints between elements are presented in fig. 4.

Total air tightness of window (and door) openings was measured by using a collector chamber which covered the whole opening (fig. 5). So the measured leakage value included both the leakage flow of joints between frame and casement and the leakage flow of the joints between frame and wall.

The coefficients of the flow equation (2) was calcutated by using the average leakage values of the sample measured to each crack type. Total air leakage measured to a window (or door) opening was divided to vertical and horizontal joints in the ratio of the total crack length of the opening.

The flow into the room is denoted by plus and the flow from the room by minus. The number of the room is denoted by index i.

The air leakage curve of the test house calculated by the model is compared with the leakage curve measured with the pressure test (see fig. 6). As weather data for calculation was used on site measured values. In calculation all wind pressure coefficients were fixed to the same wind speed measured 5 m above the roof level.

The total air leakage of the building envelope calculated by using the leakage data measured in the reference building agreed very well with the leakage curve measured with the pressure test, when the pressure difference is about 10 Pa. At 50 Pa the difference between calculated and measured air change numbers is about 10 %. Total air tightness calculated by using the average leakage values added by the standard deviation of the sample, is about two times grater than the measured value (curve $\bar{x}$+s in fig. 6).

Table 2. The share of the total air leakage of various leakage points of the building envelope at 50 Pa pressure difference calculated to a detached house with masonry wall construction.

	air change number n_{50}	
	0,75 h^{-1}	1,5-10 h^{-1}
- roof joists joints to outside wall and joints between ceiling boards	24,0 %	52-54 %
- window and door frame joists joints to outside wall	29,9 %	12-15 %
- joints between frame and casement	16,0 %	7-8 %
- penetrations of ceilings	12,7 %	12-13 %
- electrical boxes	17,4 %	11-14 %

Total air infiltration rate measured by tracer gas method was about 0,03 h^{-1}, when there were any exhaust or suppaly air arrangements in the building. Wind speed measured on site was 2,0-3,5 m/s and there were any markable changes in wind dircetion during the measurement. Corresponding air change rate calculated by the model using input data measured on site was about 0,02 h^{-1}. Pressure differences between outside and inside air calculated by the model were 0,1-0,7 Pa greater than the measured values (-2,0 Pa...+2,0 Pa).

b. Correlation between air tightness and natural ventilation rate to a detached house

Pressure test curves calculated by the model to a detached house of masonry wall structure are presented in fig. 7. The number of different leakage points used to describe the air leakage characteristics of the building envelope was about 200. The share of the total air leakage of the building envelope calculated to varios leakage points at 50 Pa pressure difference is presented in table 2.

The dependance of the average ventilation rate on the air tightness of the building envelope is presented in fig. 8. The length of the calculation period was 7 months (1.10.-30.4.). The building was equipped with a natural ventilation system.

1.4 Conclusions

According to the calculations the model is working "well enough". Differences between the calculated and measured values are related rather than incorrect calculation principle, insufficient and erroneous input data. In larger buildings many simplifications are required for input data, which probably makes the model less realistic.

2. MEASUREMENTS OF INFILTRATION AND AIRTIGHTNESS

Measurement methods have been developed for both research and practical purposes. In developing activities, we have concentrated on the measurements of airtightness. In measuring air change rates, ventilation efficiency or infiltration, traditional tracer gas methods have been used.

2.1 Air change rate measurements

To measure local air change rates and ventilation efficiency in various rooms of a building, a ten-point measurement equipment with N_2O tracer gas is used, with constant tracer gas concentration.

The N_2O concentration used during the measurements is 500 ppm. This sets certain limitations for measuring, because the spaces to be measured shall be unoccupied during the test.

An example of measured outdoor air change rates of the rooms measured in a row house dwelling equipped with mechanical exhaust ventilation system are presented in fig. 9. The total outdoor air change rate of the dwelling was 0,54 ac/h. In the house there were not any special arrangements for supply air intake, but the air came in through untight spots of the building envelope. The total airtightness measured by the pressure test was 1,2 ac/h at 50 Pa.

2.2 Local airtightness

The collector chamber method has been developed at the Technical Research Centre of Finland, as a method for testing the airtightness of building components and structural joints in field.

The principles of the collector chamber method /3/ is presented in fig.10.

Because of the very large amount of building components and structural joints, it was necessary to develop a sampling inspection procedure. Even so, the measuring process may become very slow and unpractical and remains mainly as a research method. If, however, requirements are set for local air leakages (in order to avoid serious draught risks), even the existence of such a method is important.

In Appendix 1, the sample inspection method is presented. In Appendix 2, special instructions for the use of the method are shown.

2.3 Pressure test for larger buildings /4/

For blocks of flats, or other multi-cell buildings, the original pressure method is either too slow (flat by flat), or requires heavy measurement equipment. The elimination of leakages into/from other flats will often be complicated. These problems can be avoided by using existing fans, supply or exhaust, for pressurization of depressurization (every new multi-storey building has at least an exhaust fan). Air flows in each supply or exhaust unit, and outdoor-indoor plus flat-stairway pressure differences are measured. Generally, the measurement procedure is quick and easy.

The accuracy of the method depends on the accuracy of the method and devices used to air flow measurement. Available methods in most cases are accurate enough for practical purposes, to show if the building envelope is airtight enough (pressure differences high, 30 to 100 Pa, small deviation) or too leaky (difficult to create a measurable pressure difference). In some cases the test can also show, if ventilation system is properly adjusted or not. Our latest experiences show it quite clearly that this method is applicable as well in small houses (e.g. semi-detached or row houses) as in taller buildings having good air tightness and mechanical ventilation - no "test fans"will be necessary there.

2.4 Comments

The presented methods, combined (when necessary) with conventional pressurization test and/or thermography or smoke test for localizing the leaky points in building envelope and indoor structural joints (e.g. floors, partition walls, HVAC penetrations), form the basis for a controllability of air infiltration and air tightness. Completing them with calculations, using the multi-cell model developed, we can estimate the performance of the ventilation system as a whole, including the air infiltration.

3. MEASUREMENT DATA

3.1 Outdoor air change rate of a separate room

Improvements in the airtightness should always be "compensated" by ventilation arrangements: mechanical ventilation, or at least a contralled supply air intake through the building envelope. Previosly this fact was almost totally forgotten, with increased complaints on indoor air quality problems as a result.

Until recently, no measured data on outdoor air change rates of separate room in airtight buildings has been available. The first results were gained in January 1984 in an experimental row house apartement, provided with mechanical exhaust ventilation, without controlled air supply. The apartement examined had a good air-tightness: a leakage factor of 1,1 ac/h at 50 Pa.

The results are presented in Table 3. During the cut-off period (practically very common, as an extreme of "energy conservation") the air change rate was about 0,14 ac/h as an average, but in one of the bedrooms and in the living room measured outdoor air change rates were far below 0,1 ac/h. With basic fan speed, the total air change rate was fairly sufficient, about 0,7 ac/h, but again ventilation rates of various rooms of the dwelling differs rather much from each other.

Table 3. Outdoor air change rates of the rooms measured with tracer gas equipment in a row house dwelling provided with mechanical exhaust ventilation.

	fan on	fan off
Ground floor:		
bedroom 1	0,64 ac/h	0,05 ac/h
bedroom 2	0,58 ac/h	0,13 ac/h
bedroom 3	0,80 ac/h	0,15 ac/h
sauna	1,03 ac/h	0,19 ac/h
Upper floor:		
kitchen	1,26 ac/h	0,43 ac/h
living room	0,42 ac/h	0,04 ac/h

Differences in the measured outdoor air change rates of the rooms are due to differeces in the air tightness of the building envelope. Outside weather conditions may also effect on the results (outside air temperature was -1 degree °C, wind speed varied between 3-4,5 m/s).

Pressure differencies between outdoor - indoor air varied from 22 to 33 Pa (outside over pressure). The total exhaust air flow measured from the rooms (values marked in Fig. 9 a and b) agreed very well with the total air change rate measured by the constant concentration method (difference less than 1 %).

Constant concentration method and the equipment used in measurements is accurate enough to measure outside air change rate of a separate room in a dwelling. The tracer gas method submitted by pressure difference measurements can be used to study the physical reliability of multi-cell calculation models.

4. CONCLUSIONS

1. It is necessary to develop the models further. To control the performance of ventilation in larger buildings, the combination of infiltration models, air ductwork models and acoustic calculation models shall be developed. To gain reasonable calculation costs,

certain simplifications are necessary. This may be very difficult if we try to maintain certain accuracy.

2. Our knowledge on weather data and microclimatic conditions are not sufficient. It would be necessary to transform weather data into the microclimatic parameters of the actual building. Maybe these efforts are totally unreasonable - if we compare the results from various field measurements and wind tunnel tests made in various countries.

3. "A new way of thinking" is necessary, we need increased co-operation, in design and construction of buildings, between building and HVAC. Structures and the ventilation system have influences on each other - the new calculation models are together a useful tool in approaching the design problem as a whole.

4. Requirements and standards need further developments. Indoor climate, control of pressure conditions and air flows etc. - the need of standars, based on careful calculations and practical experiences, is evident.

REFERENCES:

/1/ Railio,J., Saarnio,P. & Siitonen,V., Air infiltration research in Finland. Espoo 1980. Technical Research Centre of Finland, Laboratory of Heating and Ventilating, Report 52, 26 p. + app. 12p.

/2/ Brown,K.M., A quadratically convergent Newton - like method based upon Gaussian elimination, Siam J. Numer. Anal, 6 (1969) 4, s. 10.

/3/ Siitonen,V., Measurement of local air tightness in buildings, Espoo 1982. Technical Research Centre of Finland, Research Notes 125. 17 p + app. 12 p.

/4/ Railio, J., Saarnio, P., Methods for measuring the air tightness and air change rates in buildings. Espoo 1983. Technical Research Centre of Finland, Research Notes 253, 54p + app. 2p. (in finnish)

/5/ Sampling procedures and charts for inspection by variables for per cent defictive. Standard ISO 3951-1981. 105 p.

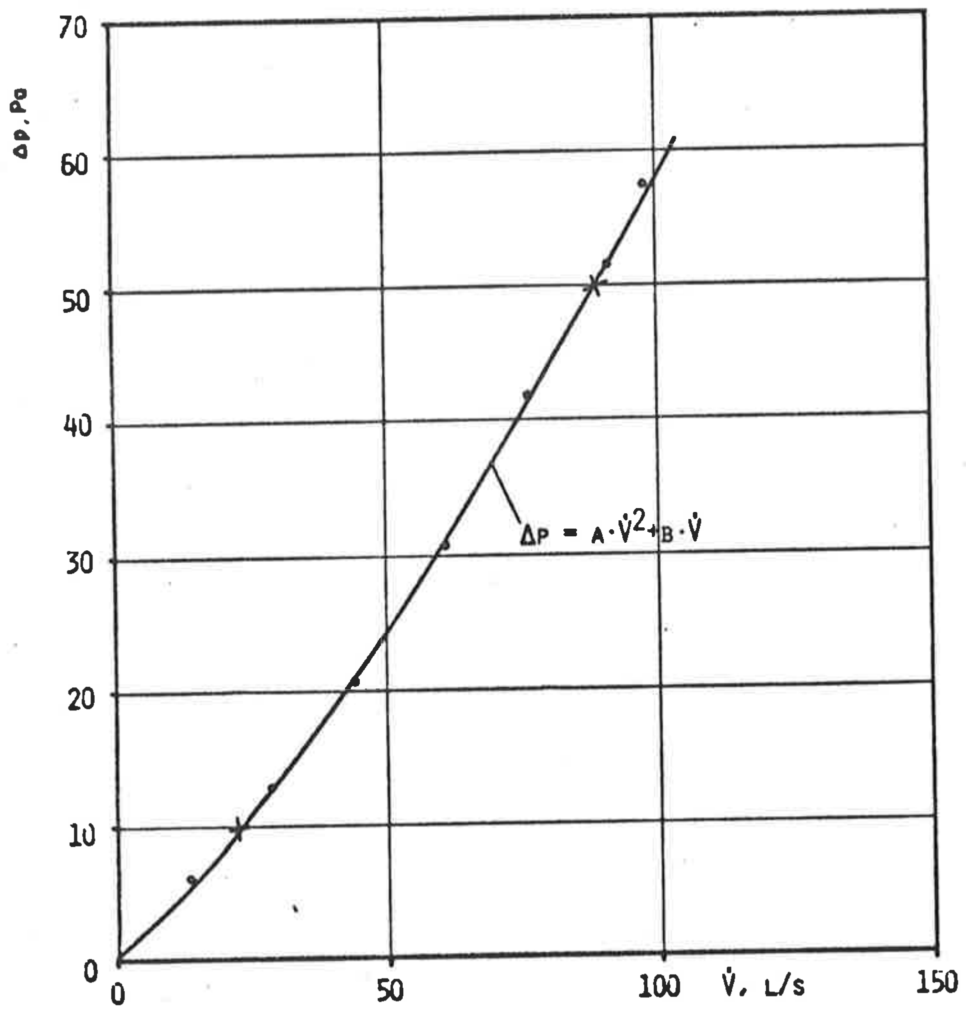

Fig. 1. Interconnection between the pressure difference and the total air leakage of building envelope. The coefficients of the quadratic flow equation were calculated from experimental values at 10 Pa and 50 Pa. Marked points are the values measured with pressure test.

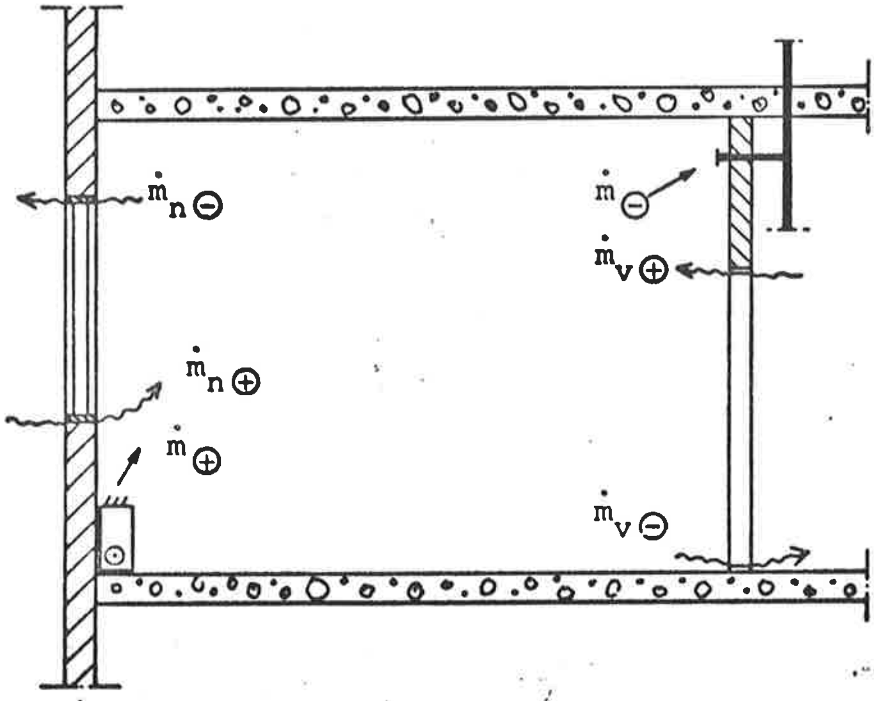

Fig. 2. The different elements of ventilation of a room

$\dot{m}_+$ supply air flow

$\dot{m}_-$ exhaust air flow

$\dot{m}_{n+}$, $\dot{m}_{n-}$, $\dot{m}_{v+}$ and $\dot{m}_{v-}$ are the air leakage flows through the outside walls and partition walls

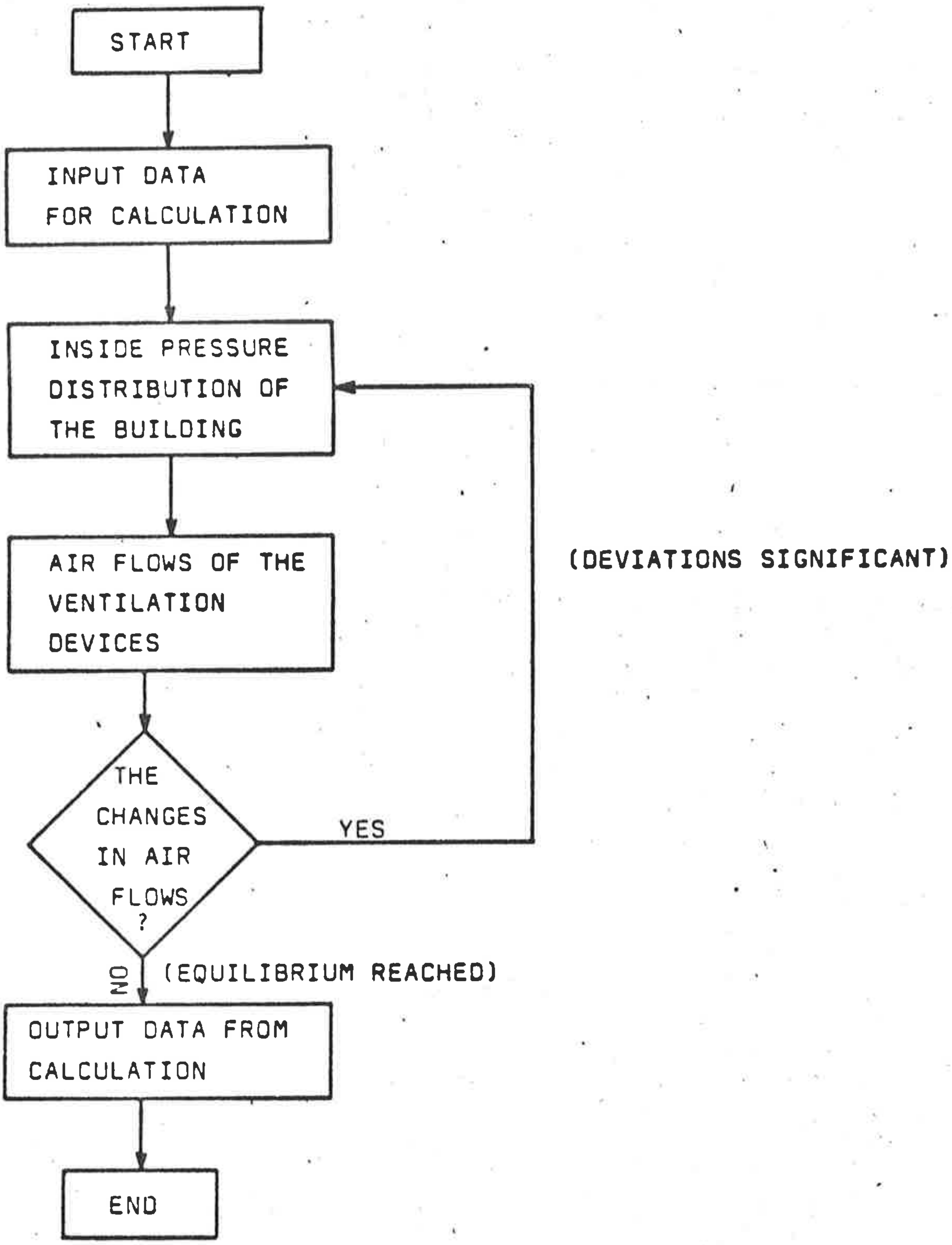

Figure 3. The calculation principle for calculation the flow equilibrium of the building.

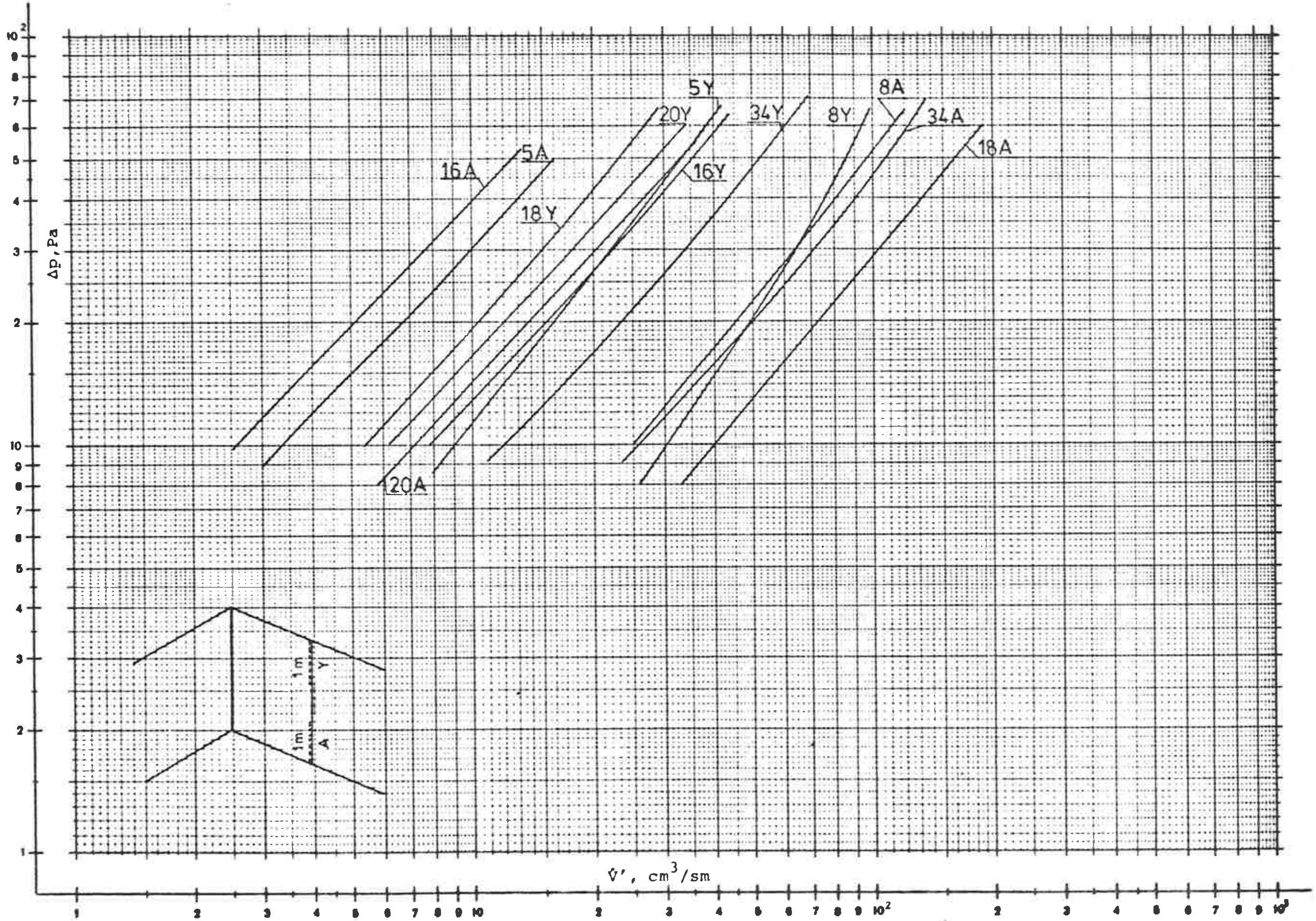

Fig. 4. Air leakage curves of vertical joints between elements measured with collector chamber method in a wooden constructed detached house.

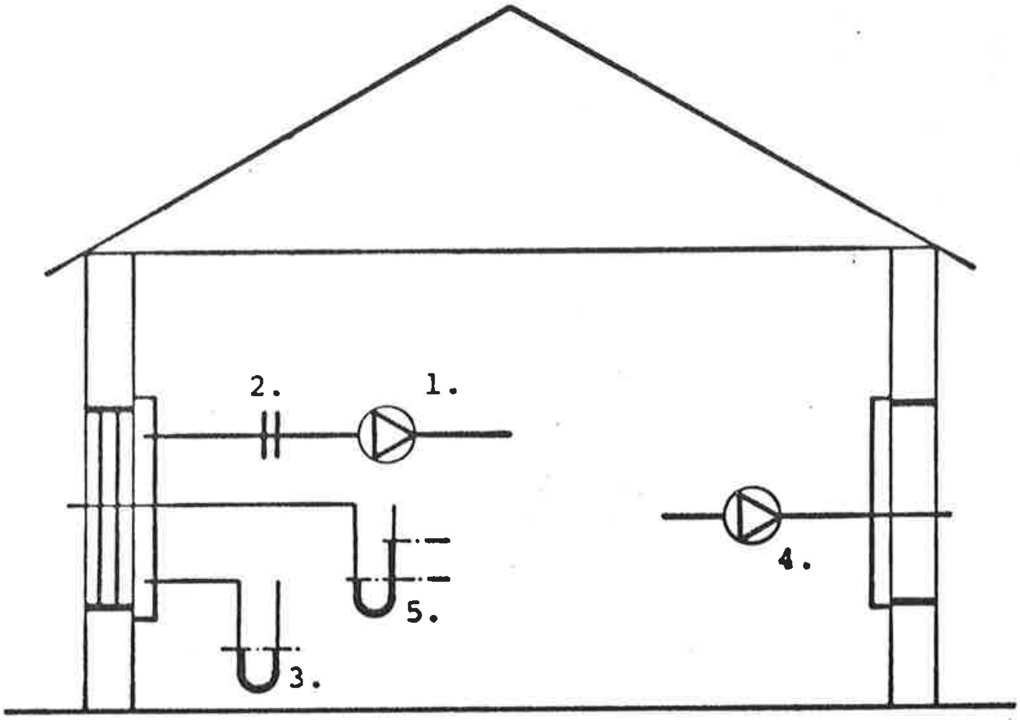

Fig. 5. Measurement of the total air leakage of a window with collector chamber method

1. Adjustable fan
2. Air flow meter (orifice plate)
3. Pressure difference between collector chamber and indoor air (electric manometer)
4. Auxiliary fan (adjustable)
5. Pressure difference across the structure

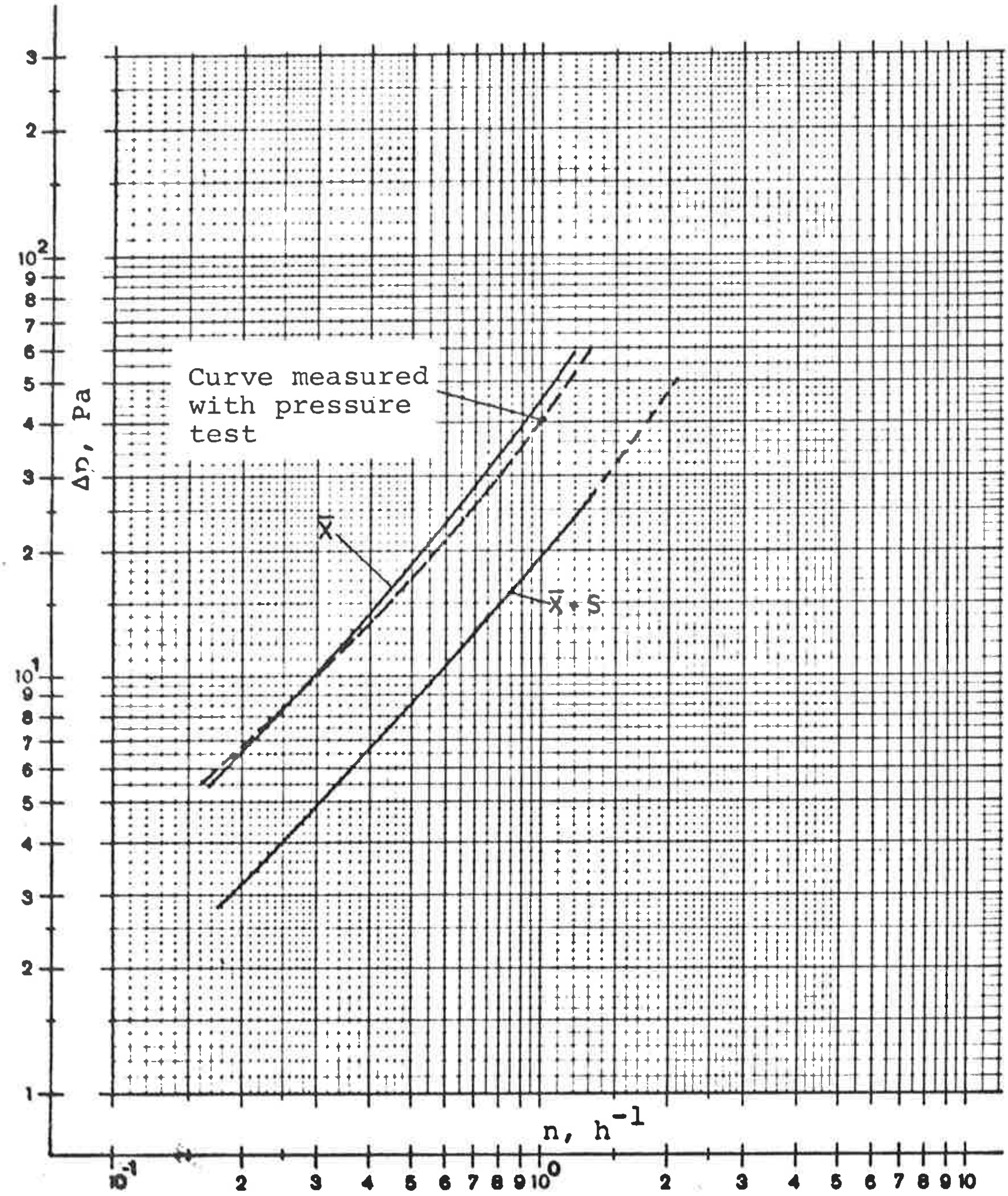

Fig. 6. Comparison of the leakage curves calculated by the model with the curve measured with the pressure test. Curve $\bar{x}$ is calculated by using the average leakage values of the samples to each crack type and curve $\bar{x}$+s by using the average values of the samples added by the standard deviation of the sample.

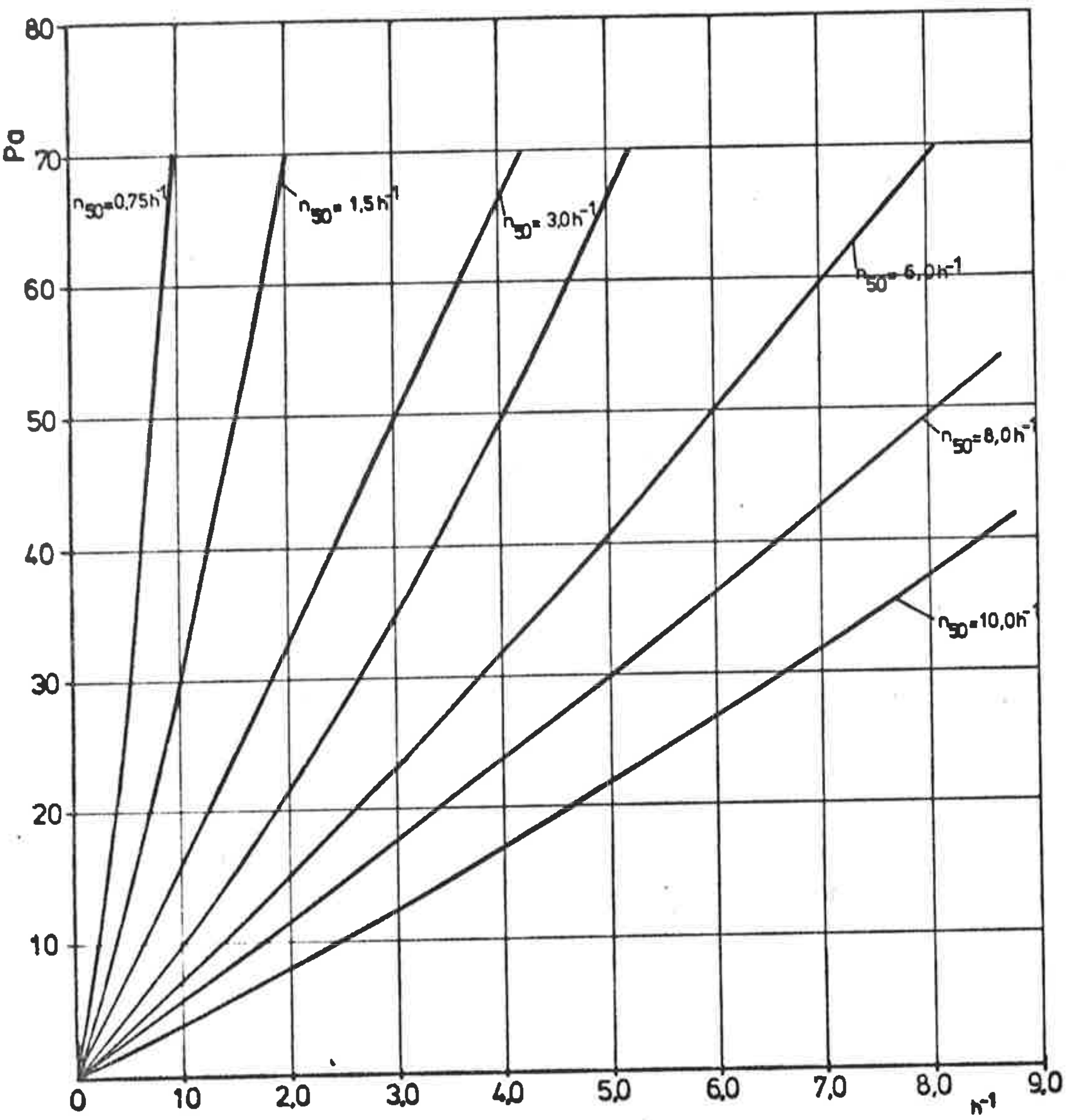

Fig. 7. Pressure test curves calculated by the model to a detached house of masonry wall stcucture.

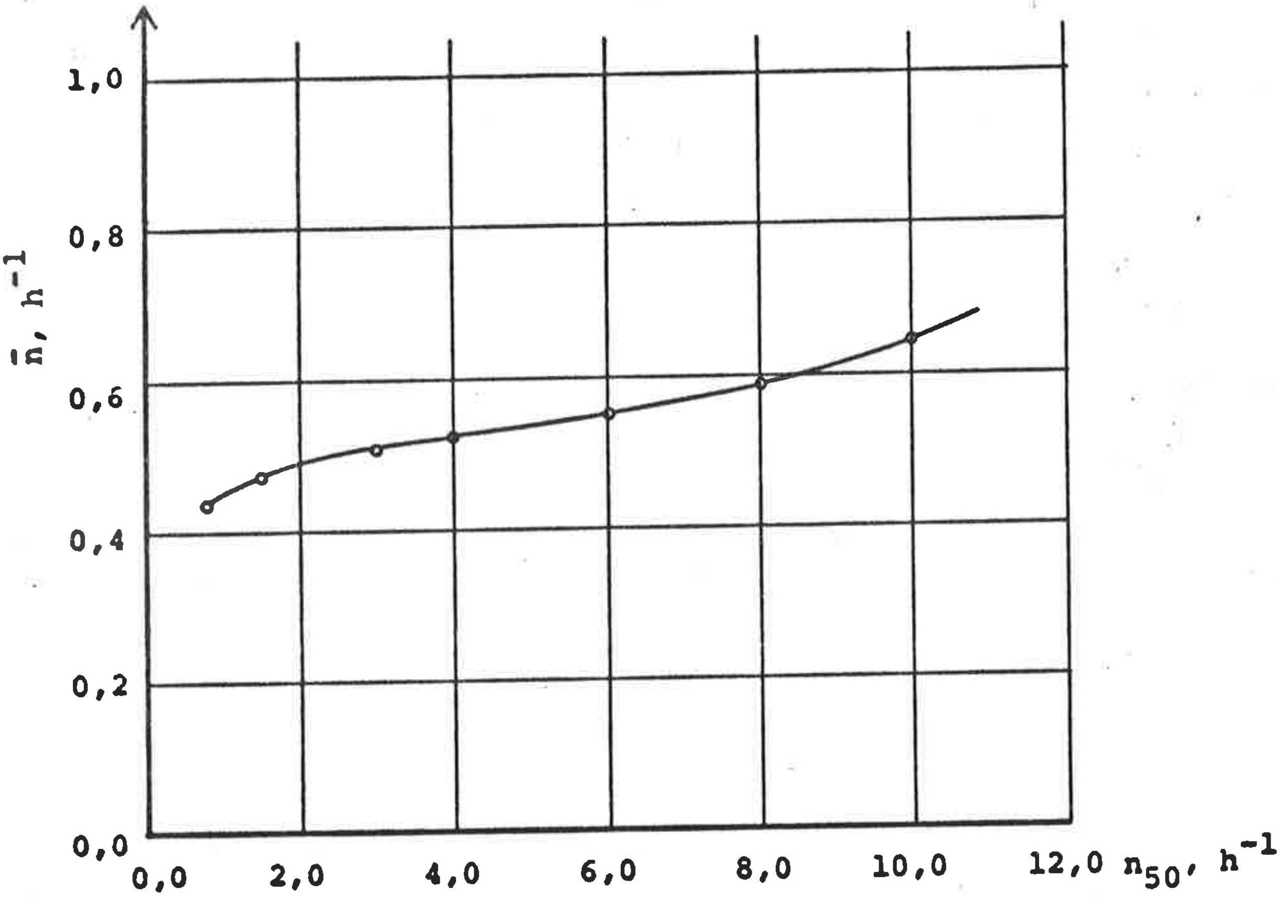

Fig. 8. The dependance of the average ventilation rate on the specific leakage of the building envelope. A detached house (masonry wall structure) equipped with natural ventilation system (+ a kitchen fan used one hour/day). The length of the calculation period was 7 months (1.10.-30.4.).

GROUND FLOOR

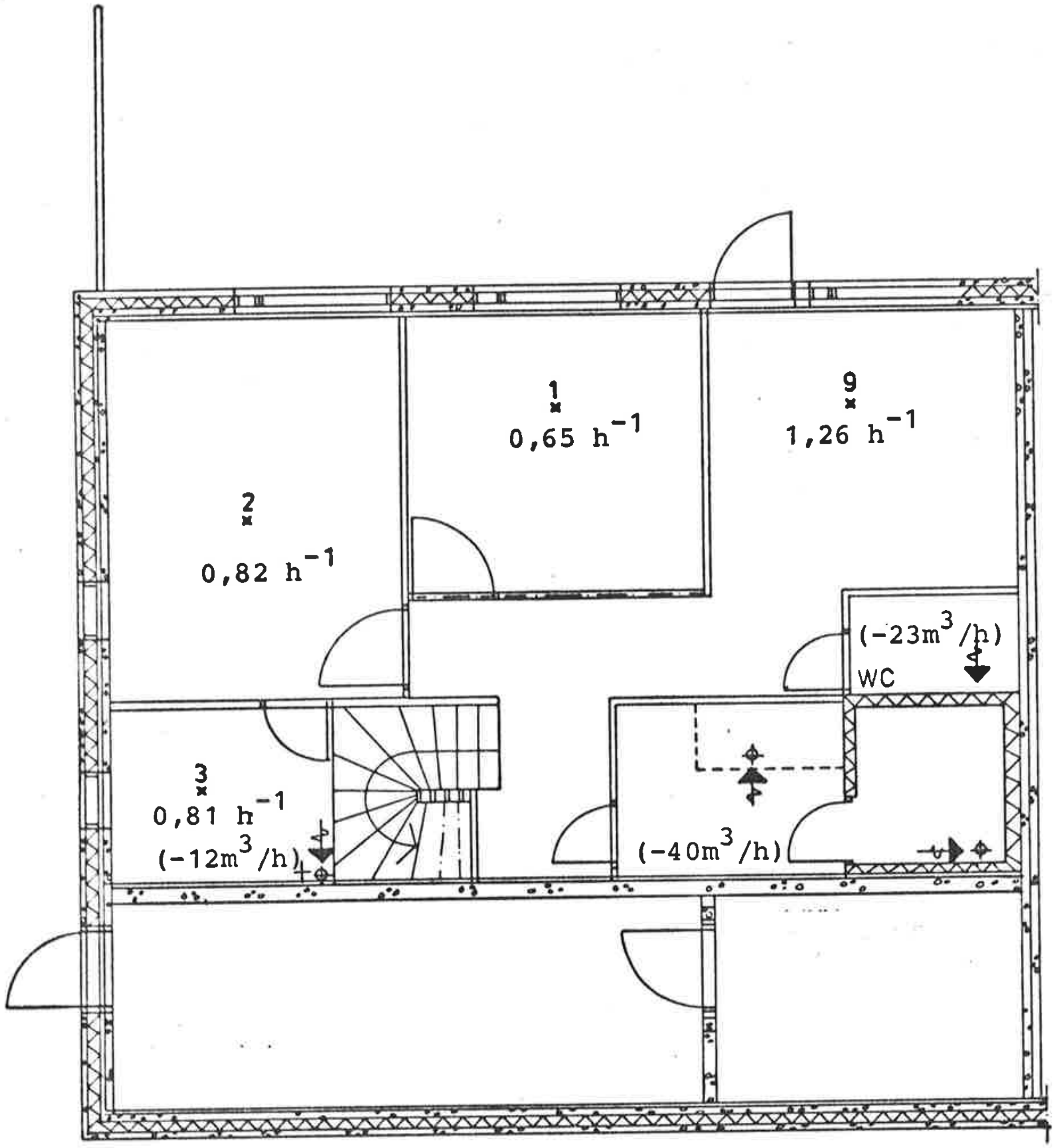

Fig. 9a. Outdoor air change rates of the rooms in the ground floor measured with the tracer gas equipment (constant concentration method). Exhaust air flows marked in paranthesis.

Measurement points:

1,2,9 bedrooms

3 clothes

UPPER FLOOR

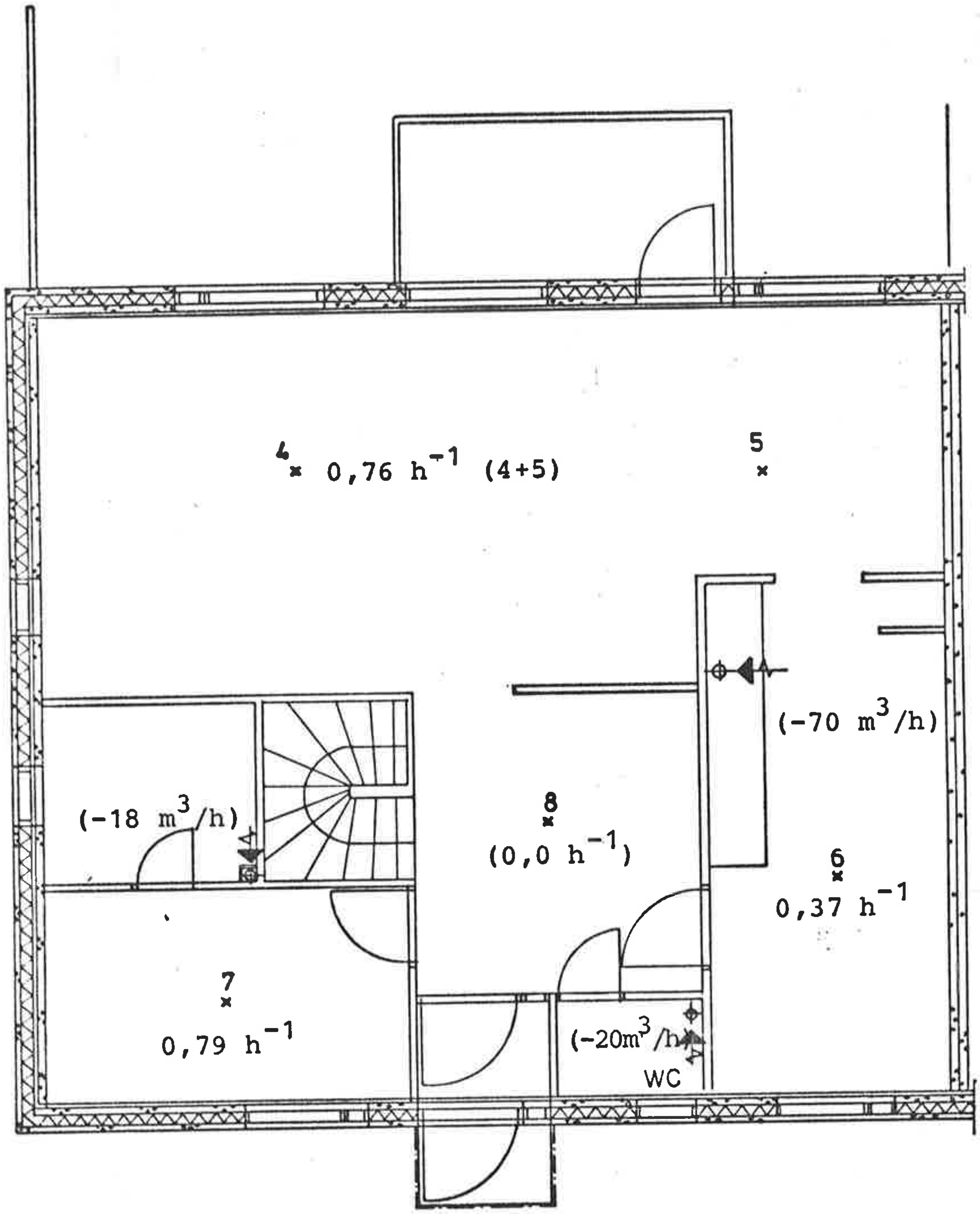

Fig. 9b. Outdoor air change rates of the rooms in the upper floor measured with the tracer gas equipment (constant concentration method). Exhaust air flows are marked in parenthesis.

Measurement points:

4,5	living room	7	bedroom
6	kitchen	8	hall

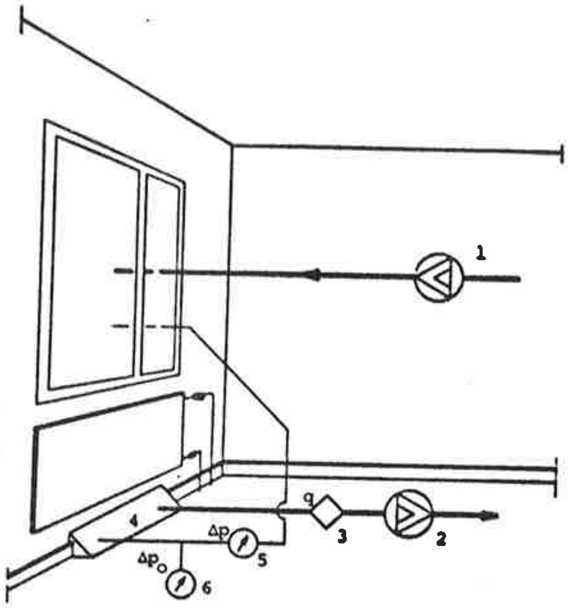

Fig. 10. Measurement of a specific air leak of the joint between outer wall and floor.

1. Adjustable auxiliary fan
2. Adjustable measurement fan
3. Volume flow meter (e.g. orifice plate)
4. Collector chamber
5. Micro-manometer for the test pressure difference Δp
6. Micro-manometer for the pressure difference Δp_o between collector chamber and room (zeroing indicator).

Sample inspection.

1. Tightness requirement

The tightness of a given lot of joints or structures is acceptable if not more than p % of items have a greater specific leak than a specification limit q_1. If q_1 is given for a unit of length or for an area, the applicable size of an item shall be specified.

2. Inspection procedure

The following is an application of the "s" method, described in reference /2/:

1) Estimate the total number of items in the lot.
2) Select the acceptable quality level p and obtain the sample size n and the acceptability constant k using table 1.
3) Take a random sample of size n and measure the specific leak q of each item in the sample.
4) Calculate from the sample

the sample mean $\bar{q} = \sum q/n$ (4)

the estimated standard deviation $s = \sqrt{\dfrac{\sum(q-\bar{q})^2}{n-1}}$ (5)

5) If $\bar{q} \leq q_1 - k\,s$ (6)

the lot is acceptable. If not, the lot must be repaired (tightened) and reinspected.

Table 1.

Sampling plan and acceptability constant k for inspection of local tightness in building. "s" method /5/.

lot size N	sample size n	Acceptable quality levels p = 2,5% k	p = 10,0% k
≤ 15	3	1,12	0,566
16 - 25	4	1,17	0,617
26 - 50	5	1,24	0,675
51 - 90	7	1,33	0,755
91 - 150	10	1,41	0,828
151 - 280	15	1,47	0,886
281 - 400	20	1,51	0,917
401 - 500	25	1,53	0,936
501 - 1200	35	1,57	0,969
1201 - 3200	50	1,61	1,00
3201 - 10000	75	1,65	1,03

Special instructions

The walls of the collector chamer shall be rigid enough to keep its volume constant at varying pressure difference. Therefore walls of, e.g. plastic foil, should be stretched and thin board walls should be supported with appropriate stiffeners.

The collector chamber can be kept in place by pressing it mechanically against the test object and tightening it, e.g. by elastic rubber strips, tape etc.

In windy weather the outside test pressure should be measured exactly in front of the object to get a correct reading.

Local temperature and altitude differences along the measurement hose between the collector chamber and the zeroing indicator may introduce disturbing pressure components into the hose. To eliminate this error, the indicator zero point shall be checked periodically by disconnecting the end of the hose from the collector chamber.

If the pressure conditions in the object are continuously varying due to, for instance wind, or the inside activitites in the building, the zeroing of the collector chamber pressure difference can be carried out as follows:
The pressure difference is varied a little by regulating the auxiliary blower. The measurement air flow remains nearly constant. Some coincident readings of test pressure difference and zero deviation of the collector chamber pressure difference are obtained. From these readings the "right" test pressure difference is determined by a graphical insterpolation, as shown in figure 1.

Another method to elimintate varying pressure conditions is to read the test pressure difference and air flow rate simultaneously when the indicator of the collector chamber pressure difference is passing through the zero point up and down. The averages of both readings are used as a result of the measurement.

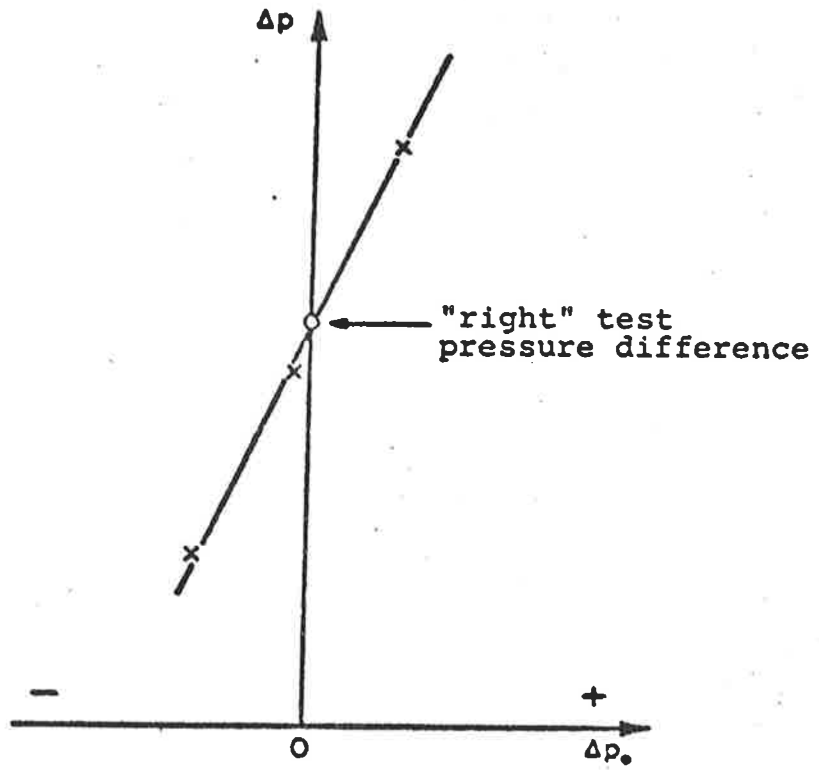

Fig. 1. The graphical zeroing of the collector chamber pressure difference when volume flow is constant.

Δp test pressure difference

Δp_o collector chamber pressure difference.