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Determination of air leakiness of building envelopes using pressurization at low pressures

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1. INTRODUCTION

Pressurization, or depressurization, of buildings is a tool to assess the airtightness of building envelopes. This is mainly of interest for testing building designs and, for particular buildings, to evaluate roughly the impact of air infiltration and exfiltration on the thermal balance of the building and, combined with infrared thermography, to detect leakage sites of building envelopes.

The pressurization or depressurization is usually carried out at a pressure difference across the building envelope sufficiently high to ensure that the effect of aeromotive forces and buoyancy forces can be neglected. A common working pressure difference is 50 Pa and the airtightness is expressed in terms of the number of air changes per hour at 50 Pa. Airtightness norms for whole buildings have been specified in the Building Code of some countries, for example Sweden and Norway.

Building pressurization in most cases requires the use of portable fans mounted on an adjustable frame that can be fitted into a window- or doorframe. This assembly is called a blower-door (see Fig. 1). Blower doors have mainly been used for houses and single apartments, pressurization of large buildings may require the use of fans that can only be transported to the site by flat-bed trucks.

For large buildings, an interesting concept is to use the fans of the ventilation system for pressurization. However, it is then not always possible to achieve a pressure difference of 50 Pa across the building envelope. This may be the case also for leaky houses even if a blower door is used.

Expressing the airtightness in terms of the number of air changes per hour at 50 Pa makes it difficult to compare the airtightness of buildings of different size. It is not self-evident how to normalize with respect to the area of the building envelope.

Fig. 1 Blower door test

In this paper we investigate in more detail a method earlier proposed (1). Applying this method one can:

1. Use low pressure data to assess the airtightness of building envelopes, and
2. Express the air leakiness in terms of a non-dimensional entity, the relative leakage area, which makes it possible to compare differently sized buildings.

The data base used in the analysis consists of pressurization-depressurization data from about 300 houses and apartments collected by the indoor climate measurement unit of the Swedish Institute for Building Research.

2. DESCRIPTION OF THE METHOD FOR ANALYSIS

Using building pressurization data to plot the air flow across the building envelope versus the pressure difference, one in general obtains a plot where data points for pressurization and depressurization fall on two slightly convex curves displaced relative to one another (see Fig. 2)

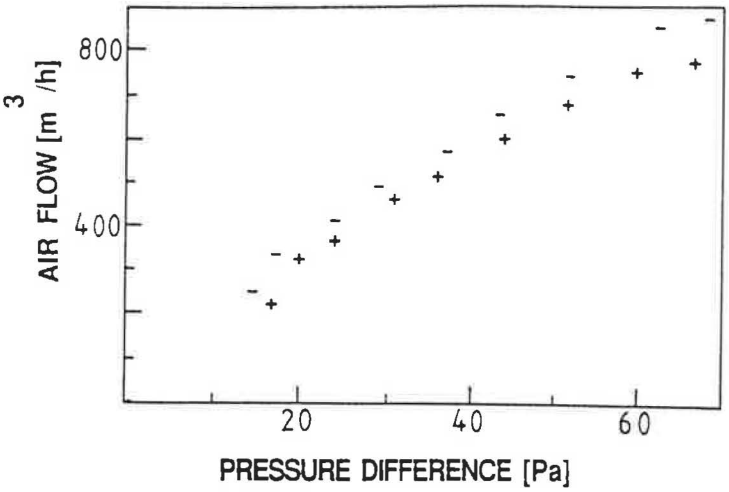

Fig. 2 **Example of data points from pressurization (+) and depressurization (-) tests.**

With data such as in Fig. 2, it is possible to interpolate the pressurization and depressurization curves to a pressure difference of 50 Pa, form the average of the corresponding air flows, and express this average in terms of air changes per hour of the building. Extrapolation of the curves in the plot to pressure differences occuring in real life, rarely above 10 Pa, is difficult because of:

1. The curvature of the data, and
2. The influence of aeromotive and buoyancy forces, and other factors.

It is quite possible to calculate theoretically a correction, Δp, to the pressure difference measured, p, that compensates for aeromotive and buoyancy forces. This is not of much practical use as one has to consider also factors such as windows and doors moving slightly inwards or outwards with changing pressures, the onset of threshold effects for flows in cracks and, perhaps the most important source of error, the placement of the outdoor pressure gauge which affects the calibration. All these factors are responsible for the displacement of the pressurization and depressurization curves, and their exact impact on data collected is not known. Therefore, instead of a theoretical determination of the pressure correction, Δp, one has to determine the magnitude of the correction from data.

What is required is an approach by which one can compensate for the above factors by bringing the pressurization and depressurization curves on top of one another and, at the same time, take away most of the curvature to facilitate extrapolations to low pressures. It is well known from hydrodynamics that the air flow rate for relevant flow regimes should grow as the square root of the pressure difference. This has been confirmed by field tests to be roughly true also for pressurization data from buildings, even if there is no reason a priori why this should be so due to the complexity of the air flows across building envelopes.

To take away the curvature, we use instead of the variables pressure difference, p, and air flow rate, q, a new set of variables, the flow speed, v, defined from

$$v=\sqrt{(2p/\varrho)},$$

ϱ being the air density, and the variable α, the relative leakage area, defined from

$$\alpha=q/(vA),$$

where A is the area of the building envelope.

The variable v has the dimension of velocity and is a measure of the average flow speed across the building envelope, while α is a dimensionless variable describing the effective cross-sectional area of cracks and holes per square meter of the building envelope.

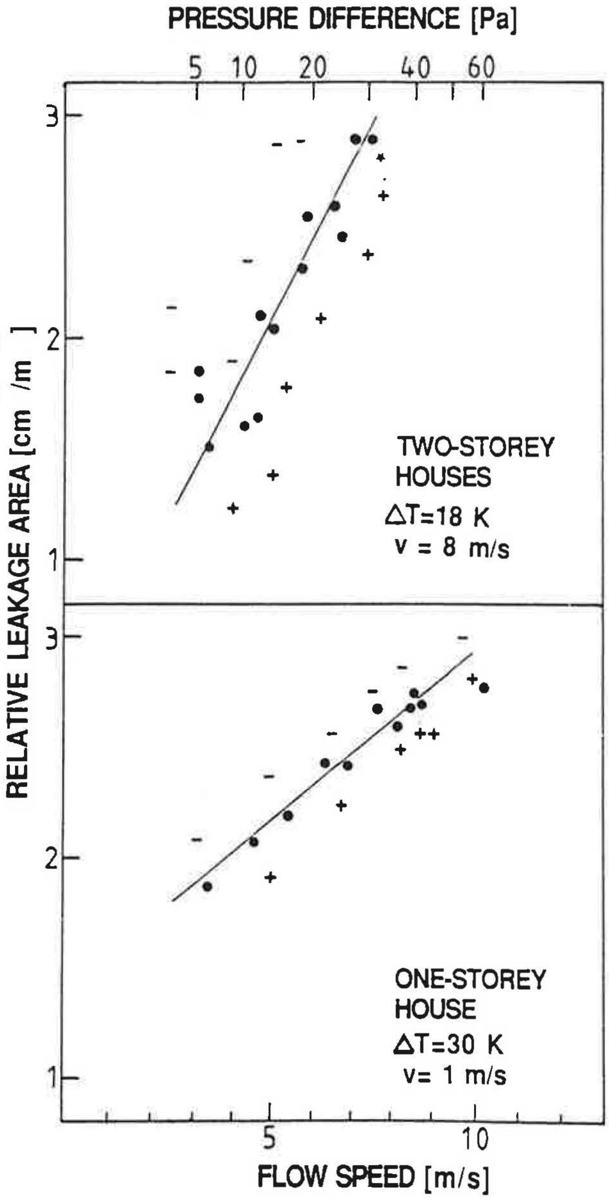

Fig. 3 Measured data points from pressurization (+), depressurization (-) and resulting data points (dots) for two houses. The full-drawn line indicates the resulting dependence of the relative leakage area on the flow speed.

Suppose we have originally two sets of data points, (p^+,q^+) and (p^-,q^-), where the upper indices + and - refer to pressurization and depressurization data, respectively (as in Fig. 2). Now apply the following procedure:

1. Construct data sets in the new variables v and α, (v^+,α^+) and (v^-,α^-). This step removes the square root type curvature and, plotting data in a (v,α) plot, one obtains data points that approximately fall on two straight lines (see Fig. 3)

2. Create a new data set common for pressurization and depressurization data by introducing new data points (v,α) where the pressures p^+ and p^- are replaced by $p^+ + \Delta p$ and $p^- - \Delta p$, respectively. Written out in full detail:
   $(v,\alpha) = (\surd[2(p^+ + \Delta p)/\varrho] \ , \ q^+/A/\surd[2(p^+ + \Delta p)/\varrho] \ )$
   for the pressurization data and,
   $(v,\alpha) = (\surd[2(p^- - \Delta p)/\varrho] \ , \ q^-/A/\surd[2(p^- - \Delta p)/\varrho] \ )$
   for the depressurization data.

The pressure correction Δp, which may be positive or negative, is now chosen so that the pressurization and depressurization data fall on the same, best fitted, straight line through all data points. This step brings the pressurization and depressurization data together. In most cases, the pressure correction Δp takes a value of a few Pa, or less.

In practice, the second step described above is carried out directly, the description of the first step here only serves an illustrational purpose. Some examples of the resulting data set are displayed in Fig. 3.

One can now choose a reference pressure (or flow speed), read off the corresponding value of the relative leakage area by interpolation or extrapolation of the straight line in the (v,α) plot, and use this value to characterize the air leakiness of the building envelope. It is common to use a value of 4 Pa (corresponding to a flow speed of 2.5 m/s) as reference pressure, a pressure roughly corresponding to the average pressure across the building envelope for external temperatures and wind speeds normal to many climatic regions. We will denote the leakage area at 4 Pa by $\alpha(4)$ and the air exchange rate per hour at 50 Pa by $n(50)$.

When does the above procedure not work? Out of 300 tested cases this method worked in all but two cases. Both were very leaky buildings where it was not possible to attain a pressure difference of more than 10 to 20 Pa using an ordinary blower door, and no air flow could be detected for pressurization until a pressure of 10 Pa was established. The original data for one of the two cases are displayed in Fig. 4.

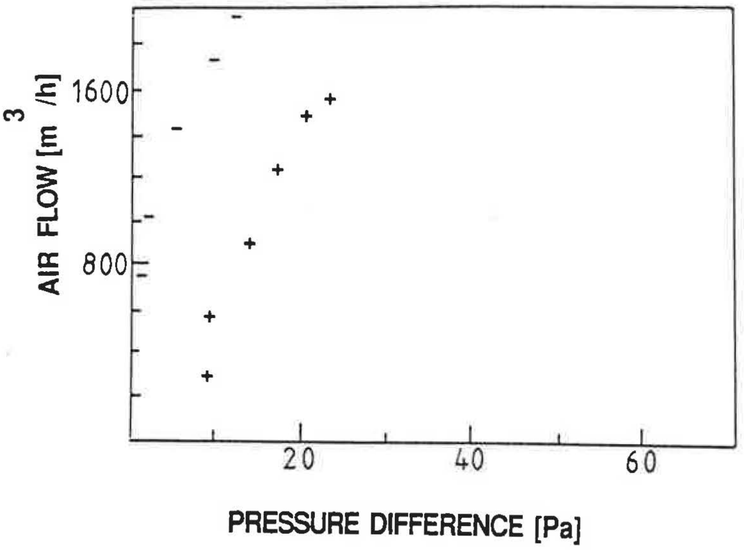

Fig. 4 Air flow across building envelope versus pressure difference for a very leaky house. (+) pressurization and (-) depressurization.

3. APPLICATION OF THE METHOD

To determine if the method described in the previous section can be used in practice, there are a number of questions that have to be answered:

1. What is the correlation between the relative leakage area at 4 Pa, $\alpha(4)$, and the rate of air change at 50 Pa, n(50)?
2. What is the reproducibility of the method?
3. What are the errors of the method?
4. Does the leakage area obtained depend on how and where the air flow was recorded and how the pressurization was carried out, for example, will the results differ if a kitchen fan is used for pressurization instead of a blower door?
5. Does the method yield the same result if low pressure data, say pressures in the range 10 to 20 Pa, are used instead of pressures in the more normal range 20 to 70 Pa?

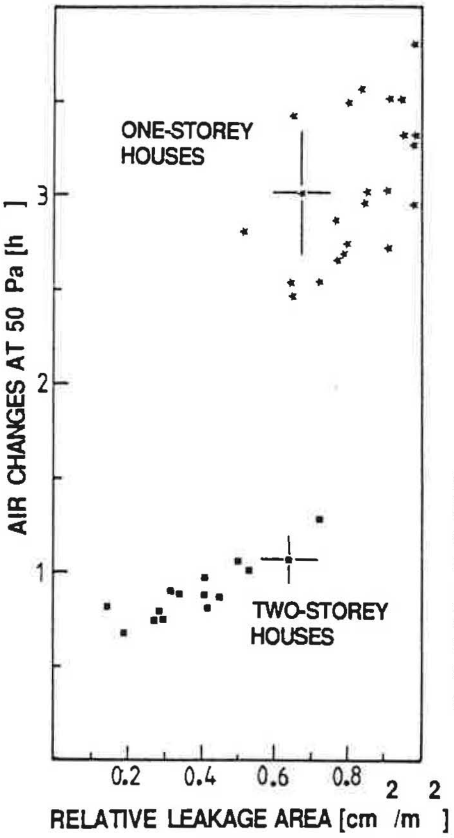

Fig. 5
Air changes per hour at 50 Pa versus relative leakage area for a group of one-storey (stars) and two-storey (squares) townhouses. The one-storey houses are known to have air leak paths at the joint between ceiling and exterior wall. The bars indice estimated size of errors.

We have used the available data set of 300 pressurization tests to provide answers to the above questions. To answer the first question, we first look at a group of 15 two-storey and 23 one-storey town-houses. The one-storey and the two-storey houses are nominally of an identical design, but thermography has revealed that the joint between the attic and the exterior walls of the one-storey houses is a major air leakage path.

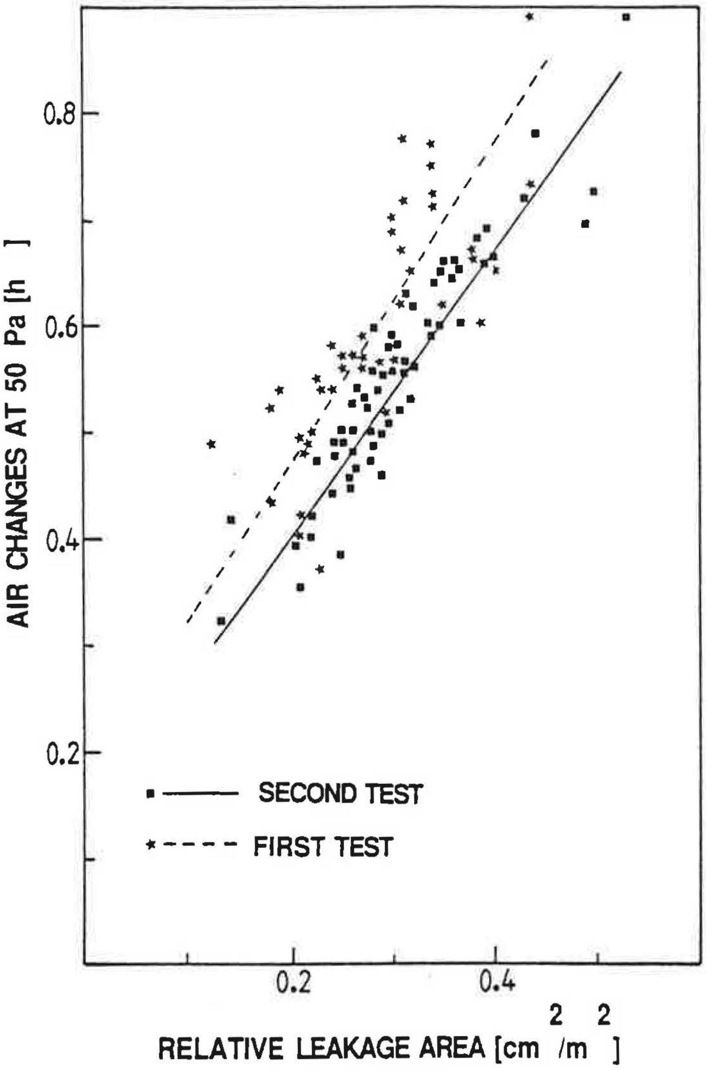

Fig. 6 Air changes per hour at 50 Pa versus relative leakage area for a group of 44 nominally identical townhouses. Pressurization tests were carried out twice within a year.

The correlation between the relative leakage area, α, and the air flow rate at 50 Pa, n(50), is rather good for the two-storey houses, the correlation coefficient is about 0.9, but not so good for the leaky one-storey houses, the correlation coeffient is smaller than 0.7. However, considering the measurement errors, the degree of correlation is acceptable. The difference in α(4) is smaller than the difference in n(50) between the two groups of houses. Data are displayed in Fig. 5.

We next study a group of 44 nominally identical, very airtight, two-storey townhouses. Pressurization tests were carried out twice with an interval between of one year. The air flow rate n(50) has been plotted versus the relative leakage area α(4) in Fig. 6. The coefficient of correlation takes a value of about 0.9.

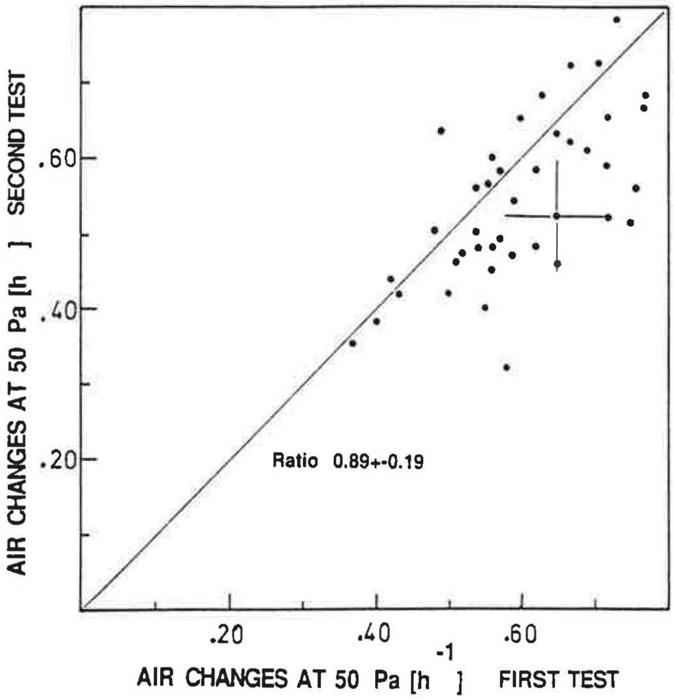

Fig. 7 **Measured air change rate per hour from one test versus corresponding data from another test for 44 nominally identical townhouses. Calibration errors result in an average ratio different from 1.0 by 10 per cent.**

Linear regression for the two data sets yields straight lines that are approximately parallel to one another, but seem to be shifted. There is obviously a calibration error, or the air-tightness has changed between the two pressurization tests.

To study this effect in more detail, and to get an estimate of the combined effect of measurement errors, we have submitted data to the following test. First plot data on n(50) and α(4) from the first pressurization test versus data from the second pressurization test (see Fig. 7 and 8). The ratio <u>of</u> the values of the first test <u>to</u> the values of the second test (the ratio First/Second) can then be calculated, yielding a value of 0.89+-0.19 for n(50) and 1.03+-0.22 for α(4).

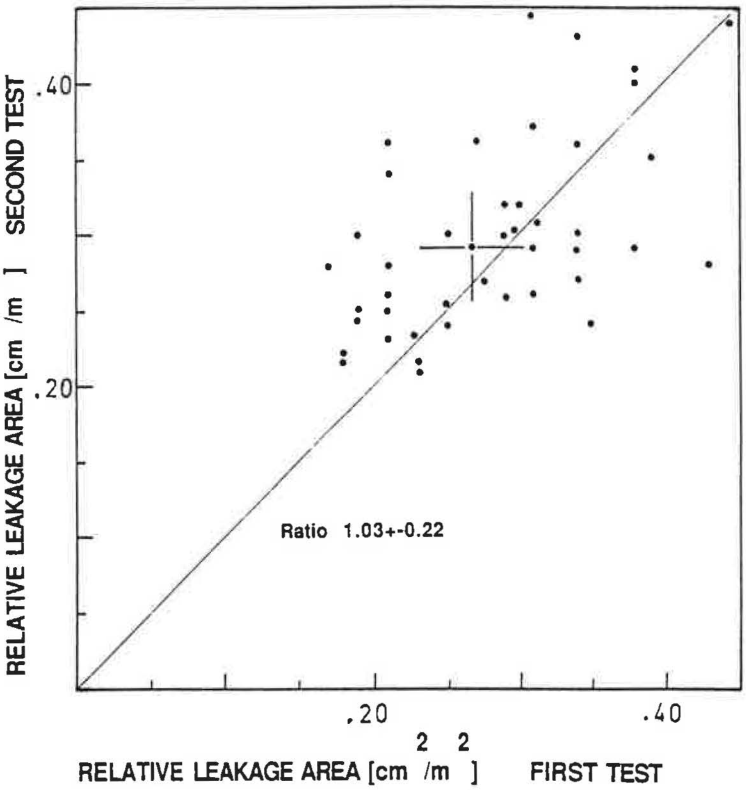

Fig. 8 Calculated relative leakage area from one test versus corresponding data from another test for 44 nominally identical townhouses. Pressure corrections reduce calibration errors from 10 (see Fig. 7) to 3 per cent.

As there is no known reason why the airtightness of the houses should have changed, this can be interpreted as there being a difference, due to calibration errors, between the first and the second test of 10% for n(50) and 3% for α(4). Obviously, the method applied in the calculation of α(4) has removed most of the calibration errors.

We then assume that a repeated number of measurements to determine the values of n(50) and α(4) for the same house would yield data sets that follow the Γ-distribution function. This distribution is sufficiently flexible that its two free parameters, the scaling factor and the average, can usually approximately accomodate data sets taking values in the range $(0,\infty)$. It is, thus, assumed that data from all houses would follow this distribution, but the values of the scaling and the average may differ between houses. The ratio First/Second then follows the F-distribution function.

One can now, after correcting for the calibration error so that the average values of n(50) and α(4) for the two test periods are the same, calculate the errors of n(50) and α(4). The analysis yields an error for n(50) of 15% and 12% and for α(4) of 20% and 18% for the two test periods, respectively. These errors are to be regarded as comprising measurement errors and errors inherent in the methods. Measurement errors should be expected to be smaller than 10%. However, the data sets for these houses include data points with pressure differences below 20 Pa only for four or five of the houses. The determination of the values of α(4) then involves a very long extrapolation (see Fig. 3) down to a pressure of 4 Pa. The error of α(4) can, therefore, be expected to decrease substantially for data sets containing low-pressure data.

The analysis above could be carried out because of the large variation in airtightness between these nominally identical houses. This may be an effect of the airtightness of the houses, small differences in the performance of the air seal can produce large relative differences in airtightness.

Judging from the data on the two groups of townhouses discussed above, there is a fairly good correlation between the air change rate n(50) and the relative leakage area α(4). The reproducibility of the methods is rather good if one uses as a criterion that the slopes of the straight lines in Fig. 6 should be similar. However, the occurence of calibration errors somewhat blurs this picture. The resulting errors, apart from calibration errors, are smaller than 15 % for n(50) and smaller than 20 % for α(4). The error for α(4) can be expected to decrease if low pressure data are used. This concludes the analysis to answer the first three questions above.

To provide an answer to the fourth question, the leakage area α(4) deduced when using a blower door has been plotted versus the value of α(4) obtained when using the kitchen fan duct for pressurization and measurements (see Fig. 9). The data are from the data set of the group of 44 nominally identical townhouses.

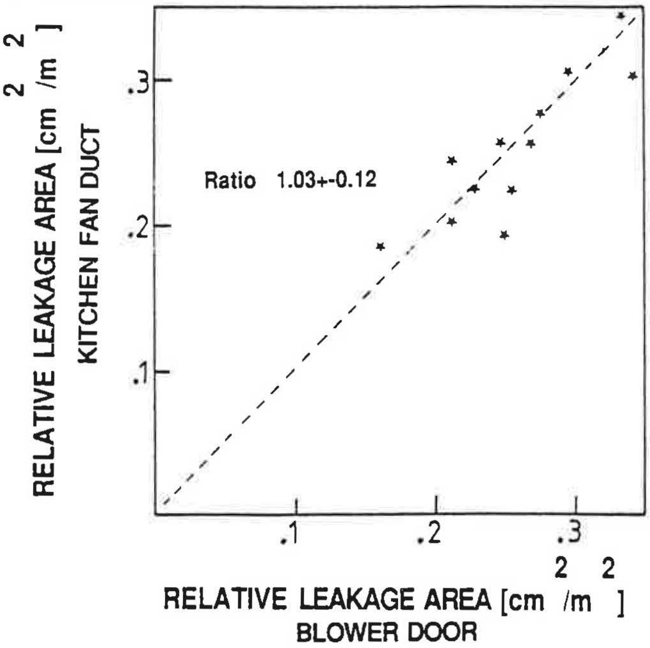

Fig. 9 Relative lekage area calculated from data measured when pressurization and measurements were carried out using the kitchen fan duct versus corresponding data using a blower door. There are no systematic differences.

In practice, a portable fan was used as the kitchen fan in these houses could not be reversed and, thereby, not be used for pressurization <u>and</u> depressurization. This experiment was carried out for twelve houses.

The average ratio <u>of</u> the leakage area obtained when using a blower door <u>to</u> the value obtained when using the kitchen fan duct is 1.03+-0.12. There is, thus, no systematic difference between the use of a blower door and the use of a kitchen fan duct for pressurization.

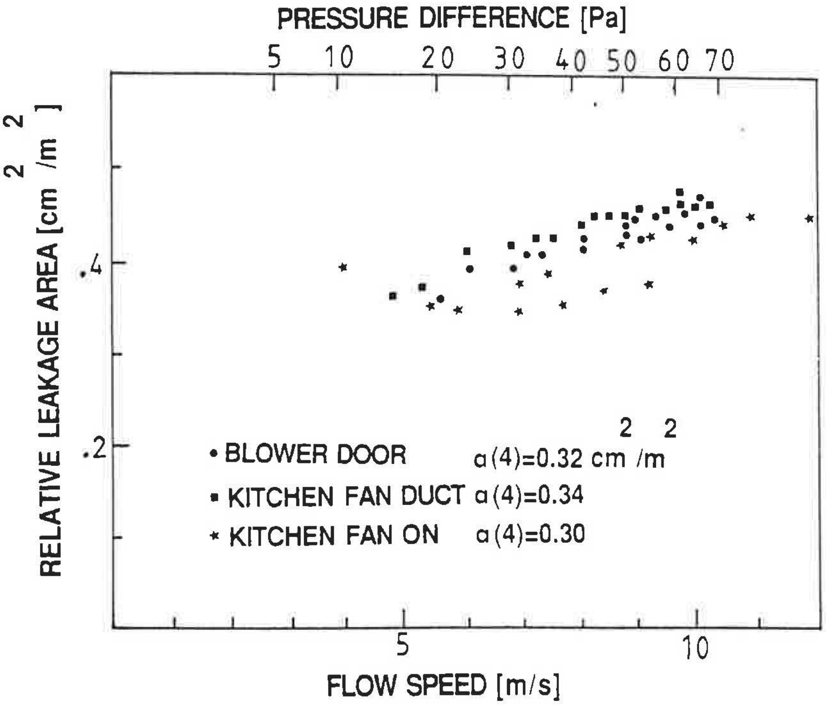

Fig. 10 Relative leakage area versus flow speed for a townhouse. Data from blower door test (dots), kitchen fan pressurization (squares) and measurements while kitchen fan running creating a pressure difference of 20 Pa across the building envelope (stars).

For some of the houses, it was investigated what was the effect if the measurements were carried out while the kitchen fan was running, creating a pressure difference of 20 Pa across the building envelope. The (α,v) plot for one of the houses is displayed in Fig. 10. The resulting value of $\alpha(4)$ is not too different from the value obtained when the kitchen fan was shut off. This indicates that it should be possible to use the method for determination of the relative leakage area also in buildings where the ventilation system must be kept running. The data did not allow for a determination of n(50).

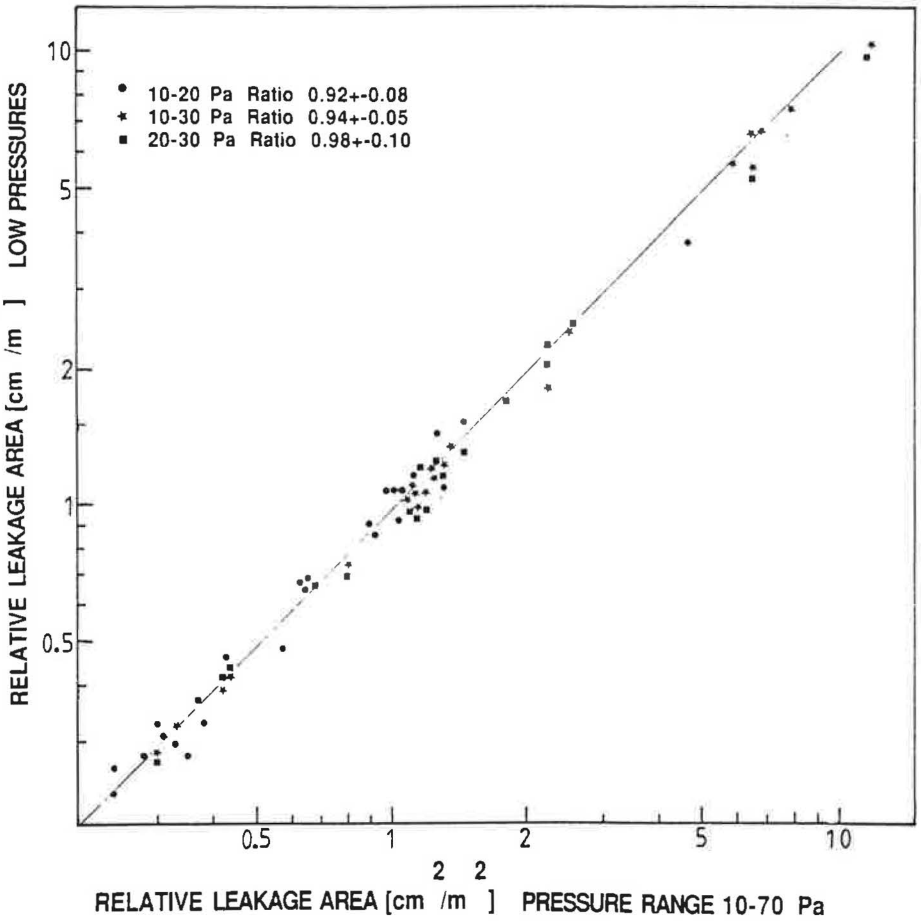

Fig. 11 Relative leakage area calculated with a pressure range of 10 to 70 Pa versus corresponding leakage area calculated from the same data set but using only the low pressure data. All ratios are compatible with being equal to 1.0. Data are from houses, townhouses and apartments.

To provide an answer to the fifth question, we have used data on houses and apartments where there are available data points in the range from 10 to 70 Pa. We have compared the resulting value of the leakage area $\alpha(4)$ when all data points in the range 10 to 70 Pa were used to the resulting value of $\alpha(4)$ when only data in the ranges 10 to 20 Pa, 10 to 30 Pa and 20 to 30 Pa were used.

The data are displayed in Fig. 11. The average number of data points available for the determination of $\alpha(4)$ in the low pressure range was four. Only data sets from houses containing at least three data points in the respective low pressure range were used.

The resulting ratio of the value of $\alpha(4)$ using low pressure data to the value obtained using the full pressure range is 0.94+-0.05 for the pressure range 10 to 30 Pa, 0.92+-0.08 for the range 10 to 20 Pa and 0.98+-0.10 for the range 20 to 30 Pa. There is then an indication that low pressure data may yield somewhat lower values of $\alpha(4)$ than data in the pressure range 20 to 70 Pa, even if all ratios are compatible with being equal to 1.0. The data span more than one order of magnitude of the relative leakage area.

One can then conclude that it should be possible to use low pressure data only to determine a relative leakage area at a pressure difference of 4 Pa to be used as an indicator of airtightness of buildings.

4. CONCLUSIONS

We have described a method for the calculation of the relative leakage area of buildings using data on air flow rate and pressure difference from pressurization/depressurization tests. As an indicator of the airtightness of building envelopes, one can use the relative leakage area at a pressure difference of 4 Pa. The value of the leakage area is obtained from a plot where the original data on the variables air flow and pressure difference are replaced by a new pair of variables.

There is a good correlation between the relative leakage area and the rate of air exchange at a pressure difference of 50 Pa. The reproducibility of the method seems to be good judging from data collected from measurements on two groups of townhouses. There is more than an indication that the method corrects for calibration errors in the raw data on air flow rate and pressure difference. The method does not appear to be sensitive to factors such as whether a blower door or a kitchen fan is used for the pressurization or whether there is a constant pressure difference across the building envelope created by the ventilation system running.

The method yields approximately the same value of the relative leakage area independent of if only low pressure data from 10 to 20 or 30 Pa are used or if pressure differences in the range from 20 to 70 Pa are used. The error of the method when pressure differences in the range from 20 or 30 to 70 Pa are used is lower than 20%, compared to an error of the rate of air exchange at 50 Pa which is lower than 15%. The error of the method is expected to decrease if low pressure data are used. The method has previously been shown to give a value of the relative leakage area that is close to the value deduced by measuring the rate of air exchange using tracer gas techniques (1).

To confirm that the method described can be put to practical use, the method should be verified by pressurization tests on more building types. One should also carry out several pressurization tests on the same building using low pressures to better estimate the error of the method.

5. REFERENCES

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