Determination of Leakages in the Building Envelope Using Pressurization Test Measurements

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Introduction

There are several methods by which the airtightness of a building can be measured. One method involves the use of a fan to pressurize or depressurize the building. This creates a known pressure difference across the building envelope. The corresponding air flow through the fan is measured and this is an indication of the airtightness of the building. This air flow rate can be expressed as the number of building air changes per hour, a useful unit when comparing buildings of different volumes.

The air flow rate could also be given in m^3/h per m^2 of the surface area of the building. However, this simple type of test does not indicate where the air leakage paths are located or if the leakages are laminar or turbulent.

A development of this method, which enables the position and type of leak to be evaluated, requires several pairs of pressure difference and air flow measurements to be made. One important condition, for this type of test, is that there should be a temperature difference between the inside and outside of the building. This in turn produces a pressure difference across the building envelope which varies with height. A second condition is that the wind speed around the building should be close to zero, thus avoiding undesirable wind pressures.

So far only simple methods have been employed to analyse this condition. However, it is possible to use a more strict scientific approach based on mathematical models and known parameter identification methods. These techniques are described in this article.

Measurements

The test is performed by making a number of discrete pairs of measurements of the net leakage air flow (flow out of the building is taken as positive), and reference pressure difference (inside overpressure taken as positive). Alternatively a continuous measurement of the same variables can be transformed into discrete measurement pairs. The measurement pairs will be denoted (y_i, p_i) $(i = 1,m)$, and the whole measurement denoted by the flow vector, y, and the pressure vector, p.

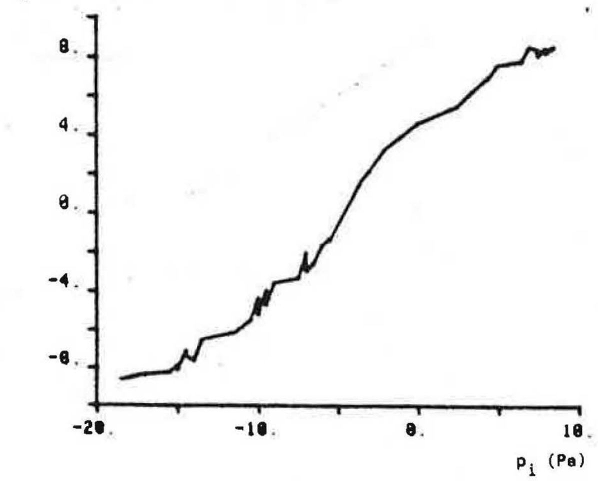

Figure 1. Net leakage flow out of the building y_i (1,000 m^3/h) as a function of pressure difference p_i (Pa).

An example of discrete measurements with 45 samples is shown in Figure 1. The building is a sports hall with a height of 16m. The indoor and outdoor air temperatures were 18°C and −2°C respectively. This gives a pressure difference gradient of 0.9 Pa/m. The measurements were performed and made available by Sune Häggbom of Tyréns.

Mathematical Models

The mathematical model describes the air flow through a given leakage structure as a function of its own parameters, the reference pressure difference, p_i, and the pressure difference gradient, g. The leakage model parameters are leakage area, vertical position and function type. The area can be concentrated at a single point or distributed along the building height. The leakage width can, in the latter case, be constant forming a rectangle or vary linearly with vertical position forming a symmetric triangle.

The flow through a concentrated leakage number, j, during measurement number, i, can be given by

$$q_{ij} = a_j \,\mathrm{sign}(p_{ij})(\mathrm{abs}[p_{ij}])^{c_j} \quad (1)$$

$$p_{ij} = p_i + gz_j \quad (2)$$

where q_{ij} = leakage flow
p_{ij} = pressure difference
a_j = leakage area
c_j = leakage function type
z_j = leakage vertical position
g = pressure difference gradient
p_i = reference pressure difference

The total net leakage flow composed of n leakages can, for a given measurement, i out of m, be written as

$$q_i = \sum_{j=1}^{n} q_{ij} \qquad (i = 1,m) \quad (3)$$

All the model parameters a_j, c_j and z_j can be arranged in a vector, x. The total model flows can also be given in vector form q (x, p) as a function of the parameter vector, x, and the pressure difference vector, p.

General Parameter Identification

It is required that a vector, x, be found to minimize the loss function V(x) which describes how well the model fits the measurements. A common loss function is the sum of the squared model error given by

$$V(x) = e^T e \quad (4)$$

and

$$y = q(x,p) + e \quad (5)$$

where e = model error vector

A method to determine a solution is to start from an initial guess of $x = x_s$. The equations in (5) are linearized with respect to x, for $x = x_s$ and $e = 0$, giving

$$y = q(x_s,p) + F(x_s,p)\,(x - x_s) \quad (6)$$

$F(x_s,p)$ is a derivative matrix where element from row i and column k is given by

$$F_{ik} = \frac{d\,q(x_s,p_i)}{dx_k} \qquad (7)$$

which means the derivative of the model flow for the measurement number, i, with respect to the model parameter, x_k.

The solution, x, or the change, $dx = x - x_s$, can be calculated with the QR-method which minimizes the equation errors in (6) if $m > n$ (over determined problem).

The calculated change is used to make a linear search that minimizes the non-linear loss function, V(x), which means

$$\min_{s} V(x_s + s + dx) \qquad (8)$$

The estimation of the parameter vector, x, is now updated as

$$x = x_s + s_{min} dx \qquad (9)$$

All computational steps are then repeated until the solution converges.

It should be pointed out that there can exist several minima to the type of non-linear problem stated above. The problem is also badly conditioned because the different leakage functions are not orthogonal to one another. The method has been tested on simulated data for up to three separate leakages, each with four parameters. The convergence was slow.

Another problem is that all the model parameters are bounded and naturally positive. Poor measurements could lead to impossible model parameters occurring, eg negative leakage areas.

The large number of model parameters also presents a difficulty.

A single rectangular leakage with both three and four parameters has been identified from the measurements presented in Figure 1. The model parameters and the mean absolute error are shown in Table 1.

Table 1

Model	a area (m^3/h)	b width (m)	z position (m)	c type (–)	mean abs error (m^3/h)
G3	2377.	11.605	5.426	(0.500)	411
G4	1426.	2.190	5.730	0.712	393

Limited Parameter Identification

A method by which the number of parameters can be limited is to distribute the leakages evenly at fixed positions, and to have a fixed function type and leakage width. The leakage width is chosen to be equal to the leakage interval for rectangular leakages and twice the leakage interval for triangular leakages.

The leakage areas are the only free parameters. This turns the problem into one of linear identification where the model flow function can be written as follows:

$$q_i = \sum_{j=1}^{n} a_i f_j(V,p_i) \qquad (10)$$

where f_j = known function
V = known model parameters

The method of least squares could be used, but the model parameters, a_j ($j = 1,n$), could then become both negative and positive.

A minimization method which works only with non-negative parameters is the well known linear programming (LP) method. This can be stated as follows:

$$\min V(x) = d^T x \qquad x \geq 0 \qquad (11)$$

when x fulfills

$$Ax = y \qquad (12)$$

where A is a given matrix and y and d are given vectors and x is an independent vector.

For each measurement, i, the following linear equation is set up to suit the LP method

$$y_i = \sum_{j=1}^{n} a_j f_j(v,p_i) + pe_i - ne_i \qquad (i = 1,m) \qquad (13)$$

where pe_i and ne_i are positive and negative model errors respectively. One of them is always zero. The loss function in this case becomes equal to the sum of the absolute model error

$$V(x) = \sum_{j=1}^{m} (pe_i + ne_i) \qquad (14)$$

The independent parameter vector, x, is composed of the area vector, a, the positive model error vector, pe, and the negative model error vector, ne.

This method has been tested on 25 simulated leakages and 50 measurements with good results.

The leakage profile has been determined for the sports hall, mentioned earlier, with 5, 10 and 20 leakages within the vertical interval (0,20)m and a fourth control case with 30 leakages within (–5,25)m. The leakage patterns have also been produced with combined concentrated and distributed leakages, both rectangular and triangular. The mean absolute errors are given in Table 2 and the leakage profiles are shown in Figure 2. The point leakage profile is drawn with a width of half the leakage position interval.

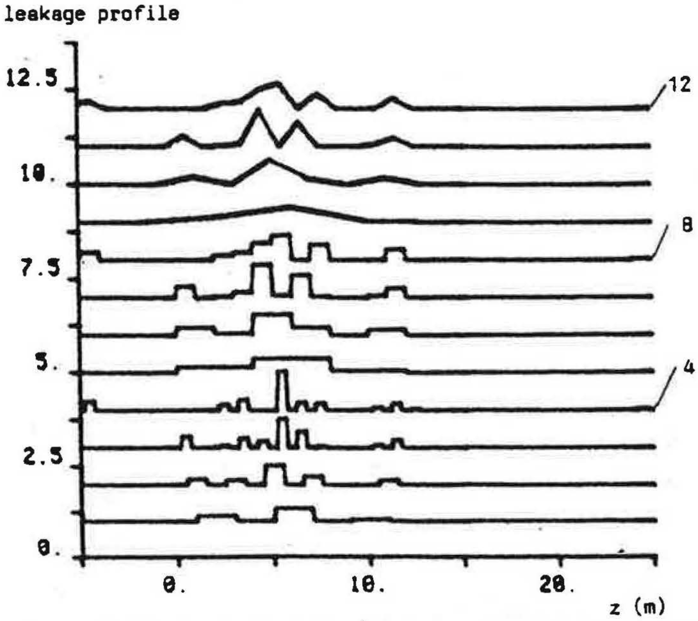

Figure 2. Twelve leakage profiled as a function of vertical position z (m) and with an offset equal to the profile number in Table 2. Point leakages number 1–4 are drawn with a width half the position interval.

Table 2

Model	Number of leakages	Mean abs error, m^3/h		
		Point	Rectangular	Triangular
S5	5	277 (1)	253 (5)	253 (9)
S10	10	220 (2)	224 (6)	224 (10)
S20	20	218 (3)	215 (7)	215 (11)
S30	30	198 (4)	196 (8)	198 (12)

Numbers within brackets indicate leakage profile number in Figure 2.

It can be seen from Figure 2 that the three geometric leakage functions give about the same leakage profile for the same number of parameters. Only minor changes occur in the profiles when the number of parameters is increased. At the same time, the mean absolute error decreases. The control case S30 indicates that only two minor leakages occur outside the building.

This simplified method gives a model error that is approximately half of that given by the general method (compare the results shown in Figures 1 and 2).

The modelled net leakage flow, q_i, and the model error, e_i, are shown in Figure 3 for model S20 with triangular leakages (profile number 11 in Table 2 and Figure 2).

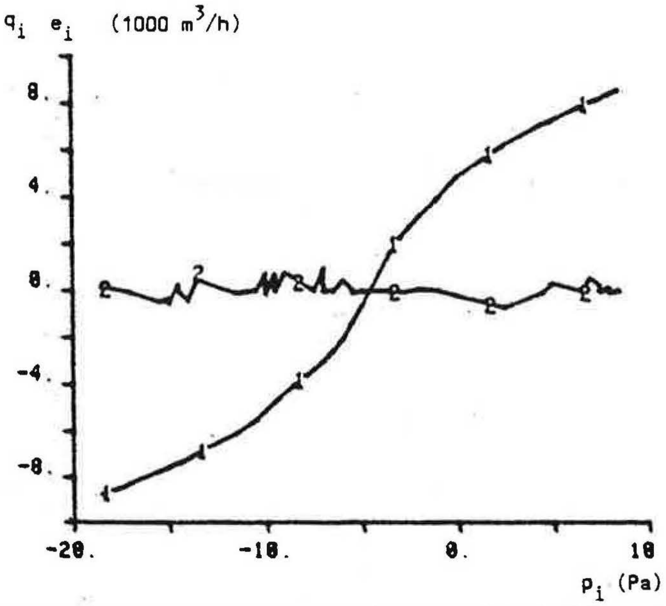

Figure 3. Modelled net leakage flow out of the building q_i(1) and model error e_i(2) (1,000 m$_3$/h) as a function of pressure difference p_i (Pa) for model S20 with triangular leakages (profile number 11 in Table 2).

Conclusions – Summary

The work presented here represents only a short study and is not part of any research project. The aim of this study has been to assess the possibilities of using different mathematical models and different known parameter identification methods to describe and determine leakages in the building envelope.

Models can always be fitted to measurements, but the results should always be tested with care. So far only two measurement cases have been studied. The better one was used as an example.

Several more suitable measurements have to be studied in order to determine whether the method is useful. The number of measurements must be at least twice the number of parameters. In the cases examined the zero pressure difference plane was outside the building envelope. This means that all the leakages were either under overpressure or underpressure for any given measurement sample. Some measurements which have the zero pressure difference plane within the building should also be made. The resolution in leakage position is crudely given by the resolution of the zero pressure difference position.

The methods should also be tested using data obtained in the laboratory from experiments with known leakages.

Both theoretical and numerical aspects of the studies should be examined further. It is important to note that laminar leakages can only be determined in terms of their total area and the centre of that area. This means that all *laminar* leakages cannot be determined in detail. Only *non-linear* leakages can be determined.

One model condition is that the function type of a leakage remains constant. In reality a leakage might be laminar at low pressure differences and turbulent at high pressure differences. In these cases it has been shown that it is possible to describe such a concentrated leakage in terms of a distributed turbulent leakage.

Another model condition is that the leakage function is an odd symmetric function with respect to the pressure difference. A leakage might, in reality, change. This can be modelled by using one leakage profile for positive pressure differences and a second leakage profile for negative pressure differences.

Reference

Jensen, L., 1985, Determination of leakages in buildings with measurements from pressurization test. Department of Building Science, Lund Institute of Technology. Internal report 1985:5 (in Swedish).

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