

AN INNOVATIVE TECHNIQUE FOR MEASUREMENT OF BUILDING LEAKAGE AT LOW PRESSURES

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ABSTRACT

Conventional techniques for the measurement of adventitious leakage of building envelopes are based on steady pressurisation at high pressures (e.g. 50 Pa) that are not normally encountered with natural or mechanical ventilation. It is the leakage at low pressures (e.g. 4 Pa) that is of interest and it is shown that the conventional technique leads to large uncertainty in the low-pressure leakage. Ideally a pressurisation of 4 Pa should be used, but with the conventional technique the uncertainty due to wind effects is unacceptably large. The paper describes a new pulse pressurisation technique that allows accurate measurement of the leakage at low pressures, even in the presence of wind effects. The technique makes use of pulse pressurisation. The three key features that have led to a successful technique are described. Examples of measurements are presented and a comparison between the new technique, the conventional steady technique and a theoretical model is shown.

KEYWORDS

Ventilation, building leakage, leakage measurement, unsteady pressurisation

INTRODUCTION

Excessive leakage of a building envelope is undesirable, because it leads to excessive energy consumption. It is now common practice in many countries to measure the adventitious leakage of an envelope to ensure that it does not exceed a maximum value. Current standards use high-pressure data (typically 50 Pa) as a measure of the infiltration potential of an envelope. The leakage at 50 Pa, Q_{50} , is measured by means of a steady pressurisation test in which the fan flow rate required to generate a steady pressure difference Δp is measured. In reality infiltration occurs at much lower pressures (typically 4 Pa) and a more accurate measure of infiltration potential is the leakage at 4 Pa, Q_4 . Unfortunately, accurate measurements at such low pressures are subject to considerable uncertainty due to wind pressures. Thus with the conventional technique one has uncertainty in Q_4 either from the extrapolation of high-pressure data to low pressures or from wind effects when measuring at low pressures. These two sources of uncertainty are first quantified below. A new unsteady pressurisation technique is then described, which allows the low-pressure leakage to be measured directly, with minimal uncertainty due to wind effects.

UNCERTAINTIES IN CONVENTIONAL LEAKAGE MEASUREMENT

Conventional measurement technique

Figure 1 shows the arrangement for a conventional steady leakage test. The purpose-provided openings are sealed and the envelope is pressurized by means of a large fan. A flow meter is used to measure the fan flow rate Q and a differential pressure transducer is used to measure the resulting

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pressure difference across the envelope. The measured pressure difference Δp_m is defined by

$$\Delta p_m = P_{ext} - P_{int} \quad (1)$$

where P_{int} is the internal pressure and P_{ext} is the external pressure. Typically, measurements are made at about ten pressures over the range 20 to 60 Pa so that the leakage at 50 Pa can be obtained by interpolation.

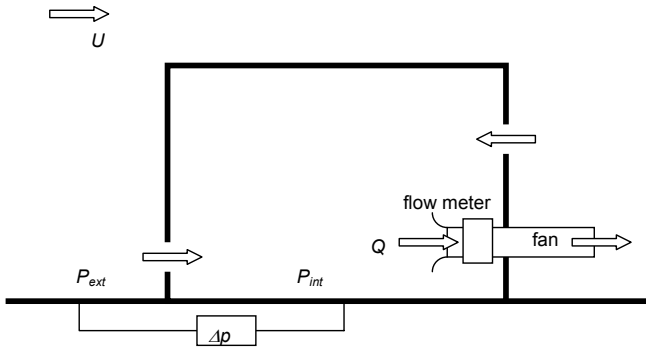


Figure 1. Leakage measurement with conventional steady technique.

As noted above, the adoption of Q_{50} is a compromise, since it is Q_4 that is of real interest. By carrying out the measurement at high pressures there is an uncertainty associated with deducing the low-pressure leakage from the high-pressure leakage. However, leakage measurements at 4 Pa are perceived to be subject to large uncertainty (error) arising from pressures generated by wind (and buoyancy) during the test. These two sources of uncertainty are quantified in the following.

Uncertainty in Q_4 due to shape of leakage characteristic

The value of Q_{50} obtained from the conventional steady test can be used to estimate Q_4 , but the estimate will be subject to uncertainty arising from the fact that the shape of the leakage characteristic is not known. The uncertainty can be estimated (Cooper and Etheridge 2006) for the simple case illustrated in Figure 1 i.e. there are two identical adventitious openings, each with the flow characteristic

$$\Delta p = aq^2 + bq \quad (2)$$

where a and b are the flow coefficients of each opening. The quadratic equation is used in preference to the power law equation (see Chiu and Etheridge 2002), because it represents more closely the flow characteristics of adventitious openings. The value of Q_4 can be found from the measured values, Q_m and Δp_m , using

$$Q_4 = Q_m \left(\sqrt{1 + 16 \frac{a}{b^2}} - 1 \right) / \left(\sqrt{1 + 4 \frac{a}{b^2} \Delta p_m} - 1 \right) \quad (3)$$

Assuming that there are no instrument errors and that there is no wind, the uncertainty in Q_4 is due purely to uncertainty in a/b^2 (the shape parameter of the leakage characteristic). The range of a/b^2 encountered for buildings is approximately 0.04 to 2.0 (Etheridge and Sandberg 1996). Equation 3 can thus be used to calculate the corresponding range of Q_4 for a given Δp_m . Figure 2 shows the consequential errors for different values of Δp_m , assuming that the true value of a/b^2 is 0.2. Thus when Q_4 is obtained from a single measurement at 50 Pa, the uncertainty is $\pm 28\%$. For a measurement at 4 Pa the uncertainty is of course equal to zero. Thus a direct measurement of Q_4

offers a large reduction in uncertainty when there is no wind effect.

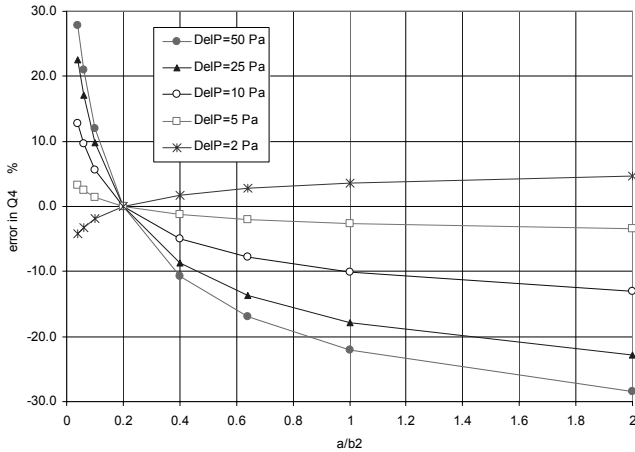


Figure 2. Uncertainty in leakage at 4 Pa when the leakage is measured at other pressures

Uncertainty in Q_4 due to wind effect

The uncertainties due to wind can be calculated using a steady flow envelope model. The wind leads to two main sources of uncertainty, namely

- (a) changes in the external wind pressure, p_{ext} , in equation 1
- (b) changes in the flow rates through the openings.

For the case of two openings the relation between q_1 , q_2 and Q_m is

$$Q_m + q_1 + q_2 = 0 \quad (4)$$

Using (2) equation 4 can be written as

$$Q_m = -\frac{b}{2a} \left(\left(\sqrt{1 + 4 \frac{a}{b^2} |p_1 - p_{ext} + \Delta p_m|} - 1 \right) S_1 + \left(\sqrt{1 + 4 \frac{a}{b^2} |p_2 - p_{ext} + \Delta p_m|} - 1 \right) S_2 \right) \quad (5)$$

where S_1 and S_2 denote the signs of Δp_1 and Δp_2 , p_1 and p_2 are the external wind pressures at the opening and p_{ext} is the pressure outside the envelope. Assigning values to these pressures and putting $\Delta p_m = 4$ Pa gives the value of Q_4 obtained in the presence of wind. Putting p_1 , p_2 and p_{ext} equal to zero gives the value when there is no wind. It is therefore a simple matter to calculate the error arising from the wind.

Figure 3 shows the error as a function of wind speed for a building that is moderately exposed to the wind (one line corresponds to a positive value of p_{ext} and the other to a negative value). Clearly the error can be very large and offsets the benefit of measuring Q_4 directly.

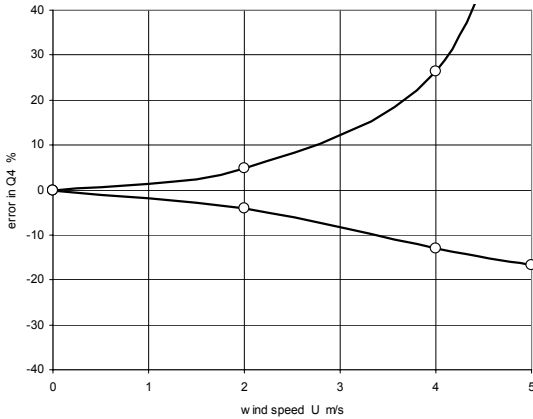


Figure 3. Error in Q_4 due to wind pressures

Reducing the uncertainty due to wind

It is clear that a direct measurement of Q_4 offers considerable reductions in uncertainty compared to the conventional high-pressure technique, but only if the uncertainty due to wind can be minimised. The new (unsteady) technique described below is capable of largely eliminating wind effects at low pressures. The basis for this can be found in Section 10.4 of (Etheridge and Sandberg 1996) where it is noted that when an envelope with a true leakage characteristic given by

$$\Delta p = a_L Q^2 + b_L Q \quad (6)$$

is tested in the presence of wind, the measured leakage characteristic is (at least in theory) given to a close approximation by a simple shift in pressure, c_L , i.e.

$$\Delta p_m = a_L Q_m^2 + b_L Q_m + c_L \quad (7)$$

This means that if one can eliminate the shift, the true leakage characteristic is known. It is not possible to evaluate c_L for the conventional technique, because the wind pressure fluctuations due to wind are at low frequency. This means that long averaging times are required to obtain mean values and over the course of a test c_L is likely to change. With the new technique the measurements with and without an applied flow are made consecutively in a matter of seconds, which means that changes in c_L can be accounted for relatively precisely. In the following the uncertainty is estimated by assuming that equation 7 is valid.

Using equation 6 with $Q_m = 0$ gives the value of c_L for the given wind conditions. The value of Δp_m with a given value of Q_m can then be measured and the change in Δp due to the applied flow is then given by $\Delta p_m - c_L$. Figure 4 shows the resulting errors in Q_4 for the same conditions as used in Figure 3. Comparison of the Figures shows that for $U = 4$ m/s, the uncertainty reduces by a large factor from either +26 or -13 % (depending on the value of p_{ext}) to +5 %. In fact the error becomes independent of p_{ext} and is due purely to the change in flow rates through the openings. The error will always be of the same sign, with its magnitude dependent on p_1 and p_2 .

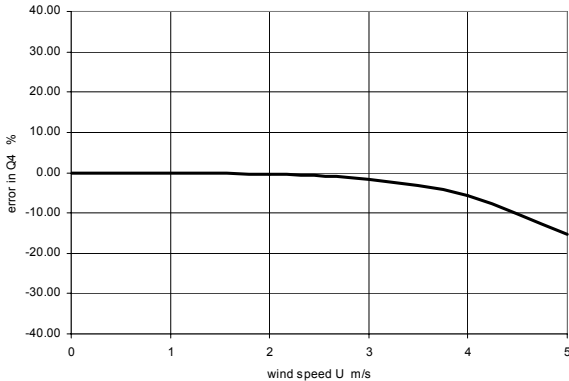


Figure 4. Error in Q_4 due to wind, using procedure in (Etheridge and Sandberg 1996)

UNSTEADY LEAKAGE MEASUREMENT

A description of the new technique is given in detail in (Cooper, Etheridge and Smith 2006). The technique subjects the envelope to a small change in volume in a short period of time i.e. it is a pulse pressurization technique. The basic idea is not new (Roulet and Vandaele 1991), but as far as is known it has never been successfully implemented before. The success of the technique is due to three innovative features. The first is to measure Δp a short time before and after the pulse. This allows wind effects to be largely eliminated in the manner described above. The second is to choose the shape and duration of the pulse such that a period of quasi-steady flow is obtained. This means that the steady leakage curve can be obtained directly from the measurements. The third is to minimise the variation of Δp during the quasi-steady period, so that envelope flexing is not a problem.

Basic concept of new technique

The basic concept can be seen in Figure 5, which shows a single cell of volume, V , with a single opening. Inside the cell is a pulse generation unit which consists of a piston inside a cylinder driven by compressed air. A displacement of the piston ΔV , with time t , leads to a piston volume flow rate, Q_p , and a flow rate through the opening, q . This will generate a pulse in the difference between the internal pressure and the external pressure Δp .

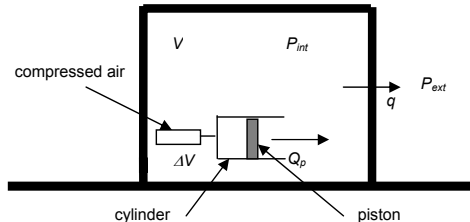


Figure 5. Basic concept of pulse technique

The pressure pulse generated by movement of the piston over a period of 1.5 s is shown by the lower curve in Figure 6. There is a rapid rise of Δp , followed by a more gradual decline. The upper curve (smooth curve) shows the prediction of a theoretical model (see below).

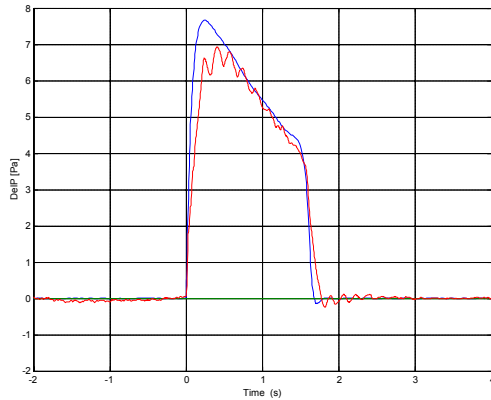


Figure 6. Typical pressure signal $\Delta p(t)$

Pulse leakage equipment

Figure 7 shows the pulse generation unit. The piston is displaced by injecting air into the cylinder from the tank of a small compressor (50 litres, 10 bar) through a solenoid valve. Typically the valve is open for a period of 1 or 2 seconds. A displacement transducer is used to measure the instantaneous position of the piston and a differential pressure transducer is connected to internal and external tappings.

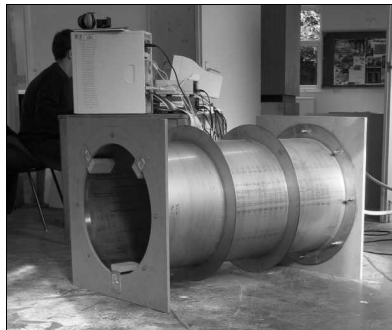


Figure 7. Prototype pulse generation unit

Measurements of piston position and pressure difference $\Delta p(t)$ are taken at a frequency of 200 Hz. The piston velocity is obtained by differentiation of the position transducer output and hence $Q_p(t)$ is known. The duration of a test is thus very short and for reasons given below it is convenient to carry out several repeat measurements.

Minimising wind effects

Figure 8 shows the pressure responses recorded for five repeated tests. The effect of wind is apparent

as a variation of $\Delta p\{t\}$ before and after the imposed pressure pulse, which also differs between tests.

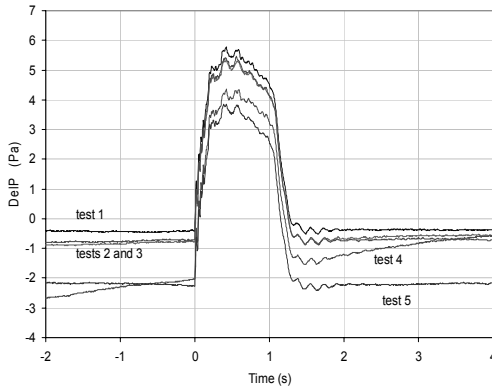


Figure 8. Recorded pressure pulses from five repeated tests, showing effect of wind on $\Delta p\{t\}$

To eliminate the shift due to wind (c_L in equation 7), a curve fit is made to the points measured before and after the pulse. This curve fit is used to define the Δp variation due to the wind during the pulse period. The still-air pulse can thus be obtained by subtracting the variation of Δp due to wind from the measured pressure response. Figure 9 shows the adjusted results and it can be seen that the individual pressure pulses collapse closely on to a single curve i.e. the still-air curve. These results also demonstrate the high level of repeatability of the technique.

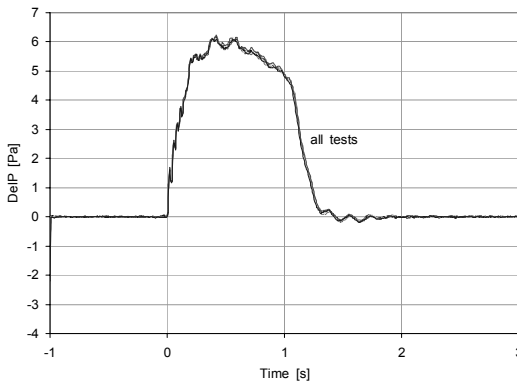


Figure 9. Pressure pulses from five repeated tests, after adjustment for wind effects

The results in Figures 8 and 9 are for a relatively small effect of wind. However the technique works well even when the variation of Δp due to wind exceeds the pressure pulse.

Determination of leakage

The still-air response is given by the average of the adjusted curves. It is then a relatively easy matter to determine the leakage. At any given time, the instantaneous values of the piston flow rate $Q_p\{t\}$ and $\Delta p\{t\}$ are known. If the flow is quasi-steady for a period of time between t_1 and t_2 , say, the leakage

characteristic is simply found by plotting Q_p against Δp over this time period. For the results shown in Figure 9, the quasi-steady period extends from about 0.6 s to 1.0 s, during which time Δp varies from 5.8 Pa to 4.8 Pa. Thus for this particular test the leakage at these low pressures has been determined. A small correction for the effective flow rate arising from compressibility of the air can easily be made.

Comparison with theory

It is necessary to determine the period over which the flow is quasi-steady. This is done by using an unsteady envelope flow model, namely the QT model described in (Etheridge 2000), to check that the unsteady term in the momentum equation is negligible. This assumes that the QT model is reasonably accurate and this has been confirmed by comparing the predictions with experimental measurement. An example of a comparison is given in Figure 6, where the smoother line is the predicted pressure pulse. Close agreement can be seen in the quasi-steady region. To carry out this comparison, the conventional steady pressurization technique was used to determine Q_{50} and a/b^2 . These values were then used in the QT model, with the measured variation of $Q_p\{t\}$ to predict the pressure response.

Flexing of envelope

Flexing of the envelope, for example deflection of components such as doors and windows, can cause errors in the conventional steady technique by changing the geometry of openings and hence their leakage characteristics. This source of error should be much reduced for the pulse technique, because the pressures are an order of magnitude lower. However, there is a potentially greater source of error. Deflection of the envelope with time is accompanied by a change in volume and an associated change in pressure with time. This would be incorrectly interpreted as a flow rate. A volume change of only 0.5 litres for a building with volume 500 m^3 would cause a pressure change of 0.14 Pa (3.5 % of 4 Pa). Although flexing can be expected during the initial part of the pulse, it is only necessary for the deflections to be negligible during the period of quasi-steady flow. Evidence that this is true is given in (Cooper, Etheridge and Smith 2006) and a means of checking for flexing is also described.

CONCLUSIONS

A new technique has been developed that allows the low-pressure leakage of building envelopes to be measured directly and to an accuracy that is not possible with the steady technique. The three key features of the technique are as follows. First, the effects of wind and buoyancy at the time of the test are minimised by taking account of the pressure variation before and after the pulse. Second, the pressure pulse is of sufficient duration for the flow to become quasi-steady. Third, by using only the later part of the pressure response, any effects of envelope flexing are minimised.

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