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REVIEW OF “PULSE” AIRTIGHTNESS MEASUREMENT SYSTEM

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CONTENTS

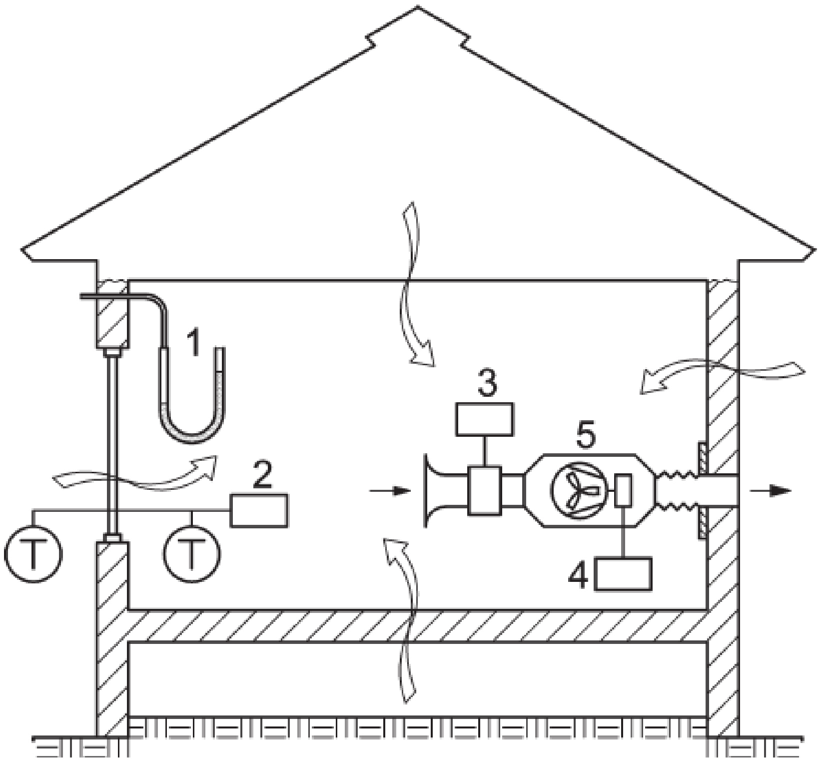
GLOSSARY/ABBREVIATIONS
EXECUTIVE SUMMARY

1 BACKGROUND....1
2 PULSE METHOD....3
2.1 INSTRUMENTATION....3
2.2 DATA FITTING....3
2.2.1 Tank pressure....3
2.2.2 Room pressure....4
3 APPRAISAL OF PULSE METHOD APPROACH....5
3.1 OVERALL APPROACH....5
3.2 APPLICABILITY OF CURRENT STANDARDS....5
3.3 POTENTIAL SYSTEM IMPROVEMENTS....6
3.4 LIMITS TO ACHIEVABLE UNCERTAINTY....6
3.5 SYSTEM CALIBRATION....7
3.6 SUGGESTED VALIDATION TESTS....7
3.7 RECOMMENDATIONS....8
4 BIBLIOGRAPHY....8

1 BACKGROUND

The air leakage rate of a building is defined as the volumetric flow across the building envelope at a specified pressure difference between inside and outside. Air permeability is this leakage rate divided by the surface area of the envelope.

The conventional way to measure the air leakage rate of a building is by use of the fan pressurisation method (Figure 1), as defined in ISO 9972. In this method, a fan is used to introduce air into the building at the steady flow rate required to generate a specific differential pressure between inside and outside. This is repeated for a range of differential pressures from 10 Pa or 20 Pa in 10 Pa steps up to maybe 90 Pa, and a log-log graph is then plotted (Figure 2) of flow rate against differential pressure.



Key

1 pressure-measuring device

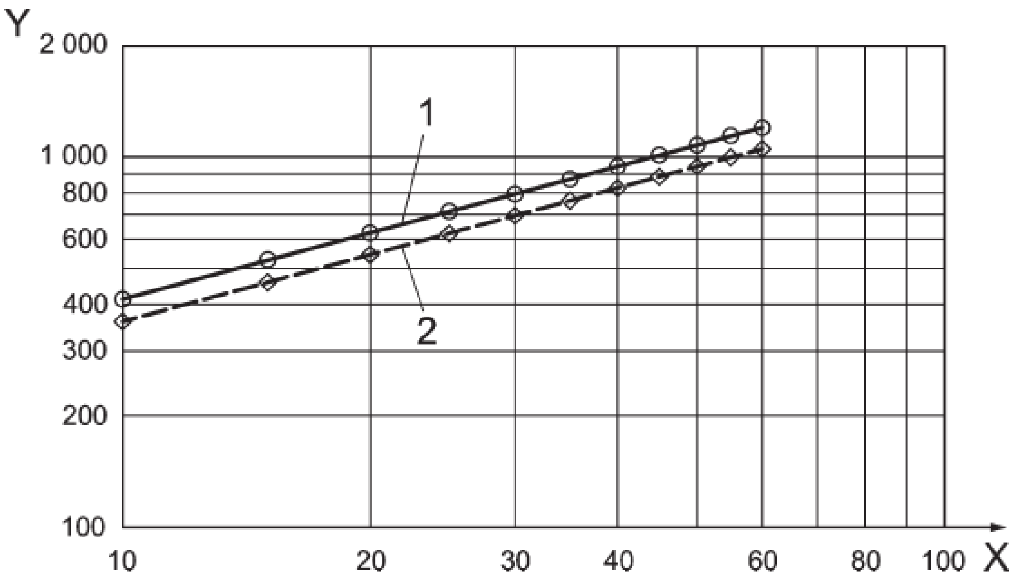
2 temperature-measuring device

3 airflow measuring system

4 fan control

5 fan

Figure 1 Diagram showing fan pressurisation method.



Key

X pressure difference, expressed in Pascal

Y air flow rate, expressed in cubic meters per hour

1 pressurization

2 depressurisation

Figure 2 Fan pressurisation method results curves.

A straight line fitted to this data gives the air flow coefficient C_{env} and exponent n relating differential pressure Δp to air flow rate q_{env} in the following equation:

$$q_{\mathrm{env}} = C_{\mathrm{env}}(\Delta p)^n$$

The air leakage coefficient C_{L} is then obtained by correcting C_{env} to standard conditions and the air leakage rate q_{pr} at a reference differential pressure Δp_{r} calculated from:

$$q_{\mathrm{pr}} = C_{\mathrm{L}}(\Delta p_{\mathrm{r}})^n$$

This reference differential pressure is usually 50 Pa, so q_{50} is calculated and reported.

Criticisms of this method include the following:

- 50 Pa is a very high differential pressure not likely to be seen in practice – air leakage at a 4 Pa differential pressure would be a much more useful value but this method cannot be used to determine it because:
  - measurement uncertainty is much higher at lower pressure differences
  - extrapolation from higher to lower pressure differences is unreliable
- Introduction of the fan can significantly affect the building envelope itself

At least two other ISO standards address methods of air flow rate in buildings. ISO 12569 details the following tracer gas dilution methods to obtain the ventilation rate or specific air flow rate:

- concentration decay
- continuous dose
- constant concentration

while ISO 16956 covers the following different methods for air flow measurement in the ducts of steadily operating ventilation and air-conditioning systems:

- multipoint air velocity measurement
- tracer gas measurement
- flow hood method
- pressure compensation measurement
- pressure difference measurement

2 PULSE METHOD

The principle behind the PULSE method, developed by Build Test Solutions Ltd (BTS), is as follows:

- a gas cylinder releases air into the building – the measured changes in the cylinder's gas pressure and temperature, together with knowledge of its volume, enable the gross air flow rate into the building to be calculated
- the change in pressure in the building (measured using a differential pressure sensor with the reference end attached to an isolated volume filled with air at the initial building pressure) and knowledge of its volume enable the net flow rate into the building to be calculated
- the difference between these two flow rates is the flow rate out of the building and this can be determined as a function of differential pressure between inside and outside
- subsequent gas releases can then be performed to determine flow rates at lower differential pressures, and a comprehensive fit can be applied to the data obtained from multiple gas releases

The results are derived from readings from two pressure sensors, various temperature sensors, and volume estimates.

2.1 INSTRUMENTATION

Tank pressure is measured by a GE UNIK 5000 pressure measurement system while the differential pressure between the room and the isolated volume is measured by a First Sensor LDE Series digital low DP sensor.

Cylinder temperatures are currently measured throughout the testing by a TE Connectivity GA10K3MCD1 thermistor, mounted within the tank, with the release starting temperature used in the calculation. The ambient room temperature does not vary significantly throughout the test and is measured with a Carel NTC015WH01 Temperature Probe.

Synchronous data acquisition is ensured by demonstrating that, for each gas release, the room pressure sensor registers a significant increase within 0.02 s of the gas cylinder sensor registering a significant drop.

2.2 DATA FITTING

This method is heavily reliant on data fitting and subsequent calculations to derive the final values.

2.2.1 Tank pressure

Tank pressure readings are taken at a rate of 50 Hz during each pulse. A polynomial fit is applied to this data and the derivative of it with respect to time is determined, generating an expression for the rate of change of pressure. Knowledge of the tank volume and initial pressure and temperature enable the volumetric flow throughout the pulse to be determined from these rates of pressure change, using ideal gas theory (1) and making the assumption that it is an adiabatic process (2):

$$pV = mR_{\text{specific}}T \tag{1}$$

$$p^{(1-\gamma)}T^{\gamma} = {p_0}^{(1-\gamma)}{T_0}^{\gamma} \tag{2}$$

$$T = \left(\frac{p_0}{p}\right)^{\frac{1-\gamma}{\gamma}} T_0 \tag{3}$$

$$m = \frac{pV}{R_{\text{specific}}T} = \frac{V}{R_{\text{specific}}T_0}\left(\frac{1}{p_0}\right)^{\frac{1-\gamma}{\gamma}} p^{\left(\frac{1}{\gamma}\right)} \tag{4}$$

$$Q_{\text{out}} = \frac{-1}{\rho_{\text{air}}}\frac{\mathrm{d}m}{\mathrm{d}t} = \frac{-V}{\rho_{\text{air}}R_{\text{specific}}T_0\gamma}\left(\frac{p}{p_0}\right)^{\frac{1-\gamma}{\gamma}}\frac{\mathrm{d}p}{\mathrm{d}t} \tag{5}$$

where:

p	= pressure / Pa
V	= internal volume of tank / m^3
m	= mass / kg
R_{specific}	= specific gas constant (287.058 for dry air) / J·kg^{-1}·K^{-1}
T	= temperature / K
γ	= ratio of constant pressure to constant volume heat capacities (1.4 for dry air)
p_0	= initial pressure of air in tank / Pa
T_0	= initial temperature of air in tank / K
Q_{out}	= volumetric flow rate of air at atmospheric pressure out of tank / m^{-3}·s^{-1}
ρ_{air}	= density of air in room / kg·m^{-3}
t	= time / s

2.2.2 Building pressure

Background pressure readings are taken at a rate of 50 Hz throughout the whole exercise, to enable any drift to be corrected for. A single fit is applied to the readings immediately prior to and then in the period after (once stable) each pulse – this fit is taken as the reference zero line and its values are subtracted from the measurements made during each pulse. A polynomial fit is then applied to these corrected values in the second part of each pulse (once the initial major disturbances have decayed) and, again, the derivative of it with respect to time is determined, generating an expression for the rate of change of pressure. Knowledge of the building volume and initial pressure enable the net volumetric flow Q_{net} into or out of the building throughout the pulse to be determined from these rates of pressure change, again using ideal gas theory and making the assumption that it is an adiabatic process.

$$Q_{\mathrm{net}} = \frac{1}{\rho_{\mathrm{air}}}\frac{\mathrm{d}m}{\mathrm{d}t} = \frac{V}{p_0\gamma}\frac{\mathrm{d}p}{\mathrm{d}t} \quad (6)$$

The air flow leaving the room Q_{outflow} is then calculated as the difference between the flow from the tank into the room and the net flow into the room:

$$Q_{\mathrm{outflow}} = Q_{\mathrm{out}} - Q_{\mathrm{net}} = \frac{-V_{\mathrm{tank}}}{\rho_{\mathrm{air}}R_{\mathrm{specific}}T_0\gamma}\left(\frac{p_{\mathrm{tank}}}{p_0}\right)^{\frac{1-\gamma}{\gamma}}\frac{\mathrm{d}p_{\mathrm{tank}}}{\mathrm{d}t} - \frac{V_{\mathrm{room}}}{p_{\mathrm{room}}\gamma}\frac{\mathrm{d}p_{\mathrm{room}}}{\mathrm{d}t} \quad (7)$$

3 APPRAISAL OF PULSE METHOD APPROACH

Having carefully studied the relevant documents and mathematical details of the PULSE method analysis, a number of conclusions / recommendations can be made in various areas. These are given in the following sections.

3.1 OVERALL APPROACH

- The physical principles behind the PULSE method are sound. The air flowing into a volume must be equal to the sum of the air leaving that volume and the additional air maintained within the volume. If measurements of air flow in and increase in maintained air can be made, the flow rate of exiting air can be calculated.

- If measurements and estimations are made with the lowest possible uncertainties, it is likely that this method could prove more accurate than the existing standard method, with fewer of its drawbacks, providing more useful air leakage values.

3.2 APPLICABILITY OF CURRENT STANDARDS

- This is a novel method for determining airtightness and, as such, existing standards are not particularly applicable with regard to specifying the methodology or validation procedures.

    - ISO 9972 covers only the fan pressurisation method described earlier. Some of the formulae relating to derived quantities may be applicable, as may the various building preparation methods, but the specified procedural steps and calculation of results are not relevant to the PULSE method.

    - ISO 12569 specifies methods for determining ventilation or air flow rates in building spaces, for the purposes of checking system performance, ensuring elimination of contaminants, or for energy conservation. However, the methods specified relate only to the use of gas dilution techniques to determine these rates and are therefore again inapplicable to the PULSE system.

    - ISO 16956 details a number of methods for air flow measurement within ducts and air control ports – despite the wide variety of methods specified, none is particularly similar to the PULSE method and none of the specified procedures are therefore applicable.

3.3 POTENTIAL SYSTEM IMPROVEMENTS

- The model assumes that the gas release is a purely adiabatic process and calculates the gas temperature, and hence mass of gas remaining in the cylinder, on this basis. Example data shows the tank pressure rising significantly between gas releases, as a result of the gas (which had cooled during the release) warming back up towards room temperature. There is no reason to believe that this warming does not start during the release, so it is likely that the process is not purely adiabatic. For an accurate estimation of the mass of gas remaining within the tank, it may be necessary to make synchronous gas pressure and temperature measurements throughout each release, and this will require a temperature sensor with a very fast response to changes in temperature. Alternatively, it may be possible to characterise the performance of the cylinder in advance – by waiting for the post-release pressure (and hence temperature) to stabilise, the mass of gas remaining in the cylinder can be accurately determined, enabling the error in released gas (and hence gas rate) resulting from non-adiabatic conditions to be estimated. However, making corrections for the subsequent releases would be more complicated as they start from non-isothermal conditions, so the cylinder performance characterisation could become very complex.

- The value of T_0 for each gas release is currently determined from a measurement of the tank temperature, rather than of the gas within it. Even if each release is purely adiabatic, a measurement of the gas temperature would be preferable, particularly for the subsequent releases as the initial gas temperature will be significantly lower than that of the tank.

- Equation (5) calculates the volumetric flow from the tank into the room from the mass flow into the room and the density of air at ambient temperature. However, the temperature of the gas leaving the tank could be significantly below ambient temperature, particularly during the subsequent releases, meaning that its density could be higher leading to an overestimation of volumetric flow. The exhausted air will eventually reach ambient temperature but, during the short period of the actual release, a calculation of volumetric flow based on the density of the air at the exhausted temperature may improve the accuracy of the calculation.

NOTE: The first two points above have been raised with, and then comprehensively investigated by, BTS. They have carried out further tests and provided the resulting data, together with a robust proposal for how they intend to deal with these issues in future iterations of the product. This proposal includes a change in the software algorithm to incorporate real-time tank gas temperature measurements, made by a faster-responding temperature sensor, taking careful consideration of its position, as there is significant temperature variability within the tank. This variability will initially be accounted for by assigning a conservative uncertainty estimate to the measured temperature value – CFD modelling and associated validation testing may enable this uncertainty to be reduced in the long term.

3.4 LIMITS TO ACHIEVABLE UNCERTAINTY

Equation (7) details how the air flow is derived from the various measurements made. The overall uncertainty for an individual air flow value is dependent on the uncertainties of the individual terms in this equation, the most dominant of which (once the temperature values are correctly calculated) are likely to be those associated with rates of change of pressure, as these are derived from the derivatives of fits to noisy data, particularly for the room pressure. However, in the example calculations seen, the use of multiple gas releases and the determination of air flow over a range of differential pressures during each release make individual uncertainties less important, as a fit is applied to all results and the uncertainty of interest is that associated with the air flow calculated from the fit at a specified differential pressure of 4 Pa. For this reason, it is those factors, such as tank and room volume estimates, that can affect the whole fit that become more significant.

3.5 SYSTEM CALIBRATION

As the system is based on the release of pressurised air, the recommended calibration procedures for fan pressurisation methods cannot be applied. The most direct and traceable calibration approach would be to use the equipment to measure airflows from volumes with known characteristics and to compare the results. However, such volumes may not be available and/or their known characteristics may have too high an uncertainty to be of use.

An alternative approach would be to ensure that all pieces of equipment used to obtain the measurement values used by the model are themselves traceably calibrated. This is not an unreasonable approach and is used, for example, in pressure calibration laboratories – the values of generated pressure are calculated from a model using inputs from mass, gravity, dimensional, and environmental measurements. To ensure that the equipment continues to perform satisfactorily, recalibration of the various sensors at reasonable intervals would be recommended, together with periodic system self-checking.

3.6 SUGGESTED VALIDATION TESTS

To give confidence that the model does give realistic values and is a reasonable physical description of the underlying gas processes, it is proposed that a set of validation tests be carried out. The following tests are suggested, for the reasons given, to demonstrate how well the algorithm performs in determining air leakage rate.

- <u>Comparisons with existing techniques</u> – agreement with the fan pressurisation method, within the combined uncertainties, would give additional confidence in the results. However, as explained earlier, the two systems work optimally over different differential pressure ranges, so the use of a common range may be slightly compromised by an increase in uncertainty. Ideally, these tests would be performed in a range of volumes with significantly different air leakage characteristics.

- <u>Test in a nearly completely sealed volume</u> – this should result in an extremely low calculated air leakage rate, testing one end of the algorithm's range.

- <u>Repeated tests in the same volume (pressure sensor in the same location)</u> – this will give a measure of repeatability of the system, for both initial and subsequent releases.

- <u>Repeated tests in the same volume (pressure sensor in different locations)</u> – the theory suggests that moving the pressure sensor should have no significant effect, and this test would demonstrate if that is indeed the case.

- <u>Repeated tests in the same volume with different cylinder starting pressure</u> – the theory suggests that changing the starting pressure should not affect the 4 Pa air leakage value, despite the fit being based on different values, and these tests will determine whether or not this is the case.

- <u>Repeated tests in the same volume with different gas release durations</u> – the theory suggests that changing the gas release durations should not affect the 4 Pa air leakage value, despite the fit being based on different values, Again, these tests will determine whether or not this is the case.

3.7 RECOMMENDATIONS

As far as standardisation activities go, once this method is validated to work correctly within specified limits, it would make sense for it to be published as an ISO standard. As it is an alternative to the fan pressurisation method specified in ISO 9972, maybe it could form the second part of an ISO 9972 series, i.e. Part 1 would be the fan pressurisation method and Part 2 would cover this gas cylinder-based approach. Alternatively it could be introduced into ISO 16956 as a sixth measurement method.

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