A Simplified Method Using Compressed Air to Determine Air Leakage

Eva B. Møller, PhD **Torben V. Rasmussen, PhD** **Asta Nicolajsen, PhD**

ABSTRACT

Airtightness of buildings is important for the control of energy loss and moisture transport through the building envelope. Different methods for testing the airtightness of the building envelope have been developed. Sometimes these methods are too elaborate. Therefore, simplified methods that are easy to use can be most useful for rough estimates of airtightness. An alternative simplified method using compressed air from a cylinder was suggested, developed, and tested in this research.

Compressed air was released inside a house and the pressure rose. After the air supply was turned off, the pressure normalized; the rate of pressure decrease induced by this process was used to describe the air leakage. A building envelope with high air leakage quickly returned to normal pressure.

A theoretical model for the relation between pressure change and air leakage was established. Then test results from the experiments in two detached houses were compared with measurements using the blower door test method.

The pressure decreased systematically and with good reproducibility, but the calculated airflows in the two test houses were underestimated by 50% and 7% compared with the airflow measured by means of the blower door test method. Changes in volume and temperature due to pressurization could not explain the differences in the two test houses. Therefore, the method was stated to be usable only for a rough estimate of the airflow with a big error margin. However, better instruments and higher pressures might improve the results and make the method more useful.

INTRODUCTION

Airtightness of buildings is becoming more important as more focus is put on the consumption of less energy. Since 2006, the Danish *Building Regulations* (DECA 2008) have prescribed a maximum air change in buildings when tested at a pressure of 50 Pa. The value must be determined as an average of measurements with depressurization and pressurization. Air changes must be determined on the basis of *EN 13829, Thermal Performance of Buildings—Determination of Air Permeability of buildings—Fan Pressurization Method* (CEN 2000), a standard equivalent to *ASTM E779-03, Standard Test Method for Determining Air Leakage Rate by Fan Pressurization* (ASTM 2003). This method requires a fan with adjustable airflow and includes recordings of the airflow, a pressure-measuring device, and a thermometer. In practice a blower door assembly is often used for the test. With the appropriate devices, the test is easy to carry out in most small buildings.

Where an Alternative Method can be Useful

The standard method can be too elaborate when only quick and approximate measurements of air leakage of buildings or small spaces are needed, e.g., when only specialists can carry out the test or it is difficult to place a fan. In such cases, a simplified method that is easy to use and robust, i.e., only slightly sensitive to operator and instrument errors, can be most useful for testing the air leakage. Such situations include the following.

Eva B. Møller *and* ***Torben V. Rasmussen*** *are senior researchers and* ***Asta Nicolajsen*** *was a senior researcher (now retired) at the Danish Building Research Institute/Aalborg University, Hørsholm, Denmark.*

- **During the construction process.** Normally a specialist performs the standard test at the end of the construction process. If the air leakage is too high, the building envelope must be tightened. This is often difficult as the inner sheeting already is in place. If craftsmen could perform a simple and inexpensive test several times during construction, when it is still relatively easy to tighten the air barrier, they could take precautionary measures against air leakage in due time. The usefulness of an alternative method depends on the price of the standard method. When this project was initiated, the standard test cost approximately US$ 10,000, but this price was later reduced by approximately 90%; consequently, the need for an alternative method has diminished.
- **In odd-sized volumes.** The standard test performed with blower door devices is made for rectangular openings, but it is difficult to place fans in odd-sized openings and still ensure airtightness of the connection. Airtightness of cavities with multiple and enclosing air barrier systems is difficult to determine with the standard method.
- **To test if pressurization is realistic.** Some renovation methods involve constant pressurization of cavities, but constant pressurization will normally only be effective if the air leakage is not too high. To decide whether pressurization is possible or if the idea should be abandoned before pressurization plans are fully developed, it would be helpful to estimate the air leakage. This could be in, for example, basements or individual rooms when it is to be decided if the air leakage is small enough to consider the envelope around the cavity as an air barrier.

Target Group

The simplified method is not precise but it is practical; the primary users are not specialists but craftsmen who want a quick answer to whether they have to tighten the air barrier further or they can continue with the construction process. Therefore, the method should be robust, that is, easy to perform and not sensitive to the handling of equipment or instruments.

Testing a Simplified Method

In this research, a simplified and quick method using compressed air from a cylinder was suggested, developed, and tested. The method is an alternative method to more precise and elaborate methods such as the blower door test method. As this was the first endeavor to develop a simplified method, to test whether the idea was viable only a few tests were made. More tests are needed to fully develop and evaluate the method.

THEORY

The air change rate of a building or cavity through the envelope can be determined in different ways:

- by using tracer gas,
- by constant pressurization of the cavity and determination of the required airflow to maintain the pressure, or
- by applying a pressure in the cavity and determining how the pressure builds up or decreases.

Except for when the tracer gas method is applied, windows, doors, and ventilation openings have to be kept shut for the entire period of measuring and all other activities must be stopped. The tracer gas method is slow; therefore, only the two other methods are discussed.

Constant Pressurization

The standard method for measuring air leakage of buildings is described in EN 13829 (CEN 2000), a system based on measuring the airflow that is required to maintain a certain pressure in a building. Although the main focus of this paper is on another method (the simplified method), the theory behind measurements of air leakage based on constant pressure is presented because this method is used to validate the simplified method.

In practice, the procedure using the blower door system is the following.

- Wind speed and temperature are recorded. Wind speed and temperature should be in a range where it is possible to obtain a satisfactory zero flow pressure difference.
- An exterior door or window is removed and replaced by the blower door device.
- Remaining exterior openings of the building (e.g., windows and doors) as well as adjustable openings are closed.
- Intentional openings (e.g., cooker hoods) are sealed.
- Zero flow difference is measured by temporarily covering the fan and measuring the inside-outside pressure difference.
- The fan is uncovered and the building pressurised. At least two sets of measurements with increments of no more than 10 Pa are made for pressurization and depressurization
- Corresponding values of pressure difference and airflow are recorded and plotted on a log-log plot.
- Using the least-squares technique, the airflow coefficient C_{env} and the airflow exponent n are determined based on Equation 1:

$$\dot{V}_{env} = C_{env}(\Delta p)^n \quad (1)$$

where

$\dot{V}_{env}$ = airflow, m^3/h

C_{env} = airflow coefficient, $m^3/(h \cdot Pa^n)$

Δp = pressure difference, Pa

n = airflow exponent, dimensionless

- Using outdoor and indoor air densities for correction, air leakage coefficients C_L for standard conditions (20°C ± 1°C and $1.013 \cdot 10^5$ Pa) are determined for depressurization and pressurization

Depressurization:

$$C_L = C_{env}\left(\frac{\rho_e}{\rho_0}\right)^{1-n} \tag{2a}$$

Pressurization:

$$C_L = C_{env}\left(\frac{\rho_i}{\rho_0}\right)^{1-n} \tag{2b}$$

where

C_L = air leakage coefficient for standard conditions, $m^3/(h \cdot Pa^n)$
ρ_e = outdoor air density, kg/m^3
ρ_i = indoor air density, kg/m^3
ρ_0 = air density at standard conditions $\approx 1.2\ kg/m^3$

- The airflow at standard conditions can now be determined as

$$\dot{V}_L = C_L(\Delta p)^n\ . \tag{3}$$

- The specific leakage rate w_{50} (at 50 Pa pressurization) describes the airflow divided by the net floor area A_F:

$$w_{50} = \frac{\dot{V}_{50}}{A_F} \tag{4}$$

The Danish *Building Regulations* (DECA 2008) state that this value has to be determined as an average of the measurements with depressurization and pressurization and must be less than 1.5 L/s per m^2 heated floor area.

Change of Pressure

An alternative method might be to apply an air pressure difference while monitoring how the air pressure developed and/or diminished. Theoretically, depressurization as well as pressurization could be used in this method; only a method with pressurization is described in this paper. As a simplification, in this paper the term *volume* is used to describe the pressurized volume. A volume could, therefore, be a pressurized building, room, or cavity.

The theoretical idea behind this study was to monitor the change in pressure over time when a building volume was pressurized by allowing compressed air from a cylinder to enter the volume. When the desired pressure difference was obtained, and if possible, the pressurization was kept at a constant level by regulating the airflow, then the air was turned off. The monitoring started at the time the cylinder was opened (pressure started to rise) and continued until the pressure difference between the inside and the outside became zero.

The outlined method included a test procedure with three phases, which are described in Figure 1. Before Phase 1 began, the external openings had to be closed and the internal openings sealed, similar to the preparations for the constant pressurization method.

- **Phase 1:** The cylinder was opened and the pressure rose. The amount of air used for this operation was measured.
- **Phase 2:** At a specific pressure, the airflow from the cylinder was controlled and the pressure was kept constant. The airflow from the cylinder corresponded to the air leakage rate.
- **Phase 3:** The airflow was turned off and the pressure decreased.

The three phases represented three different and independent ways to determine the air leakage of a volume, as the analyses and determinations of air leakage were very different. In all three phases pressure/time dependency was needed; only in Phases 1 and 2 should the flow of the cylinder also be known.

Although all three phases are outlined in this paper, only Phase 3 is discussed thoroughly, as it represents the simplified method.

Phase 1: Pressure Rise. To determine the air leakage from the pressurized volume, the amount of compressed air needed for building up the pressure and how it was supplied should be known.

Phase 2: Constant Pressure. If the pressure was kept constant, the situation was similar to constant pressurization, i.e., using the blower door method. Therefore, this phase was not investigated further.

Phase 3: Pressure Decrease. Independent of the equipment used to develop the pressure and its ability to maintain a

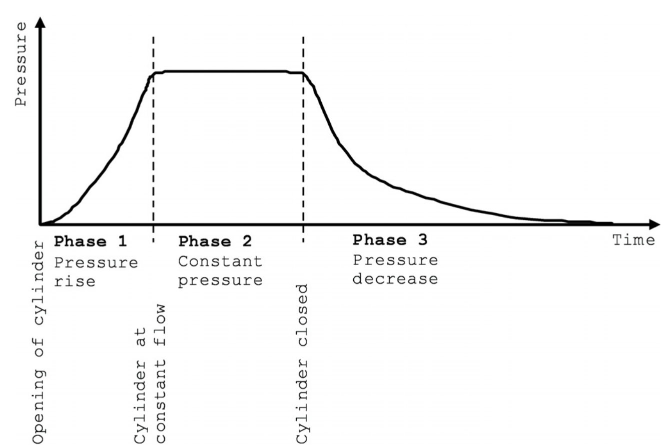

Figure 1 *Ideal time/pressure dependency when air leakage is to be determined by pressurizing a volume with compressed air. The determinations of air leakage in the three phases are independent of each other.*

constant pressure, the simplest method was to register the pressure decrease after the cylinder was turned off. The slower the pressure decrease, the more airtight was the volume.

Such a method has not been the subject of many research projects, as few reports on the method or similar methods have been found (e.g., on pulse pressurization by Sherman and Modera [1988] and Dewsbury [1996]), but Mattsson (2007) used a transient pressurization method and described in depth the theory behind it. In short, Mattsson's theory is as follows.

The general gas law states

$$m_a = \frac{P \cdot V_a}{R_a \cdot T} \quad \text{or} \quad \rho_a = \frac{P}{R_a \cdot T} \tag{5}$$

where

m_a = mass of air, kg
V_a = volume, m^3
P = pressure, Pa = total pressure = $P_0 + \Delta P$
P_0 = ambient atmospheric pressure
ΔP = pressure difference across the envelope
R_a = gas constant for air = 287 J/(K·kg)
T = temperature, K
ρ_a = air density

When the volume is pressurized, the mass of air leaving the volume due to air leakage is given by

$$\frac{dm_a}{dt} = -\rho_a \cdot \dot{V}_{env}(p) \ , \tag{6}$$

where dt is the time derivative.

When m_a and ρ_a in Equation 6 are substituted by the expressions given by Equation 5, Equation 6 can be rewritten as

$$\frac{d}{dt}\left(\frac{P \cdot V_a}{R_a \cdot T}\right) = -\frac{P}{R_a \cdot T}\dot{V}_{env}(p) \Leftrightarrow \dot{V}_{env}(p) = -\frac{T}{P} \cdot \frac{d}{dt}\left(\frac{P \cdot V_a}{T}\right) \ . \tag{7}$$

Taking the derivative of each term gives

$$\dot{V}_{env}(p) = -\frac{V_a}{P} \cdot \frac{dp}{dt} - \frac{dV_a}{dt} + \frac{V_a}{T} \cdot \frac{dT}{dt} \ . \tag{8}$$

However, not all the terms in Equation 8 are equally important. For most practical situations involving buildings, it can be assumed that the volume and the temperature are constant; therefore, Equation 8 can be simplified and the airflow expressed as the following:

$$\dot{V}_{env}(p) = -\frac{V_a}{P} \cdot \frac{dp}{dt} \tag{9}$$

Mattsson (2007) calculated the experiments' volume and temperature changes and found a volume change of 1/9000 at 100 Pa and a temperature change of 0.04 K at 50 Pa. In spite of these small changes, when using Equation 9 Mattsson underestimates the air leakage by 20% compared with the results using the method of constant pressurization. When Mattsson adds the volume variation term, the leakage is overestimated by 20%. Mattsson is able to find flows consistent with the method of constant pressurization only by using the full Equation 8. Using $P \approx P_0$, Mattsson rewrites Equation 8 as

$$\dot{V}_{env}(p) = -\frac{V_0}{P_0} \cdot \frac{dp}{dt} \cdot \left(\frac{c_v}{c_p} + \kappa_v\right), \frac{c_v}{c_p} = \frac{5}{7} \ , \tag{10}$$

where κ_v is a dimensionless constant describing the proportionality of volume to pressure.

However, for a quick and simplified method, where the estimation of airflow would be approximate, it was assumed that the simpler form (Equation 8) would be sufficient. This hypothesis was tested by analyzing data from experiments.

EXPERIMENTS

The experiments were divided into three steps:

- Initial testing
- Testing of two new houses with the simplified method
- Testing of the same houses with the blower door method

Initial Tests

Initial testing was conducted to test the equipment. Individual rooms and small buildings were chosen since it is easier to build up a pressure difference in smaller volumes. Additionally it is easier to repair minor leaks if it turned out to be difficult to achieve a sufficient pressure difference. The goal was to reach a pressure difference of at least 50 Pa corresponding to the values used in the blower door test. The reproducibility of the simplified test method was also tested in this phase.

Simplified Test Method

Based on the initial tests, equipment and test objects were chosen. The choices are described in the "Equipment" and "Studied Objects" sections. One of the initial tests, in the Cold Storage Room, was later used for comparison with the measurements in the houses.

Blower Door Tests

Concurrently with the test of the simplified method, the same two houses were tested with the blower door method. The purpose was to validate the simplified test method. As the measurements were conducted by a professional "blower door tester" with standard blower door equipment, these experiments are not described in this paper.

Equipment

The equipment for the proposed method was kept simple, as the method is intended to be a simple alternative to the blower door test. The instruments were

- a 50 L cylinder with pressurized air (20.9% O_2 and 79.1% N_2) and
- a differential pressure transmitter where results are recorded as a continuous printout of curves.

The differential pressure transmitter measured the pressure difference between atmospheric pressure and the pressure within the volume. Damping of the instrument was omitted, as each of the experiments was expected to be of short duration (less than 10 s) and the method depended on pressure measurements in small time steps. The feed rate of the measurement print-output was 1 cm/s.

Studied Objects

The air leakage from different test volumes was studied, including whole buildings as well as single rooms. In general, volumes with rigid envelopes were chosen in order to minimize volume changes due to pressure changes.

Initial Tests. For initial testing, individual rooms and a simple test building at the Danish Building Research Institute were chosen. Experiments showed that it was not possible to obtain a pressure difference of 50 Pa in these volumes; this was interpreted as the air leakage being too high. A detached house built in the 1960s was also tested. Again, no significant pressure difference could be obtained. Finally, the Cold Storage Room, no longer in use, was tested. The room had a volume of 43 m^3 and was sufficiently airtight to obtain a pressure difference of 50 Pa by using air from the cylinder. Floor, ceiling, and walls were of concrete or masonry. There were no windows and the room had only one door, which was made of steel with a rubber gasket to seal the door to the frame.

Main Tests. After the initial testing of the method, two new detached houses were tested with both the proposed method and the standardized method (the blower door test method) consecutively.

The two houses were similar in size and construction; both were one-story houses where the vapor barrier, which also served as air barrier, was secured by other building elements, thus minimizing possible volume changes due to pressure changes.

- **House A**
  Floor: concrete
  Outer walls: masonry, insulation, polyethylene (PE) foil as vapor and air barrier, and gypsum board
  Ceiling: roof tile underlay, 250 mm mineral wool, PE foil as vapor and air barrier, laths, and gypsum board; the ceiling followed the pitch of the roof
  Area: 142 m^2
  Volume: 351 m^3
- **House B**
  Floor: concrete
  Outer walls: masonry, insulation, and lightweight concrete
  Ceiling: ventilated attic with 250 mm mineral wool, PE foil as vapor and air barrier, laths, and wooden panels
  Area: 146 m^2
  Volume: 361 m^3

Execution of Experiments

Preparations similar to the preparations for the blower door test were made, i.e., external openings such as doors and windows were closed and intentional openings in the envelope were sealed. The tests were only performed when the wind speed was less than 6 m/s or 3 on the Beaufort scale.

Pressurized air from a cylinder was released and corresponding measurements of time and pressure were recorded on the printout. When a pressure of approximately 50 Pa was reached or the pressure stopped rising, the air supply was turned off. The measurements continued until the pressure returned to atmospheric pressure. The test was performed four times in the Cold Storage Room and twice in each of the houses.

RESULTS

In some of the initial tests of the simplified method it was not possible to reach a pressure close to 50 Pa. These results are not presented here, as they are only examples of the limitations of the method. The main outcome of the initial testing showed that the simplified method cannot be used when the air leakage is high.

From the initial tests, only the four tests of air leakage from the tight Cold Storage Room are presented. From the main tests, the two test results from each of the detached houses are presented as well as the blower door results. The Cold Storage Room was not tested with the blower door method.

Simplified Method

The typical course of the experiments from start to finish is shown in Figure 2. The resulting pressures are similar to the theoretical pressures shown in Figure 1.

Since only Phase 3, where the pressure decreased, is of interest to this paper, only this part is shown in Figure 3. Time and pressure readings from the printout were recorded every 0.5 s. In Figure 3, the test results of each experiment are shown as plotted points. The test results have been approximated to exponential curves, shown in Figure 3. The curves for the houses are based on two test results in each house; the curve for the Cold Storage Room is based on four test results. The constants and coefficients of determination of the curves are given in Table 1.

Figure 3 does not represent the direct measurements, however. A few adjustments have been made, as follows.

- **Parallel displacement of the timeline.** Not all tests started at the same pressure difference, and in some cases the pressure difference could not reach 50 Pa. To make direct comparison between the different volumes easier, some of the curves in Figure 3 were displaced parallel with the pressure axis; the displayed time was not the measured time in every case but was adjusted so that the curves intersected at approximately 25 Pa. That is, tests where the pressure started at 20 Pa were moved to the right to be comparable with tests that started at 50 Pa.

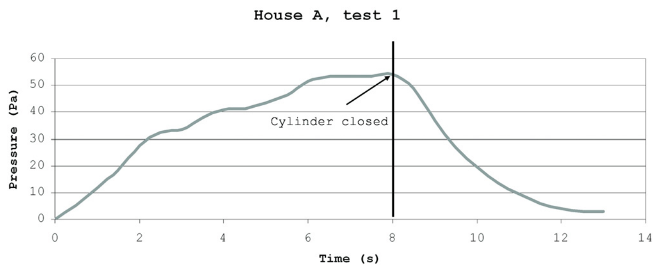

Figure 2 *An example of time versus pressure measurements, from the opening of the cylinder containing compressed air until the pressure is normalized. In this example, the cylinder is turned off after 8 s, and pressure decrease (Phase 3) begins.*

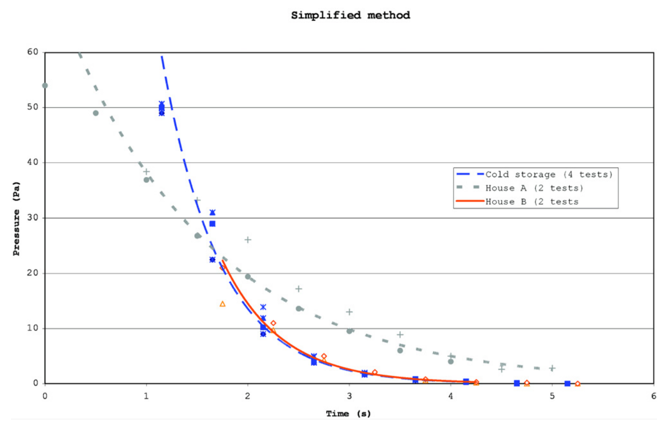

Figure 3 *The decrease of pressure over time after pressurizing a volume by a cylinder. The test is performed in three different volumes with different air leakages. The curves are exponential approximations based on four tests in the Cold Storage Room or two tests in each of Houses A and B.*

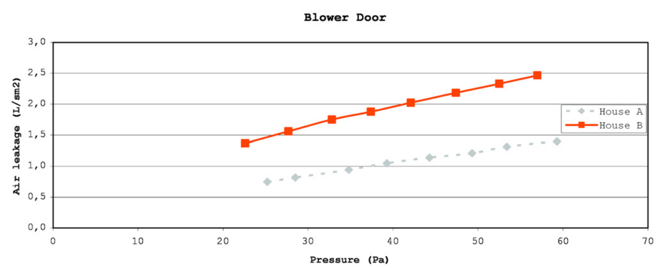

Figure 4 *Result of blower door measurements, as air leakage per square meter of heated floor area at different pressures. The Cold Storage Room was not measured by the blower door method.*

Table 1. Exponential Approximation $p(t) = Ae^{kt}$

	Cold Storage Room	House A	House B
A	438.5	75.256	460.15
k	–1.7388	–0.6784	–1.7287
Coefficient of determination R^2	0.9928	0.9673	0.9791

- **Curve based on more than one test.** The recordings of the different tests had different markings, but the curve was drawn on the basis of all displayed measurements for each volume.

The reasons for the adjustments and curve fittings are addressed further in the Discussion section.

Blower Door

To compare the simplified method with the standardized blower door test method, measurements with the blower door test method were also made. Normally blower door tests are performed with depressurization and pressurization. However, in this case only results with pressurization were relevant, as openings might react differently when subjected to positive and negative pressure differences.

Blower door measurements are shown in Figure 4, and the calculated equations, similar to Equation 1 and its results, are given in Table 2.

Table 2. Results of Measurement with Blower Door

	House A	House B
Airflow coefficient, C_L	34.907	100.87
Airflow exponent, n	0.7413	0.6307
Airflow at 50 Pa (L/s per m^2) $\dot{V}_{env} = C_{env}(\Delta p)^n$	1.2	2.3
Air change rate at 50 Pa (h^{-1})	1.81	3.30

DISCUSSION

Provided a minimum of airtightness in volumes, the results showed the following.

- It was possible to obtain air pressure in these volumes by releasing compressed air from a cylinder. When the cylinder was turned off, the pressure decreased as predicted in Figure 1.
- The results in Figure 3, obtained by the simplified test method, showed that the curves representing the Cold Storage Room and House B were very similar and steeper than the curve representing House A. Assuming that the steeper curves mean higher air leakage, the results indicated that the Cold Storage Room and House B had the same air leakage, while House A was tighter.

- The blower door test method showed that House A was more airtight than House B. Only House A met the requirements for air leakage at less than 1.5 L/s per m^2 heated floor area stipulated in the Danish *Building Regulations* (DECA 2008).

However, the results are based on only a few tests results, and further investigation is needed to fully develop the method and determine its potential and weaknesses.

Curve Fitting Results

The curves and equations presented in Figure 3 and Table 1 were based on data processing. Processed data was used to achieve a maximum use of available data and the possibility of comparing volumes directly.

Adjusted Data. The results presented in Figure 3 are not raw data but adjusted data, which made it possible to display all the data in the same figure. The parallel displacement was only an adjustment of time; the same amount of time was added to all time measurements in the individual test.

Displacement was useful for two reasons:

- it enabled direct comparison between the tested volumes and individual tests, and
- one single curve for time-pressure dependency for each volume makes Figure 3 more clear.

Figure 2 shows how the pressure changed during the whole experiment. Since only the part concerning decreasing pressure was relevant, and as the decrease did not start abruptly, it could be difficult to determine the exact starting point of the test, i.e., where $t = 0$. However, the starting point was only important when the results were displayed. The simplified method was based only on the curvature of the time-pressure dependency, and the shape of the time-pressure was not altered by adding or subtracting the same amount of time to or from all measurements in the same test. Therefore, displacement had no influence on the results.

However, it was visually easier to evaluate the shape of time-pressure dependency if the curves were placed close to each other, thereby making Figure 3 more visually informative. Instead of using a common time-dependent starting point, the curves now intersect at approximately 25 Pa.

The three test results of the different houses and the Cold Storage Room were independent, and it was not necessary to display them with a common intersection. But by doing so, it was possible at one glance to see that the method showed similar air leakage in House B and the Cold Storage Room while House A was tighter.

The air leakage could be determined in two different ways:

1. the air leakage would be determined for each test, and the final result would be an average of the tests (two tests in the houses and four tests in the Cold Storage Room), or
2. after the time adjustment, all test results of each volume would be pooled and the result would be only one curve on which the determination of air leakage would be based.

The four initial tests in the Cold Storage Room treated as four independent tests (Method 1) showed high reproducibility of the method. Therefore, it was decided to base one curve on all test results (Method 2). The difference in calculated air leakage was less than 5% when using Method 2 compared with Method 1.

Exponential Equations. As a curve fit, an exponential approximation with the constants A and k has been used:

$$p(t) = A \cdot e^{kt} \Leftrightarrow t = \frac{1}{k}\ln\frac{p(t)}{A} \tag{11}$$

With this approximation, Equation 9 can be rewritten as the following:

$$\dot{V}_{env}(p) = -\frac{V_a}{P} \cdot \frac{dp}{dt} = \frac{V_a}{P_0 + p} \cdot A \cdot k \cdot e^{k \cdot \frac{1}{k}\ln\frac{p}{A}}$$

$$\Updownarrow$$

$$\dot{V}_{env}(p) = -\frac{V_a}{P_0 + p} \cdot k \cdot p \tag{12}$$

The choice of an exponential approximation to describe time-pressure dependency was based on the best fit. Mattsson (2007) used a combination of exponential, linear, and power functions to find the best fit. Since extrapolations were only of little interest in this study, the nature of the expression itself was not as important as finding the best curve fit within the measurement range. The main objective was to find a curve fit that described the steepness of the time-pressure curve in a satisfactory way. Based on the high R^2 values shown in Table 1, the exponential function in Equation 11 fulfils this.

The curve fit is based on a ln transformation of the pressures combined with linear least-squares method. The values for the lowest pressure differences are omitted partly because very low pressure differences are encumbered with uncertainties and partly to counteract that higher pressures are discounted by the ln transformation.

In the blower door method, a power function (Equation 3) is used for the curve fit of the pressure-airflow dependency. This implies that there is a constant flow characteristic for all pressures. Knowing that the airflow through openings can be laminar or turbulent depending on the pressure, this assumption has been questioned. Walker et al. (1998) addressed this problem and evaluated the power law to quadratic formulations and found that the power law is valid for measurements of air leakage from building envelopes. This could be an indication that as long as the pressure interval is small, the changes from one type of flow to another are negligible. The flow exponent in Equation 3 has limiting values of 0.5 (fully turbulent flow) and 1 (fully laminar flow) (Walker et al. 1998). The equation describing the pressure-airflow dependency in the simplified method (Equation 12) was almost a linear function, as $P_0 \gg p$, i.e., a power function to the power of 1. This indicates fully laminar airflow, which probably is not true, especially for higher pressures. Therefore, the simplified method can only be a rough estimate.

Discussion of Results

The simplified method was expected to be useful as an alternative to the blower door test method in cases where precision is of less importance. Whether this is correct can be tested only by comparing the airflow due to air leakage in the two methods at the same pressure level. Table 3 shows airflows at different pressures calculated by the equations found for the two methods for Houses A and B. The factor K is the ratio between airflow (blower door) to airflow (simplified method).

The tendency was the same in the two houses; the calculated airflow determined by the blower door test method was higher at every pressure than when calculated by the simplified method, but the difference decreased with increasing pressure differences.

Better Agreement at Pressures Close to 50 Pa. The method was only planned for pressure levels up to 50 Pa; therefore, Table 3 stops at this level. In House B it was not possible to obtain a pressure level above 25 Pa; it might therefore not be reasonable to extrapolate air leakage calculations beyond this point. However, the curves for House B and the Cold Storage Room were very similar, which indicated the same airtightness of the two volumes. Although this might be coincidental, it was the argument for extrapolating the calculations beyond the measurement range in Figure 3. On the other hand, one must keep in mind that leaks might depend on the pressure level. Some leaks do not open until a specific pressure is reached. Conversely, some openings may close when the pressure drops below a certain level. This would cause irregularities in the curves that remain unidentified if the pressure level in question is not reached. As a consequence, the simplified method and the blower door test result should only be compared at the same pressure difference—i.e., the simplified method should start at a pressure difference of more than 50 Pa if it is to be directly compared with the standard blower door test.

The ratio of airflow (blower door) to airflow (simplified method) decreases with higher pressure difference as long as the pressure differences are within the pressure difference level of the experiment. If the curves are extrapolated beyond 50 Pa, the ratio would become 1.00 at 60 Pa in House B and at $P \approx 170$ Pa in House A. But for none of the house tests do the curves meet asymptotically because of the nature of the two equations; the simplified method is described by an almost linear equation (Equation 12) and the blower door method by a power function. This is yet another argument for not extrapolating the results.

Best Agreement in House A. Surprisingly, both houses showed better agreement at the highest pressure; one would expect more turbulent flow at higher pressures, which does not correspond to a linear function (Equation 12). At the same time, the blower door method showed a flow exponent of 0.74 in House A (see Table 2). This is a high value and would suggest more laminar flow than normally, where the exponent is in the vicinity of 0.65 (Sherman 2004). Therefore, the simplified method used in House A was expected to result in airflows more in agreement with the blower door method than when used in House B. But the results of House A were at least 50% higher than the airflow measured with the blower door. As Houses A and B are very similar except for the air leakage, there is no obvious explanation for the discrepancy in the results other than that the method becomes less reliable at an increased airtightness. This contradicts the assumption that the simplified method would be more precise in tighter buildings, as pressure decrease would be slower and the pressure difference range would be larger. More test results are needed to determine whether these results are coincidental or show a tendency.

Underestimating the Air Leakage. Equation 9 is a simplification of Equation 10, as differences in temperature and volume are ignored. Mattsson (2007) found that if volume changes are ignored, the airflow is underestimated.

In this case, the volume changes were considered to be small, as the construction of the houses left very little room for volume changes, especially at pressures less than 50 Pa. Movements of the air and vapor barriers in the ceiling were hindered by the insulation layer; in House A the insulation layer was secured by the roofing as there was no attic. Air and

Table 3. Airflow Calculated at Different Pressures

Pressure, Pa	House A: Simplified Method, m^3/h	House A: Blower Door, m^3/h	House A: Factor K	House B: Simplified Method, m^3/h	House B: Blower Door, m^3/h	House B: Factor K
10	85	192	2.28	222	431	1.95
20	169	322	1.90	443	667	1.51
30	254	434	1.71	664	862	1.30
40	338	538	1.59	886	1033	1.17
50	423	634	1.50	1107	1189	1.07

vapor barrier movements in the walls of House A were also hindered by an insulation layer. The floor in House A and the floor and outer walls in House B were of concrete and were assumed to be immovable by a pressure of 50 Pa. It is therefore assumed unlikely that the underestimation of the airflow was due to volume changes in the houses. As volume change increases with increasing pressure, the underestimation should also increase with increasing pressure. This was not the case.

Mattsson (2007) found that ignoring the temperature drop overestimates the airflow. Considering the temperature change but not the volume change would change Equation 10 to

$$\dot{V}_{env}(p) = -\frac{V_0}{P_0} \cdot \frac{5}{7}\frac{dp}{dt} , \quad (13)$$

which would increase the underestimation of the airflow. Therefore, an explanation cannot be found in the simplifications of the equations. It is more likely that the underestimation is due to other factors, e.g., the precision of instruments.

Discussion of Equipment and Method

Experiments that take place within seconds require precise and rapid reading and recording instruments and data loggers.

Precision of the Instruments. Although the print-output rate was set at the highest velocity (1 cm/s), the pressure changes might in reality have been faster—i.e., the curves should have been steeper—which could explain the underestimated airflows. House A had a smaller airflow than House B; therefore, the curve had a lower gradient. Thus, delays in the reading and recording should be of minor importance. In contrast to this, the overestimation of the airflow in House A is higher than that in House B. Better equipment might assist in determining whether there is a general overestimation due to the rate of reading and recording of pressure data.

Pressure differences below 4 Pa are in the range of natural pressure variations (Sherman 2004). Therefore, measurements of pressure differences between the outdoors and the volume within 4 Pa are encumbered with high uncertainty. To use pressure differences in this vicinity as a significant part of the method could therefore be misleading and partly explain the differences in Houses A and B that we have not been able to account for.

When the cylinder was closed, the pressure was supposed to drop immediately but, as shown in Figure 2, the curve does not break but is rounded at the top; this is due to delays in the measurements or equipment. The first measurements could therefore have a higher uncertainty than the following measurements. The uncertainty increases again as the pressure difference reaches the range of natural pressure variations. If the first two measurements in House A were omitted from Figure 3, the estimated exponential function would have been steeper and the calculated airflow would have increased by 6%. This indicates that better equipment and instruments could improve the simplified method.

It is remarkable how close the curves for the Cold Storage Room and House B are. The natural assumption is that the air leakage from the two volumes was similar. However, it could also just show the limits of the instruments; it could be the fastest way that the instruments can record a pressure decrease and consequently be the result of every volume with air leakage beyond a certain level. If true, this would be a result just as useful as the information that it is impossible to build up a significant pressure in a given volume, i.e., the air leakage is too high. Yet the calculated airflow in House B was relatively close to that of the blower door test results and much closer than the results for House A. Unfortunately, no blower door measurements were performed on the Cold Storage Room, and the simplified method was not used in another house with an airtightness close to that of House A or better. For the time being it must be regarded as a coincidence that the two volumes had the same air leakage. But the results could also be due to instrumental limitations, and in that case the good agreement with the blower door results in House B would be coincidental.

Reproducibility. The initial testing in the Cold Storage Room showed good reproducibility in the experiments; the four tests could be approximated to the same curve with a coefficient of determination of 0.99. It was therefore assumed that two tests per house would be sufficient. However, if the curves only show instrumental limitations, there is no guarantee of reproducibility. On the other hand, the two sets of measurements in House A also indicated good reproducibility.

Practical Issues. For practical reasons the nozzle of the cylinder should be shielded, diverting and spreading the airstream; otherwise the airstream can cause damage in occupied houses.

In some of the initial tested volumes it was impossible to obtain a pressure of 50 Pa; with hindsight it was clear that the volumes were not tight enough. In practice the same phenomenon sometimes occurs with the blower door method. In those houses, the air leakage is not determined but is known to be too high to comply with the Danish *Building Regulations* (DECA 2008). In these cases the simplified method would also fail, but thereby fulfil its purpose: it would be a quick method to discard too-leaky air barriers. In larger volumes, the blower door method can be performed with more fans. The simplified test could be performed with more than one cylinder, but the cylinders are to be turned off at approximately the same time, which makes the method more sensible to operator errors and requires more detailed interpretation of results. Therefore, the simplified method should only be used in volumes not larger than detached houses.

Limitations. This alternative method was meant as a simple method, not as precise as the blower door test method but faster and easier to perform. When this work began, the blower door method was new and expensive in Denmark. Therefore, a more inexpensive method was needed, especially if it enabled craftsmen to make a simple test before the specialist made the final test with the blower door. In that way the simplified method could be useful as a tool to be performed several times during the construction process, ensuring that leaks would be mended in time. The blower door test would simply be the proof of the airtightness of the building and would only be performed once.

Consequently, the method was supposed to be useful as a way to make a quick estimation of the magnitude of the air leakage with instruments that are inexpensive and easy to use. To achieve this aim, relatively simple instruments were used in this work. This has probably affected the results and might be the main cause of the poor agreement between the calculated airflows obtained by using the two different methods.

Having said that, the measurements of the simplified method have poor correlation to the blower door measurements. It must be emphasized that the method with this equipment was not supposed to be very accurate. In many cases a tolerance within 50% would be sufficient, or it might be enough to know that the air leakage is beyond a given point. The question is how large an error margin would be acceptable. Normally the acceptable error margin decreases as results approach an acceptable value for the airflow.

FUTURE APPLICATIONS

A simplified method cannot be used as the only test method unless its results are on the safe side. But as long as it is difficult to obtain sufficient airtightness in building envelopes and consequently expensive to achieve airtightness, a more precise method will be chosen if it is not too expensive. Some of the motivation for developing an alternative to the blower door method has been eliminated, as blower door tests have become much less expensive (1/10 of the price in 2005) and contractors have learned to build more airtight volumes and therefore have fewer problems meeting the requirements of airtightness. The need for testing during the building process seems to be obsolete. However, there is no registration of how often building envelopes fail the blower door test and have to be tightened and retested, a process that continues until the airtightness complies with the Danish Building Regulations. Only the final test is registered by the authorities; the craftsmen have no interest in revealing the number of attempts. Therefore, the need for a test during the construction process might be underestimated.

A simple method might nonetheless be useful in more special cases, such as cavities where it can be difficult to place the fan of the blower door, e.g., in crawlspaces or single building parts where airtightness is important. In these special cases the method could be used by an expert with better instruments. Thus, an alternative to the blower door method might still be needed. To reduce the effect of natural pressure differences, the method will probably be most useful if the pressure difference is not between the pressurized volume and the outdoors but between the pressurized volume and a non-pressurized indoor volume. In that case, low-pressure measurements can be more exact.

Despite the simple instruments used in this work, the method provides perspective, as the curves in Figure 3 are reproducible and show a systematic decrease of pressure. Although the deviations from the results of the blower door test have not been fully explained, better instruments and pressures that would at least reach the level of the blower door method could improve the results of the method. If the release of air could be fully controlled, Phases 1 and 2 could possibly be used for determining the air leakage in three different independent ways virtually within seconds.

CONCLUSIONS

A simplified method was developed and tested that determines the air leakage from volumes by pressurizing the volumes with air from a cylinder and measuring the pressure decrease over time. The results were compared with measurements using the blower door test. The method could be explained theoretically and the measurements showed reproducibility and systematic pressure decrease: steeper curves with higher air leakage. But the calculated airflows at 50 Pa were different from the calculations based on the blower door method. In House A, the tightest house, with an air change rate of 1.2 L/s per m^2 at 50 Pa, the calculated airflow was 50% higher than calculations based on the blower door method. In House B, the air change rate was 2.6 L/s per m^2 at 50 Pa and the calculated airflow was only 7% higher than calculations based on the blower door method.

The different results for the two houses could not be fully explained; the two houses were very similar and in both cases volume changes due to the pressurization were assumed to be small and therefore ignored. The pressure decrease took place within seconds and delays and damping of instruments and recordings could in both cases be responsible for underestimation of the airflow but not for the much higher underestimation in House A. However, the method was only used for two houses, and more extensive testing is needed to determine whether these test results show a general tendency or are only fluctuations in the method.

The commercial motivation for developing an alternative to the blower door method has diminished; however, the method could still be useful in special cases or as a quick indicator. At the current stage, the results can only be used as a qualified guess of the air leakage in a house. The hypothesis that the method could be used as a simplified and quick method is therefore only partly corroborated.

Better instruments and more measurements in different houses, and thereby different air leakages, and at higher pressures could improve the method.

ACKNOWLEDGMENTS

The authors would like to thank the Aase and Ejnar Danielsens Foundation for financial support and Lars Due, Isolink, for performing the blower door tests.

REFERENCES

ASTM. 2003. *ASTM Standard E779-03, Standard Test Method for Determining Air Leakage Rate by Fan Pressurization*. West Conshohocken, PA: ASTM International.

CEN. 2000. *EN 13829, Thermal Performance of Buildings—Determination of Air Permeability of Buildings—Fan Pressurization Method* (ISO 9972:1996 modified). Brussels, Belgium: European Committee for Standardization.

Dewsbury, J. 1996. AC pressurisation: Analysis by non-linear optimisation. *Building Services Engineering Research and Technology* 17(65).

DECA. 2008. *Bygningsreglement 2008 (Building Regulations 2008)*, 2nd ed. Copenhagen, Denmark: Danish Enterprise and Construction Authority.

Mattsson, B. 2007. Studies on building air leakage—A transient pressurization method, measurements and modelling. Doctoral thesis, Chalmers University of Technology, Göteborg, Sweden.

Sherman, M., and R. Chan. 2004. *Building Airtightness: Research and Practice.* Report no. LBNL-53356, Lawrence Berkeley National Laboratories, Berkeley, CA.

Sherman, M., and M. Modera. 1988. Signal attenuation due to cavity leakage. *Journal of Acoustical Society in America* 84(6).

Walker, I.S., D.J. Wilson, and M.H. Sherman. 1998. A comparison of the power law to quadratic formulations for air infiltration calculations. *Energy and Buildings* 27:293–99.