BUILDING AND DUCTWORK AIRTIGHTNESS

A SELECTION OF PAPERS FROM THE PROCEEDINGS OF THE 33rd AIVC - 2nd TIGHTVENT CONFERENCE, OCTOBER 2012 COPENHAGEN

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BUILDING AND DUCTWORK AIRTIGHTNESS

A selection of papers from the Proceedings of the 33rd AIVC- 2nd TightVent Conference, October 2012, Copenhagen

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33RD AIVC AND 2ND TIGHTVENT CONFERENCE- SUMMING UP OF AIRTIGHTNESS TRACK

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Synopsis

The airtightness track at the AIVC conference consisted of 29 presentations organized in 7 sessions. In 3 sessions research work was presented dealing with various airtightness related aspects as requested in the call for papers. In 4 sessions invited presentations and structured discussions were offered to give an overview of some specific conference topics:

- Ductwork airtightness
- Quality and building airtightness
- Quality of domestic ventilation systems
- Philosophy and approaches for building airtightness requirements

In the following paragraphs a bird's eye view is given of trends and conclusions that appeared in the presentations and discussions in the airtightness track.

From airtightness requirements to quality assurance

A number of presentations showed experimental evidence of the fact that new buildings become increasingly more airtight, compared to buildings built in previous decades. This evolution is attributed to the strengthening of energy performance requirements, typically in European countries, and to innovations in construction practice. According to the European Energy Performance of Buildings Directive (EPBD) the influence of air infiltration on the energy use of a building is taken into account when assessing the energy performance. As a result, building designers pay more attention to airtightness in order to meet more severe energy performance requirements for new buildings. However, in some countries also explicit airtightness requirements are set in order to prepare the market for a change towards ‘nearly zero energy buildings’. An example of this approach is the French RT2012 legislation, which requires the airtightness of all new residential buildings to be tested in order to show compliance to legal limits.

Several presentations showed that the specification of airtightness requirements alone is not enough to achieve good building airtightness in reality. When no quality framework is adopted, design intents for airtightness are not systematically met because of flaws and variations in workmanship. This was shown in a project in Greenland where a large number of identical flats in a building was tested and a standard deviation of 47% was reported. Creating airtight building envelopes entails profound changes in design and construction practice and requires careful planning of the overall building process. Therefore a number of quality management and training schemes were presented in order to master this process. Sweden has a long experience with the implementation of quality ductwork systems and has included quality requirements in the AMA specification guidelines, based on subsequent partial testing. In France regulatory quality management processes are operational for building airtightness compliance by constructors, based on self-declared testing of a sample of the housing production. Control tests have shown that these schemes are very effective in achieving good airtightness in practice (Figure 1). Good examples of certification schemes for craftsmen were given by FLiB in Germany (Fachverband Luftdichtheit im Bauwesen), with guidelines for selection and installation of air barrier systems.

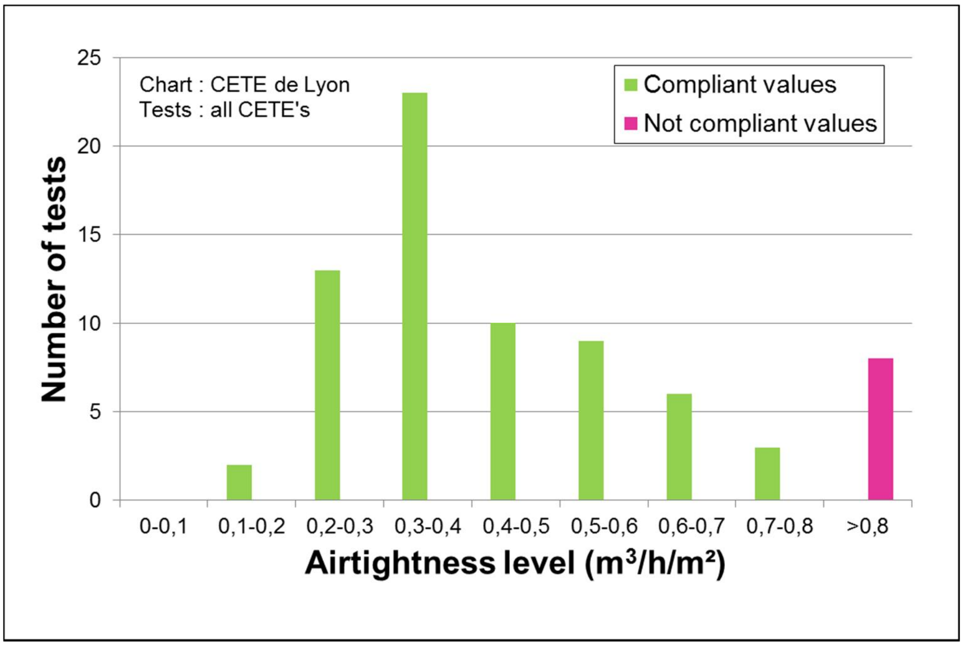

Figure 1: Results of control tests showing effectiveness of French quality framework for building airtightness compliance (85% compliance demanded, 89% compliance achieved) [1]

Air leakage testing and infiltration modeling

When airtightness requirements become more severe, also fan pressurization equipment and testing procedures to show compliance should allow obtaining reliable and repeatable test results. Several presentations were dealing with these issues. For testing single apartments in multifamily buildings different experimental procedures exist, and it is not always clear what one is measuring. A number of test results were presented quantifying the leakage distribution in apartments for different purposes: e.g. to assess the transfer of pollution between individual flats, or to assess the air leakage distribution ratio between internal and external partitions of apartments. A large-scale measuring campaign in high rise residential buildings in South Korea revealed that internal walls between flats often show the highest leakage (30-60% of total leakage).

A better knowledge of the air leakage distribution over the building envelope is also important to come to a more reliable extrapolation of fan pressurization test results at 50 Pa to air infiltration rates under natural driving forces (and related heat losses). While this extrapolation is typically based on rules of thumbs (the 'rule-of-20') or simplified steady-state models (Normalized Leakage), advanced simulation studies were presented to analyse the influence of uneven leakage distribution and unsteady wind conditions on air infiltration rates. Ultimately these studies should allow developing more refined and accurate leakage models for infiltration heat loss assessment in high performance buildings.

IAQ and ventilation in airtight buildings

The fact that new buildings become more airtight is good news for the energy performance of buildings, but is also a reason for concern when indoor air quality and health issues are considered. In countries where residential ventilation traditionally relied on air leakage and on occasional opening of windows, such as in New Zealand, it is now found necessary to introduce reliable ventilation solutions to achieve acceptable IAQ and moisture control in new airtight houses. Even in countries where the installation of residential ventilation systems is part of the building code requirements, such as in most European countries, acceptable indoor air quality is not necessarily achieved. A number of multizone simulation studies were presented addressing IAQ performance in airtight houses. Although simulations showed that IAQ may improve with enhanced building air tightness, specifically for exhaust ventilation systems where designed air transfer is reinforced, the IAQ and indoor humidity achieved in airtight houses is sensitive to ventilation system design, sizing and installation errors.

However, some presentations discussed results of large-scale field studies showing striking evidence that installation quality of residential ventilation systems is typically insufficient. This was the case for studies performed in the Netherlands, Belgium and Estonia. Common shortcomings were insufficient supply ventilation capacity compared to design standards (in more than half of the investigated houses, Figure 2), increased noise levels in case of mechanical ventilation systems, and poor operation and maintenance. An overall conclusion was that together with increased building airtightness, more attention should be paid to ventilation system performance and installation quality, in order to guarantee healthy indoor environments. This requires a change of mind set, not only with building practitioners, but also with builders who should be more willing to pay the price for good quality ventilation systems.

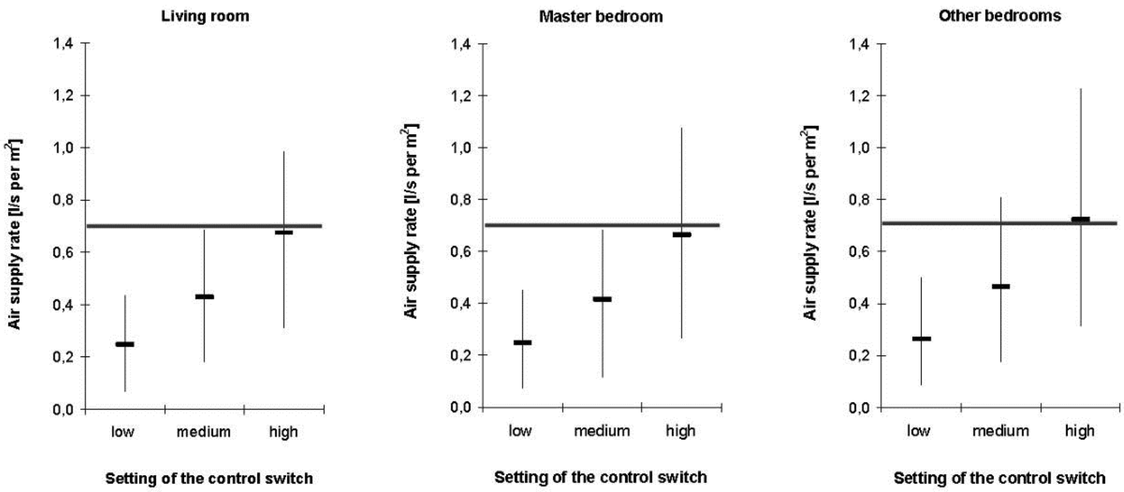

Figure 2: Air supply rates (average, P10 and P90) in the living room, master bedroom and other bedrooms in dwellings with balanced mechanical ventilation, at different control settings. The horizontal line gives the reference (minimum) level according to the Dutch Building Code (0, 7 $l/s/m^2$), [2].

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AIR LEAKAGE OF US HOMES: REGRESSION ANALYSIS AND IMPROVEMENTS FROM RETROFIT

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Abstract

LBNL Residential Diagnostics Database (ResDB) contains blower door measurements and other diagnostic test results of homes in United States. Of these, approximately 134,000 single-family detached homes have sufficient information for the analysis of air leakage in relation to a number of housing characteristics. We performed regression analysis to consider the correlation between normalized leakage and a number of explanatory variables: IECC climate zone, floor area, height, year built, foundation type, duct location, and other housing characteristics. The regression model explains 68% of the observed variability in normalized leakage. ResDB also contains the before and after retrofit air leakage measurements of approximately 23,000 homes that participated in weatherization assistant programs (WAPs) or residential energy efficiency programs. The two types of programs achieve rather similar reductions in normalized leakage: 30% for WAPs and 20% for other energy programs.

Keywords

Blower door, fan pressurization measurements, air infiltration, weatherization, retrofit

Introduction

Residential energy efficiency and weatherization assistance programs (WAPs) have led to many measurements of air leakage being made in recent years. Building envelope airtightness is important because heating and cooling accounts for about 50% of the total energy consumption by US households [1]. Therefore, knowledge on the current state of the US housing stock, and factors that are associated with excessive air leakage, can have substantial energy implications.

In 2011, we collected a large number of air leakage measurements and updated the LBNL Residential Diagnostics Database (ResDB). Our latest efforts not only increased the number of data points, but also improved the spatial representation of the dataset. It is the goal of this regression analysis to identify housing characteristics that explain the observed variability in air leakage of single-family detached homes. In addition, we compared the air leakage measurements of homes before and after retrofit. Insulation upgrades and air sealing are commonly performed in a retrofit. In the US, the expected energy saving in heating and cooling bills from tightening the building envelope and reducing air infiltration is 10% to 20% [2]. But many factors can influence the energy savings and cost-effectiveness of air sealing and other retrofit measures, such as the initial air leakage of the house, and the expected improvement in airtightness from retrofit. This analysis will characterize the airtightness of the current US housing stock, and provide some of the needed data to evaluate the energy saving potential from reducing air infiltration via retrofit.

Data description

Data Sources

The newly updated ResDB contains air leakage data from 134,000 single-family detached homes. However, many missing data are present. The handling of these missing data, including year built, foundation type, and duct location, will be explained in greater details below. Overall, forty-three states are represented. The median year built and floor area is 1969 and 140 m^2, respectively.

Income-qualified WAPs are the major sources of data, accounting for about half of the blower door measurements. In prior versions of ResDB [3, 4], Ohio was the only WAP present. ResDB now contains WAP data from eleven other states, including Arkansas, California, Iowa, Idaho, Minnesota, Montana, Pennsylvania, Utah, Virginia, Washington, and Wisconsin.

Residential energy efficiency programs are another major source of data. For example, the Home Performance with ENERGY STAR program[1] is implemented in over 30 US states to improve energy efficiency of homes. New Jersey and Minnesota are the two states with the most pre- and post-retrofit blower door measurements in ResDB. There are also many data from programs in Vermont, Indiana, California, and Georgia.

Other sources that contributed air leakage and other diagnostic measurements include new homes that were tested to obtain an energy efficiency rating, or to demonstrate that they met an airtightness guideline. Homes are identified as energy efficiency rated according to the programs that collected the data, so there are likely some differences in rating criteria between the energy efficient homes. Moreover, there are also data that were collected for research studies or other purposes. Sources voluntarily contributed data to ResDB.

[1] http://www.energystar.gov/index.cfm?c=home_improvement.hm_improvement_index

Therefore, even though ResDB contains a large volume of data, the self-selected samples are not representative of the homes in US.

Normalized Leakage

Most of the air leakage data in ResDB are blower door measurements at 50 Pa pressure difference. Air leakage measurements are converted to normalized leakage (NL) for this analysis, as follows:

$$NL = 1000\left(\frac{ELA_{4\text{ Pa}}}{Area}\right)\left(\frac{H}{2.5\text{ m}}\right)^{0.3} \quad \text{where} \quad ELA_{4\text{ Pa}} = \sqrt{\frac{\rho}{2\times 4\text{ Pa}}}\left(Q_{50\text{ Pa}}\right)\left(\frac{4\text{ Pa}}{50\text{ Pa}}\right)^{n} \qquad (1)$$

$ELA_{4\text{ Pa}}$ (m^2) is the effective leakage area at 4 Pa, $Area$ (m^2) is the dwelling floor area, H (m) is the dwelling height, $\rho = 1.2$ kg/m^3, and $Q_{50\text{ Pa}}$ (m^3/s) is the airflow rate at 50 Pa measured by the blower door. NL is roughly lognormal distributed, with a geometric mean of 0.61 and a geometric standard deviation of 2.5. ResDB contains 7,000 measurements of pressure exponent, n, which are used to compute NL when available. The distribution of n is roughly normal with a mean of 0.65, and a standard deviation of 0.06. n is assumed to be 0.65 for all other cases [5].

If H is not provided in the data, we assumed 2.5 m for each story, and an additional 0.5 m for ground level and inter-floor framing. In some cases where both the number of story and house height are unknown, we assumed that houses <200 m^2 are single-story, and >200 m^2 are two-story. This simple allocation based on 200 m^2 as the reference point is the same as used in previous analyses of ResDB [3, 4]. About 80% of single-story detached houses in US are <200 m^2, but only half of the multi-story detached houses are <200 m^2 [6]. Our method of using the house size to approximate number of story is reasonable, but it is a source of uncertain.

Multiple blower door measurements exist for some homes in ResDB. If additional tests were performed to verify a measurement, then the average value is used. If a house was tested under different configurations, then the one that best described the occupied condition is used, i.e., exclude attic, but include or exclude basement depending on the normal winter condition.

Regression model

The multivariate regression considers the relationship between NL and these housing characteristics:

- Floor area $Area$ (m^2)
- House height H (m)

- Year built $\overleftrightarrow{I_{year}}$: before 1960, 60–69, 70–79, 80–89, 90–99, 2000 and after
- IECC climate zones $\overleftrightarrow{I_{cz}}$: 12 categories
- Homes participated in WAP: $I_{LI} = 1$
- Homes rated for energy efficiency: $I_e = 1$
- Foundation type: I_{slab}, I_{floor1}, or I_{floor2}
- Duct location: I_{cond}, I_{duct1}, or I_{duct2}

Area and *H* are continuous variables, and all the remaining ones are indicator variables. Twelve of the 16 IECC climate zones[2] are represented: humid (5), dry (3), marine (2), and Alaska (2). The climate zone is determined by the house location, which is typically available by state and county, and the climate zone is identified correspondingly. For WAPs and other data with measurements before and after retrofit, the before values were used in the regression below. Homes are identified as energy efficiency rated by the programs that contributed the data.

Most of the data are missing foundation type and duct location. As a result, we first preformed the regression without these two parameters, as shown in Eq (2).

$$\ln(NL) = \beta_{area} Area + \beta_h H + \overleftrightarrow{\beta_{year}}\,\overleftrightarrow{I_{year}} + \beta_{LI} I_{LI} + \beta_e I_e + \overleftrightarrow{\beta_{cz}}\,\overleftrightarrow{I_{cz}} \tag{2}$$

Using the coefficient estimates from Eq (2), the model residuals NL' are computed as follows:

$$\ln(NL') = \ln(NL) - \left[\beta_{area} Area + \beta_h H + \overleftrightarrow{\beta_{year}}\,\overleftrightarrow{I_{year}} + \beta_{LI} I_{LI} + \beta_e I_e + \overleftrightarrow{\beta_{cz}}\,\overleftrightarrow{I_{cz}}\right] \tag{3a}$$

We then considered the effects of foundation type and duct location on the model residuals to estimate their influence on NL. Only the data with known foundation type or duct location is considered in Eq (3b) and (3c) respectively, so the values of NL' used for the regression are different in the two equations.

$$\ln(NL') = \beta_{slab} I_{slab} + \beta_{floor1} I_{floor1} + \beta_{floor2} I_{floor2} \tag{3b}$$
$$\ln(NL') = \beta_{cond} I_{cond} + \beta_{duct1} I_{duct1} + \beta_{duct2} I_{duct2} \tag{3c}$$

[2] See http://energycode.pnl.gov/EnergyCodeReqs/ for IECC climate zone classification.

From our previous work, we expected NL to be strongly correlated with year built [3,4]. To maximize the number of data considered in the regression, we categorized year built by decades from 1960 and onwards. But even when year built is treated as a categorical variable, one-quarter of the data are still missing this information. For these data, we imputed a year built category as follows. We first performed a regression by using three-quarters of the data with no missing data (i.e., year built is known). From this regression, we determined that ln(NL) decreases at an average rate of 0.14 from one year built category to the next newer category. Using this result, we imputed a year built category such that the predicted ln(NL) would best fit the measurements that contain missing data. The results are shown in Figure 1.

The imputation does not change the portion of homes in the different year built categories (Figure 1 (a)). Homes that are built before 1960 and after 2000 remain the most common. This imputation method allows more data to be included in the regression model. Otherwise, homes in dry climate zones B-4, 5, and 6, and in marine climate zones C-3 and 4, would not be sufficiently represented in the regression.

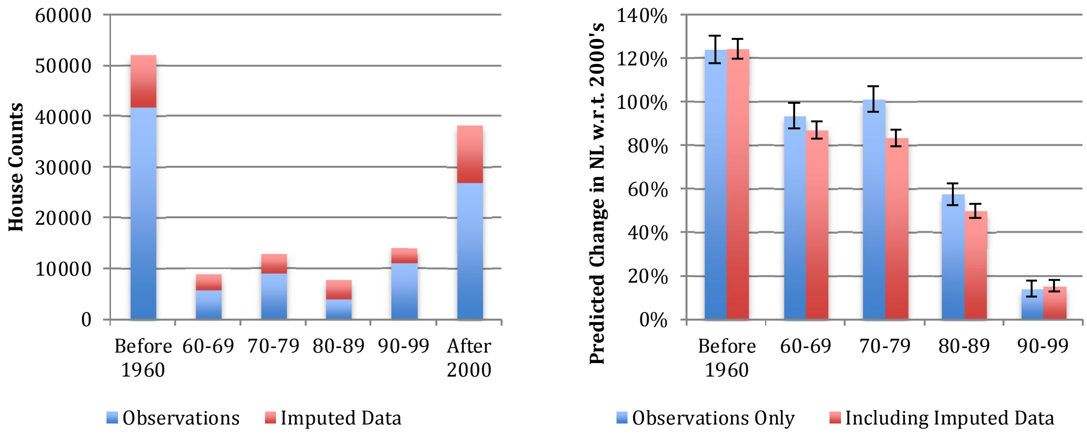


Figure 1: (a) Observed and imputed year built categories of single-family detached homes considered in the regression analysis. (b) Comparison of the predicted change in NL with respect to homes that are built in 2000's with and without imputation. Error bars show the 95% confidence interval.

Table 1 shows the regression results using the imputed data. Homes located in climate zone A-6, 7 are selected as the reference, but other choices would give the same relative results. The model explains about 68% of the observed variability. The residuals ln(NL') are normally distributed: mean = 6.2e-17, and variance = 0.20.

One drawback of the imputation method used is that it can lead to underestimation of the differences between the observed and predicted values. In this case, however, the fit of model with (R^2=0.683) and without (R^2=0.682) the imputed data was essentially unchanged. With the imputed data, the predicted differences in NL for homes in different year built also remain roughly the same, as shown in Figure 1(b).

Figure 1(b) shows that homes built from more recent years have lower NL. This indicates that new homes were built with a more airtight building envelope compared to homes dated from earlier years. A recent study of new homes in California that are built between 2002 and 2004 also found that homes are built tighter compared to homes built in the 1980s and 1990s [7]. In addition to improvement in construction practices leading to tighter building envelope, it is also possible that there is a relationship between NL and house age. Older homes have higher NL not only because they were constructed that way, but also because the building envelope became leakier over time. Both of these factors together likely explain a significant portion of the variability in NL among houses. Further analysis to isolate these two factors will be discussed in future analyses of ResDB.

Explanatory Variable	**Coefficient Estimates**	**Standard Error**	**Pr(>|t|)**	**95% Confidence Interval**
Area (m^2)	-0.00208	0.0000179	< 2e-16	-0.00211; -0.00204
Height (m)	0.064	0.00125	< 2e-16	0.061; 0.066
Year: Before 1960	-0.250	0.00705	< 2e-16	-0.264; -0.236
1960-69	-0.433	0.00811	< 2e-16	-0.449; -0.417
1970-79	-0.452	0.00762	< 2e-16	-0.467; -0.437
1980-89	-0.654	0.00836	< 2e-16	-0.670; -0.637
1990-99	-0.915	0.00816	< 2e-16	-0.931; -0.899
After 2000	-1.058	0.00748	< 2e-16	-1.073; -1.043
WAP Homes (pre-weatherization)	0.420	0.00428	< 2e-16	0.411; 0.428
Energy-Efficient Homes	-0.384	0.00453	< 2e-16	-0.393; -0.375
Humid A-1,2	0.473	0.01015	< 2e-16	0.453; 0.493
A-3	0.253	0.00653	< 2e-16	0.240; 0.266
A-4	0.326	0.00586	< 2e-16	0.315; 0.338
A-5	0.112	0.00551	< 2e-16	0.101; 0.123
A-6,7	0	--	--	--
Dry B-2,3	-0.038	0.00759	7.57e-07	-0.052; -0.023
B-4,5	-0.009	0.00684	2.00e-01	-0.022; 0.005
B-6	0.019	0.00988	4.91e-03	0.00008; 0.039
Marine C-3	0.048	0.01407	6.02e-04	0.021; 0.076
C-4	0.258	0.01133	< 2e-16	0.236; 0.281
Alaska AK-7	0.026	0.00589	1.42e-05	0.014; 0.037
AK-8	-0.512	0.00938	< 2e-16	-0.530; -0.439

Table 1: Results of regression model (β's in Eq. (2)) without considering foundation type and duct location.

All the coefficient estimates from the above regression are statistically significant at the 95% confidence interval, with the exception of climate zone B-4,5. This means that homes in climate zone B-4,5 tend to be less leaky than in the reference zone A-6,7, but the difference is small, and we cannot exclude the possibility that this apparent difference occurs only by chance in our data sample. We observed no effect on the overall model fit if homes B-4,5 and A-6,7 are grouped together or separately. Since these two climate areas are geographically far apart, for completeness we decided to keep all 12 climate zones in the model.

Foundation Type and Duct Location

For foundation type and duct location, we performed the regression analyses using a subset of the data, and assumed that the coefficient estimates also apply to the larger dataset. There are 12,500 houses with known foundation types: $I_{slab} = 1$ means house is built on slab, $I_{floor1} = 1$ means conditioned basement or unvented crawlspace, and $I_{floor2} = 1$ means unconditioned basement or vented crawlspace. These categories are chosen because after adjusting for the other parameters using Eq. (3a), homes with slab have the lowest NL, followed by homes where $I_{floor1} = 1$, and homes with $I_{floor2} = 1$ have the highest NL (Figure 2 (a)).

Figure 2 (b) shows a similar comparison but for duct locations using another subset of the data where this information is available. Homes with ducts located inside the conditioned space have the lowest NL, followed by homes with ducts located in the unconditioned attic or basement, and homes with ducts located in the vented crawlspace have the highest NL. However, the comparison by duct location is uncertain because it is based on very few data (526 houses).

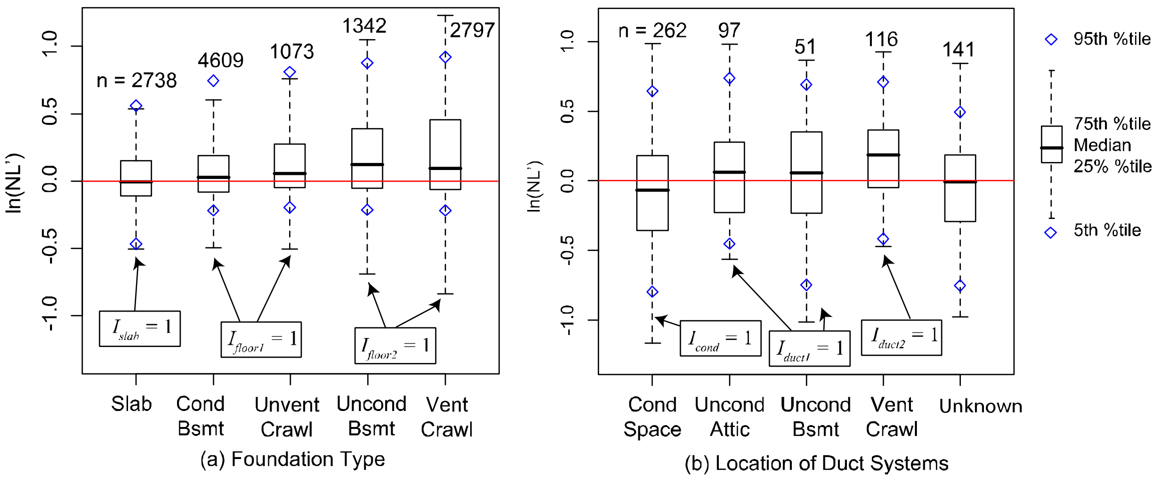


Figure 2: Model residuals of NL, computed using Eq. (3a), for homes with known (a) foundation type and (b) duct location (n = house counts). ln(NL') > 0 means that houses have NL higher than is predicted by Eq. (2).

Results of the regression (Table 2) show that the indicator variables considered are all statistically significant at 95% confidence interval. The coefficient estimates, β's, describe the influences of foundation type and duct location on NL as illustrated in the residual plots (Figure 2). Houses that are built on a slab and have ducts located inside the conditioned space tend to have the lowest NL. On the other hand, houses that have a vented crawlspace tend to have the highest NL, especially if the ducts are located in the crawlspace.

	Coefficient Estimates	Standard Error	Pr(>|t|)	95% Confidence Interval
(a) Foundation Type				
β_{slab}	-0.037	0.00709	1.85e-07	-0.051; -0.023
β_{floor1}	0.109	0.00492	< 2e-16	0.099; 0.118
β_{floor2}	0.180	0.00577	< 2e-16	0.169; 0.192
(b) Duct Location				
β_{cond}	-0.124	0.0255	1.53e-06	-0.174; -0.074
β_{duct1}	0.071	0.0339	3.59e-02	0.0047; 0.138
β_{duct2}	0.181	0.0383	2.98e-06	0.106; 0.256

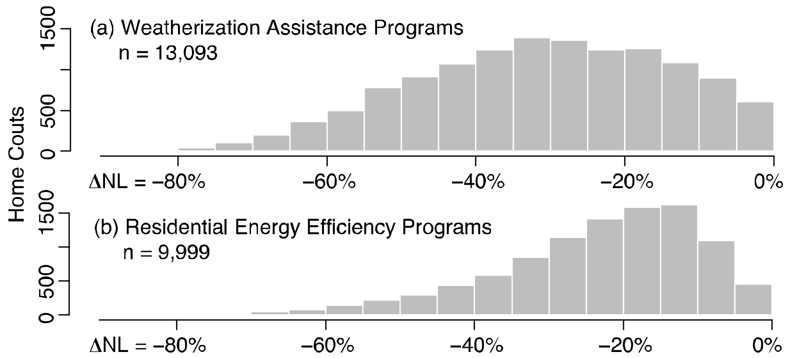
Table 2: Results of regression model considering the effects of (a) foundation type and (b) duct location.

Retrofit improvements

There are 23,000 houses with pre- and post-retrofit blower door measurements. Paired data that showed no improvements (462 homes) or increase in NL (449 homes) were excluded from this analysis. It is likely that those records reflect cases where retrofit did not include air sealing or other work that would reduce air leakage. In homes where NL increased, the percent change from the pre-retrofit measurement is <10% in half of the homes.

There are many differences in how WAPs and residential energy efficiency programs are implemented. WAPs use the minimum ventilation rate limit without mechanical ventilation (based on ASHRAE 62.2) as the target. The resulting savings-to-investment ratio must be greater than one for the work to qualified as allowable expenditures. On the other hand, energy efficiency programs, typically sponsored by utilities, tend to offer rebates and other financial incentives for homeowners to perform an energy audit, and to follow through with its recommendations.

Figure 3 shows a larger reduction in NL pre- and post-retrofit from WAPs overall, compared to the residential energy efficiency programs. When the two programs are considered together, the median ΔNL is -25%. Aside from differences in how the two types of programs are implemented, there are also other state-by-state differences in the kinds of retrofit measures performed, and how the air leakage measurements were collected and documented. As a result, there can be many explanations for the differences between the two programs.



Percent Change in NL:

$$\Delta NL = \left(\frac{NL_{post}}{NL_{pre}} - 1\right) \times 100\%$$

ΔNL	(a) WAPs	(b) E. Prog.
Median	-30%	-21%
25^{th} to 75^{th} Percentiles	-18 to -43%	-13 to -31%
5^{th} to 95^{th} Percentiles	-5 to -61%	-5 to -50%

Figure 3: Reduction in NL as a result of retrofit from (a) WAPs and (b) residential energy efficiency programs.

As shown by the regression model, WAP homes tend to have a higher NL pre-weatherization. This may be one of the reasons why WAPs appear to achieve a higher reduction in NL. It is easier to reduce obvious air leakage pathways that exist in leaky homes, than to make significant improvements in homes that are more airtight to begin with. To test this hypothesis, we considered the relationship between ΔNL and NL_{pre}, and also with other variables, including: climate zone, house dimensions, and year built. Regression analysis suggests that for WAPs, only NL_{pre}, floor area, and height are useful parameters in explaining ΔNL, but not climate zone or year built. However, this relationship does not hold for houses that participated in residential energy efficiency programs, where the regression analysis shows that none of the parameters considered are useful in explaining ΔNL.

Results and discussion

Figure 4 compares the potential influence of the various explanatory variables on NL predictions, including:

a) Other climate zones compared with respect to A-6,7

b) WAP homes versus non-WAP; homes rated for energy efficiency or not

c) Floor area increased by 100 m^2; height increased by 2.5 m

d) Other foundation types: conditioned basement or unvented crawlspace (*floor1*), or unconditioned basement or vented crawlspace (*floor2*), compared with respect to slab (*slab*)

e) Duct located inside conditioned space (*cond*) or in unvented crawlspace (*duct2)* versus in unconditioned attic or basement (*duct1*)

The percent change in NL is computed using the coefficient estimates of the regression model, as shown in Table 1 and 2. For example, Figure 4(a) shows that houses in climate zone A-1,2 are 60% higher in NL than homes in A-6,7. This is computed by exp(0.473) – 1 = 0.6. The effects of year built are shown in Figure 1 (b), and are not repeated here.

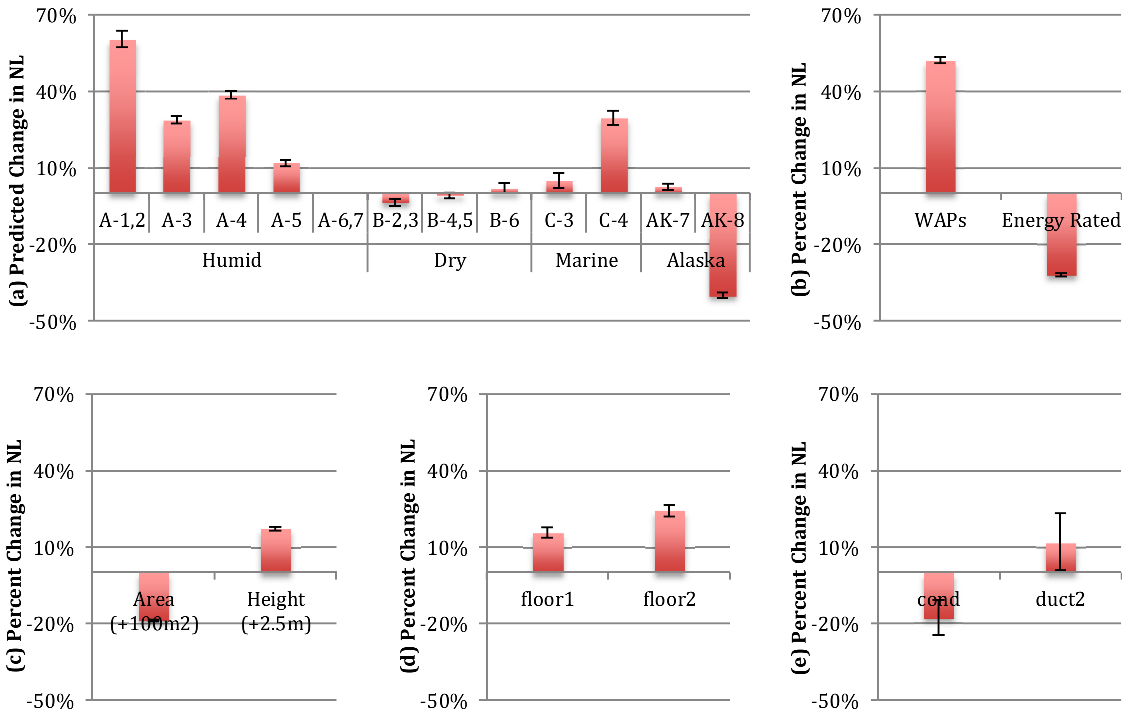


Figure 4: Predicted change in NL for homes in (a) difference climate zones with respect to climate zone A-6,7, and (b–e) other variables considered in the regression. Error bars show the 95% confidence interval.

Much of the variability observed in NL is associated with (a) climate zone, and (b) whether the houses are participants in WAPs or are energy efficiency rated homes. The difference in NL between the two extreme climate zones, A-1,2 and AK-8, is a factor of 2.7. The remaining factors, namely: (c) floor area and house height, (d) foundation type, and (e) duct location, each explain some differences in NL in the 10% to 20% range. In comparison, their importance is secondary for predicting NL. Overall, year built remains an important attribute to consider for predicting NL (see Figure 1(b)). The difference in NL between homes that are built before 1960 and after 2000 is a factor of 2.2.

The regression model presented here gives an estimate of NL based on a number of housing characteristics. For a housing stock, the model can explain 68% of the observed variability. However, the model is much more uncertain when it is applied to one house. This is because of the residual term. For example, the model predicts NL = 0.47 for a 150 m^2, single-story house built in 1990s that is located in climate zone C-3. The 95% confidence interval of this prediction is 0.44 to 0.50. However, the model residual ln(NL') has a variance of 0.20. This means that there is only about 10% probability that a house with the exact characteristics will have NL between 0.44 and 0.50. For this one house, the model predicts there is a 95% probability that its NL is between 0.2 and 1.1. But, for many homes with the same characteristics, the regression model predicts with 95% confidence that the values of NL will likely center in between 0.44 and 0.50.

Conclusion

Many blower door measurements have been added to LBNL Residential Diagnostics Database from housing units across the US. Regression analyses were performed on 134,00 single-family detached homes to describe the relationships between NL and house characteristics. By improving the spatial coverage of ResDB, more meaningful relationships were observed with climate zones. The predictive model explains about 68% of the observed variability, most of which are explained through year built, climate zone, and whether the houses are part of a WAP or energy efficiency rating program. Houses that are older, located in hot and humid areas of the US (climate zone A-1,2), and are occupied by households eligible for WAPs based on income are likely to have higher NL. Other characteristics that are associated with higher air leakage include houses with a vented crawlspace, and especially when ducts are located in the crawlspace as well. This information is useful for estimating the air leakage baseline of US homes, and can be used to target homes that would likely benefit the most from airtightness improvements to lower their energy costs.

Comparison of the before and after retrofit blower door measurements shows a reduction of NL in the 20% to 30% range. WAPs achieved somewhat higher reduction in NL than other residential energy efficiency programs, likely because WAP homes were more leaky pre-weatherization. The current data show comparably reduction in NL across all retrofit programs regardless of house location or year built. This is important because construction methods and practices vary greatly in the US. This analysis suggests that improvement in airtightness is possible across the US housing stock.

Acknowledgements

We greatly appreciate organizations and individuals who shared their blower door and other diagnostic data with us. This work was supported by the California Energy Commission Public Interest Energy Research Program award number CEC-500-07-006 and the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under contract No. DE-AC02-05CH11231.

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LESSONS LEARNED ON VENTILATION SYSTEMS FROM THE IAQ CALCULATIONS ON TIGHT ENERGY PERFORMANT BUILDINGS

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Abstract

During the project QUAD-BBC, several ventilation systems have been studied in residential (individual house and collective dwellings) and non-residential (school, offices) and assessed by the evaluation of an IAQ multi-criteria.

These calculations have shown some typical evolution of pollutants in very tight low consumption buildings and can alert on some possible effects.

For instance, formaldehyde and VOCs criteria are increasing at night when ventilation is shut off which indicates that passive measurement methods are in this case evaluating an average exposure not representative of occupation. It also shows how much airflow should be maintained to reduce the exposure to these pollutants or how much time before

occupation the system should be started. Other lessons can be learnt from the pollutions in the kitchen during cooking, the humidity of drying clothes in houses and the impact of occupant behaviour.

Humidity evolution in case of insufficient ventilation in rooms with a high density of occupation (classrooms, meeting rooms…) has also a much stronger impact in a very tight building. The study also shows that the ventilation performance can be improved, especially in main rooms when improving building airtightness. While we could fear the contrary, improved airtightness appears to be beneficial to IAQ in our test cases.

This paper presents the main lessons learnt from the calculation analysis in these buildings.

Keywords

IAQ, Air tightness, ventilation efficiency, simulation

Introduction

Low-energy buildings are built with well-insulated envelope in order to reduce the energy demand. In France, the conventional primary energy consumption should be inferior to 50 kWh/m^2/year for the residential low-energy buildings. This consumption takes into account the energy demand for heating, which includes the energy demand of ventilation and infiltration, space lighting, air-conditioning, ventilation auxiliaries and hot water production.

The up-coming French thermal regulation RT2012 will apply this specification for the new built buildings. Nevertheless, the regulation on ventilation does not specially deal with low energy buildings. One then can wonder about the energy impact of ventilation in such buildings. This concept of buildings brings out additional questioning on the link between innovative ventilation systems and indoor air quality (IAQ). The main concern is: which ventilation systems are suitable for low-energy buildings? In these conditions, the part of ventilation in the energy consumption would increase in these buildings The adequate ventilation system should meet the energy requirements while providing acceptable indoor air quality.

During the project QUAD-BBC [1] several ventilation systems have been studied in residential (individual house and collective dwellings) and non-residential (school, offices) and assessed by the evaluation of an IAQ multi-criteria.

This criteria takes into account:

- Humidity (number of hours above 80%) linked to occupants and their activities

And 4 specifics indexes related to common activity or impact

- A CO_2 as index of confinement linked to occupation,

- B NO_2, SO_2 (dwellings) and O_3 (offices) linked to occupant activities,
- C CO and 7 VOC linked to materials, activities and occupants behaviour,
- D PM $_{2.5}$ and PM $_{10}$ linked to activities.

The specific indexes are built for each group of pollutants.

For example, the index for occupant activities (Group B) is calculated as in equation 1:

$$I_B = \frac{[NO_2]}{ref\ value\ NO_2} + \frac{[SO_2]}{ref\ value\ SO_2} \quad (1)$$

The lowest index corresponds to the best Indoor Air Quality regarding this type of pollutant.

These calculations have shown some typical evolution of pollutants in very tight low consumption buildings and can alert on some possible effects.

Method

We use, for the simulations, SIMBAD, a Building and HVAC Toolbox developed by CSTB [2]. This tool implements multizone and nodal building models in MATLAB/Simulink environment by combining heat and mass transfer phenomena. On the one hand, the thermal model is composed of detailed wall models describing the material layers and their properties, window models, heating and cooling devices, lighting systems, etc. It so deals with conduction, convection and radiation phenomena for calculating surface temperatures, mean radiant and indoor air temperatures.

On the other hand, the airflow model is made of airflow paths. In order to assess the performances of ventilation systems, this model includes the following systems: balanced ventilation with heat recovery and free-cooling, demanded-controlled ventilation based on humidity, CO_2 concentration or presence detection, and natural ventilation. It also deals with the characteristics of fans, ducts, heat exchanger, filters, and airflow paths.

The coupling of both models is done through the "ping-pong" method in which both models run in sequence and each model uses the previous time step results of the other [3]. The obtained simulation tool is then able to predict energy consumption and indoor air quality according to the pollution schedule and the ventilation system.

Material emissions

In offices and schools, all ventilation systems simulated show an increase of formaldehyde concentrations at night and during week-end, when ventilation is shut off after occupation.

Figure 1 shows for the classroom the fluctuation of formaldehyde concentration on one typical week.

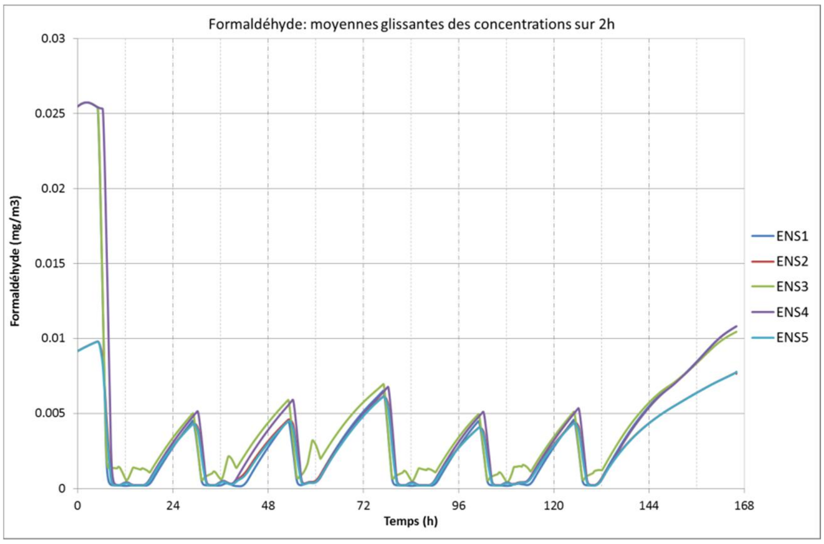

Figure 1: Evolution of formaldehyde in a classroom on one week for the 5 ventilation systems simulated, all shut off at night.

The systems ENS 2 and ENS 5 are supply and exhaust mechanical ventilation (blue and red curves). Figure 2 shows the formaldehyde fluctuation when 10% of nominal airflow is kept at night to deal with the material emissions.

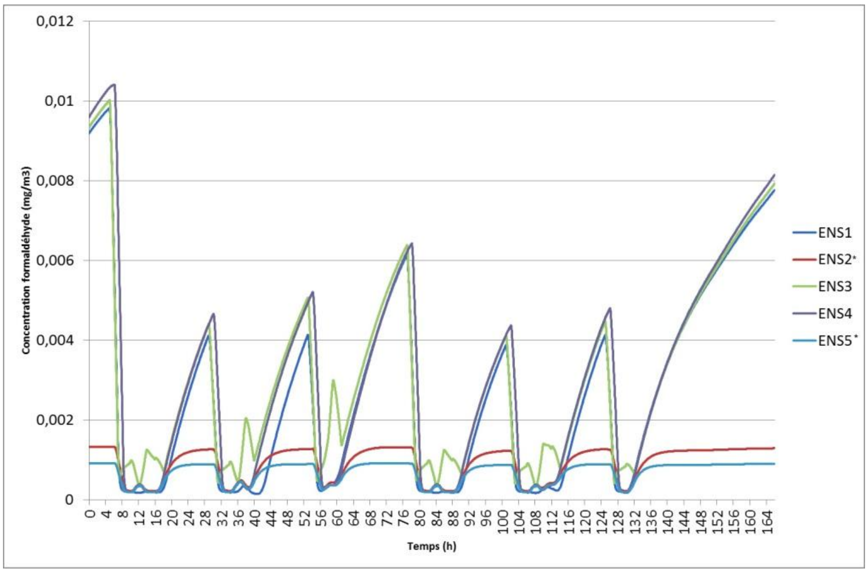

Figure 2: Evolution of formaldehyde in a classroom on one week for the 5 ventilation systems simulated, ENS 2* and ENS 5* kept at 10% nominal flow, others shut off at night.

When a minimum airflow is maintained at night, the fluctuation is strongly reduced. Yet from the energy point of view, starting ventilation 1 hour before occupants' arrival leads to the same result and will spend less energy.

In France, a new law [4] plans to reduce by 2015 the maximum value of formaldehyde and to measure on site the results. At the moment, passive tubes are considered as the most reliable measurement and tubes are left generally 3 to 5 days on site. Due to the possible losses during this duration on site, the values can be under evaluated in regard of the real values.

It is often asked for DCV (Demand Control Ventilation) if the decrease of airflow when occupants are absent is consistent with maintaining of a good air quality taking into account the emission of materials. In France to get a technical agreement, these systems must have a clock to restart before occupation, stop after occupation and maintain 10% of nominal airflow when occupants are absent of the room but still during the occupation hours of the building. We note that these requirements are enough to correctly deal with the material emissions that have been chosen for our calculations. Recently, the Observatory of IAQ in France has launched a campaign on schools. On site measurements are in average at higher concentrations that in our calculations which would indicate that our scenario of emission may be underestimated. Yet to reach this average amount of formaldehyde in school (the limit from the law is at a concentration of 30 $\mu g/m^3$ since 2013), we note that the systems answering the technical agreement are still satisfactory. We note also that satisfactory target values of formaldehyde for health can be achieved at much lower flow than those indicated for low polluting materials in the Perceived Air Quality method of EN 15251[5].

Airing

Using window airing in school is not sufficient to ensure a correct IAQ. Windows are manually opened from 7h till 8 h, from 12h till 13h and one quarter during the breaks of 10 and 4 pm. Confinement is too high (35 students in a 60m^2 room) and the different indexes are incorrect. CO_2 levels reach 6000 ppm 15 minutes after the window is closed; this has already been shown many times. But in this quite tight building (1,7 $m^3/h/m^2$@4 Pa), it is important to note that indoor humidity increases strongly. On the full year, more than 3000 hours are reported over 75% HR, which shows that in highly occupied rooms of tight building, there is a severe risk of condensation which is both unhealthy for occupants and doesn't preserve the building itself.

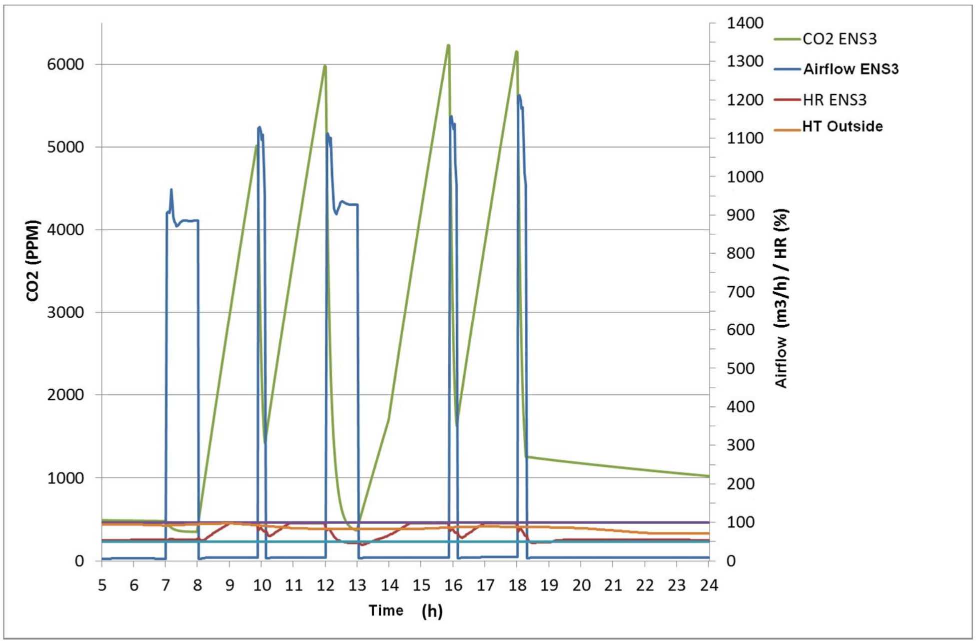

Figure 3: system ENS 3 (windows airing) - CO_2, indoor and outdoor humidity and ventilation airflow on a winter day (average temperature 11°C, 5 m/s wind) in a 35 children classroom.

Building airtightness

Enhancing building air tightness can improve the ventilation system performance, mainly for single exhaust, by improving air transfer and allowing air to enter where it's planned by design.

For both systems (single exhaust, supply & exhaust), in individual house for instance, improving air tightness slightly improves air quality by decreasing the pollutant concentration.

In this 2 floors' house, air entering the first floor goes down to ground floor to be extracted in the kitchen when air tightness is between 0,3 and 0,6 $m^3/h.m^2$ @4Pa while above, stack effect leads and air going up from the ground floor reduces the entrance of fresh air in the first floor bedrooms.

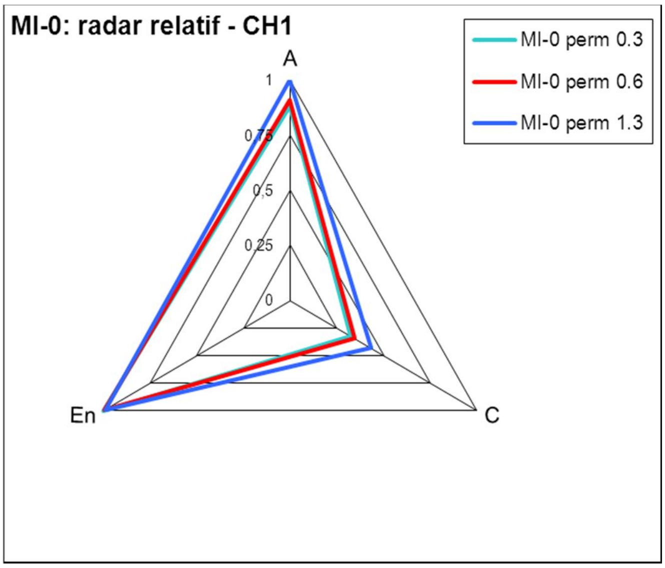

Figure 4: example of savings on IAQ indexes (A and C) and energy for single exhaust (MI-0) (1st floor of the individual house studied)

It is interesting to note that improving air tightness doesn't reduce IAQ and on the opposite, tends to reinforce the designed air transfer and the efficiency of ventilation in the house. For instance, for single exhaust system in the house, the IAQ linked to material emissions is increased by 20 to 25 % (index C reduced from the same percentage as shown in figure 4 MI-0) and index A (concerning CO2 concentration) by around 10%.

In collective dwelling, we had similar conclusion: when leakages are reduced from 1,7 down to 0,3 m3/h/m²@4 Pa, index A decreased by 11% and index C decreased by 17%, which represent better IAQ.

Kitchen ventilation

5 ventilation systems (single exhaust and supply & exhaust) have been studied in the house, 2 of them (LC3 and LC4) including a kitchen hood with a specific air inlet in the kitchen, opened only when hood is switched on. Figure 5 shows that the ventilation system (single or balanced) has no influence in the kitchen, but the presence of hood is efficient on combustion products.

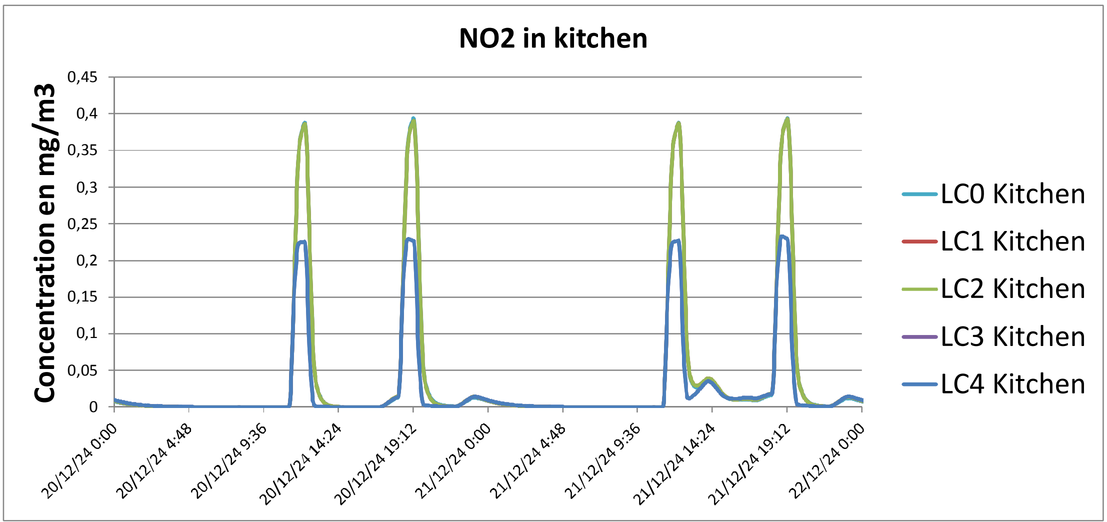

Figure 5: NO_2 Concentrations in the collective dwelling kitchen for the various ventilation systems studied.

In airtight houses and dwellings, the boost airflow in kitchen and the presence of hood with integrated air inlet are absolutely needed to deal with pollutants load. This conclusion is obvious on combustion products (but also depend on emissions scenario) but also valid for formaldehyde and material emissions in the kitchen.

Occupants behaviour

The use of incense or tobacco has much more impact (more than 10 times bigger) on IAQ indexes than material emissions. Figure 6 shows this effect on formaldehyde only. A better knowledge of real emissions indoor is needed because today, only a few studies exist and show a lot of discrepancies in their results.

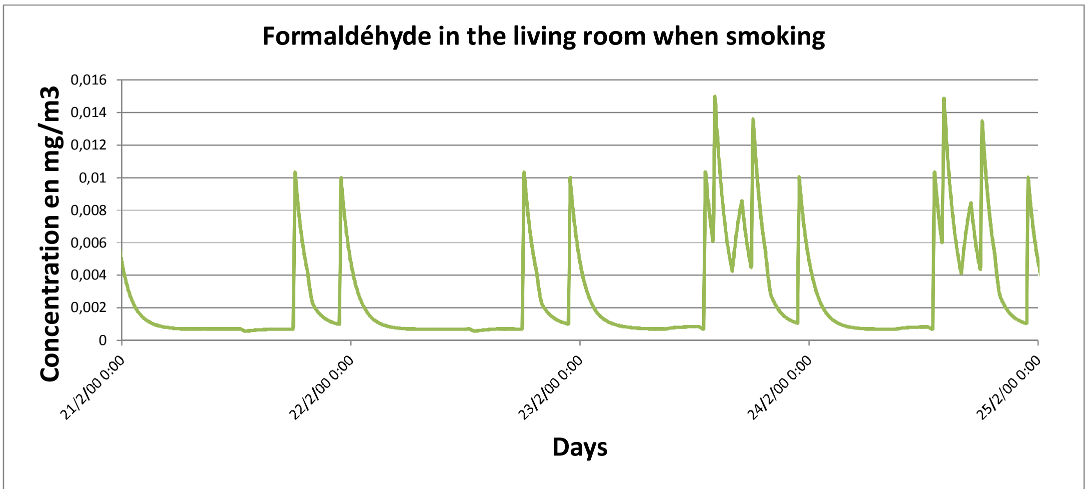

Figure 6: Formaldehyde concentration in the collective dwelling living room when 2 cigarettes are smocked per day and 6 during the week-end

Conclusion

As we can note, some interesting conclusions are possible from this study based only on simulations. The absence of measurements need however to be careful of the impact of hypotheses assumed on emissions scenario. The evolution of building toward more tightness can be an asset for the performance of ventilation but also need to design and install correctly the ventilation system to rely on it. Humidity may be the first adverse effect visible in case of low ventilation in a tight building before any increase of other pollutants may be noticed.

Acknowledgements

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INFLUENCE OF IMPROVEMENT OF AIR-TIGHTNESS ON ENERGY RETROFIT OF SOCIAL HOUSING, A CASE STUDY IN A MEDITERRANEAN CLIMATE

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Abstract

In Spain, the residential sector is the third principal source of energy consumption; many of these dwellings are obsolete and do not have optimal conditions of comfort. For this reason, their energy retrofitting means an enormous step towards the energy efficiency. Under the general intervention strategies, the study and analysis of the air-tightness of the building envelope (as measured by the degree of infiltration) is a fundamental factor, because of its impact on energy efficiency, thermal comfort of occupants and indoor air quality. For this purpose, it has become a regular research field in other European countries and the USA. However, there is a lack of studies with adequate roominess to allow a proper analysis and interpretation of what happens in our regional climate and construction typology.

The aims of this paper is presenting a case study for the energy retrofit of 68 social multi-dwelling units in Cordoba (Southern Spain) evaluating their global energy demand and analysing the importance of air-tightness.

An in-situ air-tightness measurement campaign was carried out in these multi-dwelling units, before and after retrofitting, using Blower Door equipment. The best method for obtaining these parameters is pressurization/depressurization tests. It has been effectuated some modifications on façades and windows in order to obtain a better air-tightness.

The energy consumption was evaluated for the different levels of air-tightness by some tests which have allowed models to be generated. These models have been analyzed using Design Builder Energy Simulation software program, based on the DOE 2.2 calculation engine, obtaining

predictive energy consumption, before and after retrofitting, including only air tightness changes and other retrofitting improvements (insulation, solar protection, U-transmittance in windows and facades) for the dwelling-units during a typical year.

Keywords

Energy efficiency, building retrofitting, social housing buildings, energy consumption, air-tightness

Introduction

In Spain, construction and operation of residential buildings accounts for the third highest energy consumption, after traffic and industry. The increased consumption that occurs in homes built in Spain is due to the climate. According to sources at the Institute for Diversification and Saving of Energy [1] air-conditioning accounts for approximately 49% of that consumption.

Social housing represents a significant proportion of the residential building stock of Southern Europe, which, when added to the socioeconomic characteristics of their occupants, necessitates special consideration of the methods to be used for the reduction of their energy consumption, especially that associated with their thermal comfort.

The most effective route for the reduction of energy consumption derived from the control of the energy demand associated with the transfers through the envelope using passive strategies. This intervention can be approached in two ways: the efficient construction of new buildings and the energy retrofit of existing residential buildings, a field of action that presents great potential for energy saving due to the importance of the housing stock built, and in use, in the last 50 years, it is also encouraged by the recent release of the Energy Performance of Buildings Directive, EPBD [2].

The air-tightness of building envelopes is one of the aspects which most affects the hygrothermal performance, indoor air quality and energy consumption of the building. In multi-story dwellings it contributes significantly to the overall demand for heating or cooling.

The magnitude of the effects of air-tightness depends on many factors such as weather conditions (temperature, wind speed and direction), the design and geometry of the building and especially the quality of construction (design and execution), which complicates the analysis procedure [3,4,5].

As a result of the impact of the air-tightness of the building envelope (as measured by the degree of infiltration) on energy efficiency, thermal comfort of occupants and the indoor air quality, its study and analysis has become a regular field of research in other European countries and the USA. However, in our regional area, studies lack adequate breadth to allow a proper analysis and interpretation of the impact of air-tightness, in the context of the climate and construction types of the region.

The work of M. Sherman and the Lawrence Berkeley National Laboratory (LBNL) must be highlighted as a main reference in this field. It was associated with construction programmes in the USA which focused, primarily, on the housing field, and carried out extensive characterization campaigns and the development of predictive and calculation models for the phenomena of natural ventilation and uncontrolled infiltration processes. Our goal is to transfer and adapt these techniques and methodologies to our constructional reality and building processes in Spain.

To establish correlations between air flow and the energy performance of residential buildings, reference is again made to Sherman's work, with the Energy Performance of Buildings group of the LBNL[6] and those of Liddament [7] from the Air Infiltration and Ventilation Centre. This work investigates how current levels of ventilation affect energy demand and the estimated energy savings involved in adapting that ventilation to an appropriate indoor air quality, using the ASHRAE Standards 62, 119 and 136 to estimate the ventilation requirements and energy consumption.

The objective of this work was to analyse the importance of the infiltration in the energy demand reduction included in the residential retrofit sector, analysing a case study of multi dwelling units in the Mediterranean area. This was carried out on a building for which architect Rafael Suarez, co-author of this paper, designed a recently completed retrofit, boosting saving and energy efficiency.

Case study

The object of the study and analysis is a building of 68 social housing units, all of them rented, located in the city of Córdoba (Figure 1) in the south of Spain.

This building is a symmetrical U-shaped block five stories high, with housing units and an underground car park. Its construction dates from 1994 and it was retrofitted in 2011. The retrofit project was promoted by the Córdoba Town Council and financed by the State Fund for Employment and Local Sustainability [8].

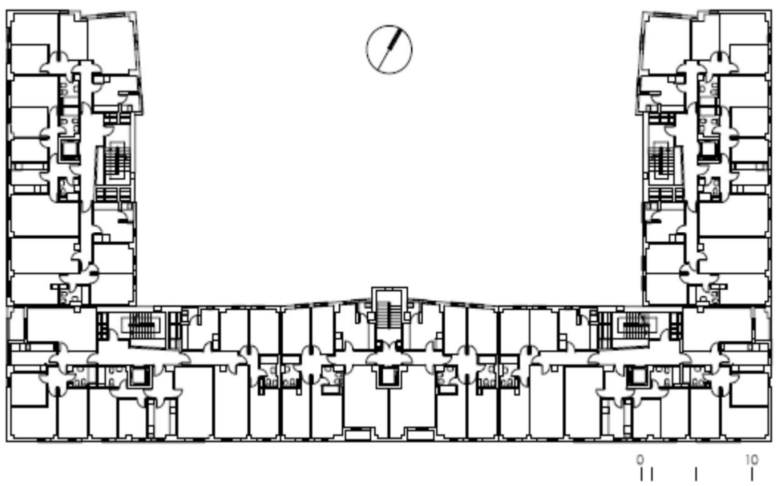

Figure 1: Floor plan

The thermal envelope of the building (Table 1) presents low insulation levels, particularly on façades and floors in contact with the exterior, without any type of insulation, and in openings with single glazing.

Building element		U(W/m^{2}K) Original	Retrofitting	Retrofit improvement
Facades	24 cm porous ceramics bricks with exterior rendering and interior plastering	0.94	0.33	Ventilated facade with 6cm Mineral Wood
Openings	Anodised aluminium frames with 5mm single glazing	5.70	3.8	Double glazed 4+6+4
Roof in contact with outdoor	Ceramic tiles, key mortar, brick board bedded on sand, slopes formed with 10 cm cellular concrete and 5 cm extruded polystyrene.	0.47	0.47	
Floor in contact with car parking	Unidirectional framework 25+5 semi-resistant joists finished with terrazo flooring and plaster	2.25	0.54	5cm extruded polystyrene insulation, air chamber and metal false ceiling.

Table 1: Characterization of the thermal envelope

Climate

The climatic profile used comes from the EnergyPlus weather files (EPW) database, part of the energy simulation software created by the U.S. Department of Energy. The file selected for Córdoba, CÓRDOBA SWEC (Spanish Weather for Energy Calculations), was created from the data originating from the Spanish National Institute of Meteorology (Table 2)

Location: Córdoba (Spain) (N 37º 53 ') (W 4º 54 ') (GMT +1.0 Hour)

Elevation: 90 m above sea level: Standard atmospheric pressure: 100953 Pa

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average monthly temperature (^{0}C)	9.2	10.9	13.5	15.4	19	23.5	27.3	27.2	24	18.5	13.2	10.2
Average monthly wind velocity (km/h)	8	8	9.6	10.6	8.9	9.6	9.5	9.6	8.7	8.5	8	8.3

Table 2: Climate values in Cordoba

The climate is sub-continental Mediterranean with warm summers, very high temperatures (maximum average temperatures of 36 °C) and an average of over 300 hours of sun per month from June to September. The winters are mild and last from November to March, with short springs and autumns.

Methods

Passive strategies through the envelope are the most effective strategies to reduce the energy demand in the residential buildings. The original state of the building performance must be known to calculate the potential reduction of the energy demand.

In the analysis of the original state of the building the solar radiation was studied with Ecotect Analysis version 5.50, the thermal bridges and common air leakage paths with an infrared camera, the air tightness with the blower door , the air and superficial temperature with a data logger and energy analysis with Design Builder. Based on the study of data obtained, it is possible to elaborate a profile of the energy demand and set strategies to improve the energy consumption and thermal conditions. The most efficient strategies was chosen and their demand energy reduction was calculated.

Air tightness measurements using Blower Door

To know the original and retrofitting air tightness of the residential building, pressurization and depressurization tests were carried out using Blower Door equipment, which provides airtightness to the dwelling unit, the Air Leakage rate at 50 Pascals which take place as a result of the infiltrations through the building envelope.

Figure 2: Blower Door Test

In order to carry out these tests a blower door fan was placed at the external door of the housing unit, in order to extract (depressurization) or introduce (pressurization) air into the unit until a negative or positive pressure of 50 Pa was reached and the airflow was measured.

As this was a multifamily residential building, it was not measured as a single space, since staircases, lifts and other elements of the communal areas are not airtight and create air currents that are too large to ensure reliable measurements. Measurements were carried out on individual dwelling units, measuring at least one of them on the top floor, one on an intermediate floor and another on the ground floor.

These tests were executed in the original conditions to locate the main routes of air leakage with infrared thermography. After the retrofitting the tests were carried out in order to prove their improvement.

Energy models

To establish the energy performance of the original and retrofitted building the computer program Design Builder version 2.2.5.004 was used, whose simulation engine, Energy Plus, methodology developed by the United States Department of Energy and recognized by the International Energy Agency, enabled the authors to obtain precise data on annual or monthly demand for its original condition and for the retrofit project.

Each dwelling unit in the model was considered as a single space to be climatized. The official protocol for conditions of use and operation in Spain for the use of alternative energy simulation programs was followed [9].

<table>
<tr><th rowspan="2">Activity</th><th rowspan="2">Period</th><th rowspan="2">Value</th><th colspan="6">Schedule</th></tr>
<tr><th colspan="2">Weekdays</th><th colspan="2">Weekends</th><th colspan="2">Holidays</th></tr>
<tr><td rowspan="2">Occupation</td><td>Winter</td><td rowspan="2">0.056 pers/m^2</td><td rowspan="2">00:00 a 07:00
07:00 a 16:00
16:00 a 23:00</td><td rowspan="2">100%
25%
50%</td><td colspan="2">00:00 a 24:00</td><td colspan="2">50%</td></tr>
<tr><td>Summer</td><td>00:00 a 24:00</td><td>100%</td><td>00:00 a 24:00</td><td>0 %</td></tr>
<tr><td rowspan="2">Equipment
&
Lighting</td><td>Winter</td><td rowspan="2">8.88 W/m^2 (4.44x2)</td><td colspan="3" rowspan="2">00:00 a 08:00
08:00 a 19:00
19:00 a 20:00
20:00 a 23:00
23:00 a 24:00</td><td colspan="3" rowspan="2">10%
30%
50%
100%
50%</td></tr>
<tr><td>Summer</td></tr>
<tr><td rowspan="2">Ventilation</td><td>Winter</td><td rowspan="2">3 ac/h</td><td colspan="3">00:00 a 24:00</td><td colspan="3">0%</td></tr>
<tr><td>Summer</td><td colspan="3">00:00 a 08:00
08:00 a 24:00</td><td colspan="3">100%
0%</td></tr>
</table>

Table 3: Protocol for conditions of use and operation in Spain.

Results and Discussion

Retrofitting

Simulations were produced for the original conditions as well as for each of the intervention solutions proposed in order to obtain increased improvements in the energy demand of the building for its retrofit [10].

The program calibration was carried out in the EFFICACIA Project [11].

After analyzing the original state of the case study, the principal paths and factors where the building was losing energy were found and the main strategies in the retrofit proposal were:

- Encouragement of airflow, mainly through natural ventilation at night during the summer depending on exterior conditions.

- Energy conservation, improving insulation, and the accumulation of energy through thermal inertia. To guarantee complete efficiency in the summer time the thermal mass must be in contact with the night airflow to ensure passive cooling, while in winter the wall must receive solar radiation.

- Solar Radiation and Solar Control, capturing solar radiation in winter and ensuring suitable protection from radiation in summer (solar protection of the openings with the most solar exposure, depending on orientation, using sliding, folding, or fixed slat systems. East and west windows are protected by external movable shading devices which are activated during the cooling period).

- Thermal envelope insulation (Table 1) using a ventilated façade system, with a ceramic or metal finish. This system reduces thermal bridges in beams and pillars and along the joints between bricks and load-bearing structure.

- Thermal transmittance of windows, incorporating double glazing and improving insulation on external framework.

Figure 3: Case study, before and after retrofit.

Airtightness retrofitting

The values of the Blower Door tests cannot be used directly for determining the annual infiltration value, because it responds to conditions of depression and pressure differential inside / outside very high, which fundamental mission is the determination of Air-Tightness at 50 Pa.

Attributed to (and often denied by) Kronvall [12] and Persily [13], there was a rule of thumb that seemed to relate Blower-Door data to seasonal air change data in spite of its simplicity

$$ACH = ACH_{50}/20 \quad (1)$$

That is, the seasonal amount of natural air exchange could be related to air flow necessary to pressurize the building to 50 Pascals, where "ACH" is the natural air changes per hour and "ACH50 " are the air changes induced by a 50 Pa pressure using a fan. We assume the uncertainty in the calculations using the following correction factors [14]:

-Dwelling units are 1 story, their height correction factor is 1.

-Dwelling units are situated in the city, surrounding of other buildings, their shielding correction factor is 1.

-N of leakages is about 0,7, their lakiness correction factor is 1

V_{50} and ACH_{50} values obtained from the Blower Door tests and MDU characteristics, before and after retrofitting are represented in table 4.

Before retrofitting, ACH varies between 0.500 and 0.638, its averages is 0,550 and its standard deviation is 0.054. Although the construction system is the same, there are a significant degree of dispersion in air tightness tests, it can be due to constructive problems.

In most European countries the minimum ventilation standard ranges between 0.35 and 0.5 air changes per hour. However, in Spain, from the approval of the Technical Building Code in 2006, the requirements are much higher and the amount increases to 0.9-1 air changes per hour in new residential buildings.

After retrofitting, ACH varies between 0.426 and 0.536, its averages is 0.467 and its standard deviation is 0.041.

It is observed that the dispersion is lower than before retrofitting.

In both cases there was not relation of facade area and window area with air tightness.

These infiltration values aren´t for envelope, they are for whole dwelling units.

	Volume (m^3)	Facades	Facade Area (m^2)	Window Area (m^2)	Indoor Temperature (ºC)	Outdoor Temperature (ºC)	V_{50}	ACH $_{50}$	ACH
P1-V1	177,72	3(N,W,E)	64,16	12,61	32 (30)	34 (35)	1825 (1529)	10,27 (8,60)	0,513 (0,430)
P3-V2	176,53	1(0)	34,69	7,92	30 (29)	30 (36)	1966 (1695)	11,14 (9,60)	0,557 (0,480)
P3-V3	178,98	2(E,O)	39,94	10,33	32 (31)	32 (37)	2019 (1713)	11,28 (9,57)	0,564 (0,479)
P4-V12	177,72	3(N,W,E)	64,16	12,61	36 (31)	37 (34)	1778 (1513)	10,01 (8,51)	0,500 (0,426)
P4-V13	176,53	1(E)	34,69	7,92	(36)	(39)	(1603)	(9,08)	(0,454)
P5-V1	133,78	3(N,W,E)	58,31	9,28	32 (33)	33 (35)	1707 (1433)	12,76 (10,71)	0,638 (0,536)
Average							1859 (1631)	11,09 (9,35)	0,550 (0,467)
Desvest							130 (109,7)	1,08 (0,81)	0,054 (0,041)

Table 4: Multi dwelling unit characteristics and Blower Door test before and (after retrofitting)

This infiltration reduction is due to the thermal insulation that seal the joint between the facade and the window frame (figure 4) and the substitution of the simple glass from the window for a double glass 4+6+4 and the improvement of the lock of the frame

Figure 4: Envelope retrofit

Energy demand

The study and analysis of the demand of the existing building revealed major energy losses in winter, due mainly to infiltrations, glazing and lack of insulation on façades, while in summer the main gains resulted from transmissions through openings and infiltrations.

Windows play a very important role in thermal operation as they are elements for direct solar capture, natural ventilation and let in daylight.

Of the calculated overall annual demands, most correspond to heating (58% vs. 42% of cooling) resulting from the building orientation, the generation of its own shade, its shape (0.30) and the deficient insulation of the thermal envelope which translate into major energy losses. This demand differs considerably in relation to orientation, so that correction measures take this factor into account.

After retrofitting, the total energy demand reduction varies between 34 % and 46%, while the heating demand reduction is bigger varies between 7% and 41% , the cooling energy demand is lower varies between 1,6% and 16%.

There is a notable improvement of the energy efficiency after the energy retrofit. That is entailed in a consumption energy reduction of 42% respect to the initial stay, while a reduction of 17% respect to original conditions is due to actions that influence the air-tightness level of multi-dwellings. This fact emphasizes the importance of this parameter on consumption reduction.

Uncertainly and errors in calculations are due to the simplify transfer from ACH 50 to ACH, as discussed above, but this affects both states, before and after retrofitting. The airtightness change is due only to the improvement of the envelope.

	Multi Dwelling Units	P1-V1	P3-V1	P3-V2	P3-V3	P4-V12	P4-V13	P5-V1	Average
Total (kWh/m^2)	Original conditions	67	73	68	63	82	96	91	77
	Infiltration retrofit	63	62	55	52	65	68	79	63
	Additional retrofit measures	41	40	38	35	48	52	60	45
Cooling (kWh/m^2)	Original conditions	21	30	41	29	36	41	31	33
	Infiltration retrofit	20	27	37	26	31	34	28	29
	Additional retrofit measures	14	21	25	19	25	29	24	23
Heating (kWh/m^2)	Original conditions	46	43	26	34	47	58	60	45

	Infiltration retrofit	43	35	18	26	34	34	51	34
	Additional retrofit measures	27	19	12	15	23	23	35	22
Increasing about total original conditions (%)	Infiltration retrofit	-5	-15	-19	-18	-20	-29	-12	-17
	Additional retrofit measures	-39	-45	-44	-45	-42	-46	-34	-42
Increasing about cooling original conditions (%)	Infiltration retrofit	-2	-9	-11	-10	-12	-16	-9	-10
	Additional retrofit measures	-34	-29	-38	-32	-31	-30	-20	-31
Increasing about heating original conditions (%)	Infiltration retrofit	-7	-19	-32	-24	-28	-41	-14	-24
	Additional retrofit measures	-42	-56	-53	-55	-51	-60	-41	-51

Table 5: Energy demand based on calculations

Energy demand results was obtained with Design Builder because their retrofit works have just finished, but a monitoring campaign is planned for the building.

Conclusion

Following the intervention proposal considerable improvement was observed in the thermal behaviour of the building for all energy models simulated and analyzed, more so in winter conditions, with a 51% reduction in demand, contrasting with a reduction of the demand for cooling of 31%, with an estimated reduction of total demand of 42%. Moreover, this reduction in demand translates into an improvement of thermal stability and reduction of temperature oscillations, with considerable repercussions on the increase of internal thermal comfort [10].

A great part of this energy demand reduction is due to an improvement in the air tightness after retrofitting, a 40% on the total reduction, it is most important in heating 46% than in cooling 32%. For this reason, testing and review processes are essential to identify the common leakage paths through the envelope. These studies have to be presented in such a way that they can be easily put into practice as protocols to control the construction quality and reduce the energy demand in residential buildings.

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BLOWER DOOR TESTS OF A GROUP OF IDENTICAL FLATS IN A NEW STUDENT ACCOMMODATION IN THE ARCTIC

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Abstract

A new student accommodation for engineering students “Apisseq” was built in the town of Sisimiut, Greenland in 2010. Its purpose is not only to provide accommodation for students. Thanks to its complex monitoring system it enables researchers to evaluate the building’s energy performance and indoor air quality (IAQ) as well as performance of some single components. In summer 2012 a blower door test was performed on all 37 living units out of which 33 are identical single room flats and 4 are larger double room flats. The purpose was to evaluate the air tightness of the envelope and to find out how much the flats differ from each other in terms of air tightness. The overall average specific leakage measured was $w_{50} = 2.05$ l/(s·m^2) of heated floor area corresponding to an air change n_{50} of 2.96 h^{-1}. Furthermore, the results showed that the difference between the most and the least tight flat is as high as 400%. This result is without consideration of one particular flat which had the extreme result of being 940% as leaky as the unit with the highest air tightness. The reasons for such poor air tightness are lack of the installation gap between the vapour barrier and the inner wall, and insufficient connections of the vapour barrier to the interior walls as explained in the paper. The large variation in results can be attributed to insufficient consideration of the importance of airtightness during construction of some parts of the building – despite of an intent to make a rather air tight building.

Keywords

Blower Door Test, Air Tightness, Cold Climates, Residential Buildings

Introduction

In summer 2010 the new student accommodation for engineering students 'Apisseq' was finished in the town of Sisimiut, Greenland. The intention was to build an energy efficient building in which modern technologies, not yet commonly used in the Arctic, would be installed and which would provide its occupants with a healthy and comfortable indoor environment. Since balanced mechanical ventilation with heat recovery was installed, natural ventilation due to infiltration was no longer needed. In order to minimize infiltration heat losses, special attention was paid to the air tightness of the envelope.

There are no standard requirements on air tightness in the current Greenlandic building code, however the intention was to meet the current Danish requirement [1] which is that air changes through leakage in the building envelope must not exceed 1.5 $l/(s \cdot m^2)$ of the heated floor area when tested at the pressure of 50 Pa.

The aim of this study was not only to test the actual air tightness of the student accommodation, but also to study the distribution of the air tightness over a large number of identical flats by using statistical analysis.

Building key data

The floor plan of the building has the shape of an open circle, and has a partially heated ground floor and two upper floors. A main technical room and janitor´s office are in the heated part of the ground floor and small storage compartments for each flat are in the unheated part together with small technical rooms with ventilation units. The 1st and 2nd floor consist of 33 identical single room flats, and four double room flats at the gables of the building. In addition, there is a common room with a kitchen and a laundry room on the first floor (Figure 1 shows the floor plans). In the second floor, the common room and laundry is replaced with single room flats. There is also a glazed atrium with a staircase in the centre of the building. Each single room flat has a total floor area of 23 m^2 and consists of an entrance (3.3 m^2), a bathroom (2.8 m^2) and a living room with a kitchenette (16.8 m^2). The double room flats have a floor area of 50.2 m^2. All living units have a small balcony.

The aim to build an energy efficient building resulted in a well-insulated, air and vapour tight envelope supplemented by modern technology for space heating and mechanical ventilation of occupied spaces. The source for heating and domestic hot water (DHW) is district heating supported by evacuated tubular solar collectors connected to two accumulation tanks (2000 l each). The building is heated with radiators, floor heating is used in bathrooms and entrances. Ventilation is provided by two identical ventilation units.

Fresh air is delivered into the living rooms, and the polluted air is extracted through the kitchen hoods and exhausts in the bathrooms.

Figure 1: Floor plans of Apisseq

Methods

Methodology of measurement

Standard procedure for measurements of air permeability of buildings and their parts in field specified in the standard [2] was followed. This standard offers two methods of air tightness measurement - method A where the air tightness of the object in use is measured and method B, when the air tightness of the building envelope is measured. Each of these methods requires a specific procedure of the object preparation before the measurement starts. Since the air exchange in all flats is ensured by means of mechanical ventilation there are not any ventilation elements or connections to the ambient, there is no difference between methods A and B in this case. All windows and doors to the ambient were closed, all air terminal devices were taped and internal doors were kept open to ensure equal pressure within the measured enclosure. The ventilation system was switched off.

Measuring equipment

The Retrotec Blower Door Test assembly was used to perform the tests. It consists of calibrated fan Retrotec 2200 Series, pressure gauge DM-2 and a cloth door panel. As the measuring and evaluation software was used the Retrotec FanTestic.

Measurement procedure

The fan was placed into the entrance door of an flat by using the cloth door panel. The measurement was automatically controlled by the software. The zero-flow pressure difference based on 10 baseline pressures taken for 10 sec each was taken at the beginning and at the end of every test. Subsequently the pressurization sequence was performed in 12 pressure steps by 5 Pa taken for 20 sec each from the initial level of 10 Pa to the final level of 65 Pa. After the pressurization sequence, the depressurization sequence was done. The results are the averages of these two measurements. The consistency of the measurements is given by correlation factor. The data are considered consistent when the correlation factor is 95% or higher.

In accordance with the standard, outdoor and indoor temperatures and the wind speed were monitored at the beginning and end of each test.

There have been changes of indoor and outdoor temperatures throughout the measurements. Calculation of airflow into the room through the fan is calculated can be affected by temperature fluctuations as they have effect on air density. However since the maximum difference between the temperatures had not been higher than 5K, the impact of these fluctuations is negligible.

In the case of flat 2.05 the blower door test was carried out on the balcony door after the first set of measurements. The second measurement was done through the balcony door. The intention was to compare the air tightness of the front door with the balcony door.

Some results were considered too far from normal. To enhance the preciseness of the measurements and to eliminate errors, the blower door test was repeated in flats 2.05, 2.12, and 2.20.

The characteristics of measured flats

The drawings of typical single and double room flats are shown in figure Figure 2 and the values used for the calculations are summarized in Table 1.

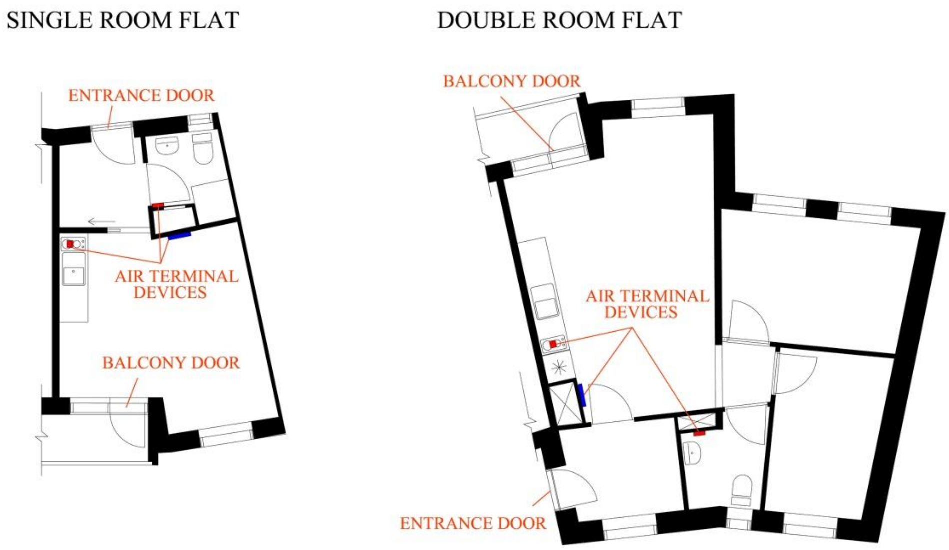

Figure 2: Drawings of the flats

	Single room flat	Double room flat
Volume [m^3]	57,5	131,8
Total Envelope area [m^2]	96	183,4
Floor area [m^2]	23	52,7

Table 1: Specification of flats

Evaluation of the measured data

Descriptive statistical analysis was performed on the results of specific air leakage. The possible relations in specific leakage between neighboring flats in certain part of the building were tested by means of the t-test and Pearson's correlation test. P-values of 0,05 were used to determine statistical significance. Statistical software R and MS Excel were used for the statistical analyses.

Results

Overall results

The correlation factor is, except for three measurements, always higher than 95%. Only depressurization of flats 1.07 and 1.12 and pressurization of flat 1.10 is between 92% and 95%.

The differences between pressurization and depressurization tests (see Figure 3) are on average 9.1%. When comparing the positive and negative differences, a two sample t-test yields a P-value of 0.95 which indicates that there is no prevalent trend of one of the tests (pressurization or depressurization) giving constantly higher or lower result.

The mean value of specific leakages obtained from Apisseq is 2.05 l/(s·m^2) with standard deviation of 0.96 l/(s·m^2) corresponding to an air change n_{50} of 2.96 h^{-1} with standard deviation of 1.38 h^{-1}. The distribution can be seen from the box plot in Figure 3. It can be observed that the maximum value, which is the test result of flat 2.20, lies significantly above the 3rd quartile. To eliminate the measurement error we repeated the test next day. The result was only 3% different from the first test. This may indicate an abnormality due to construction problems in this flat. More discussion follows in the Discussion section.

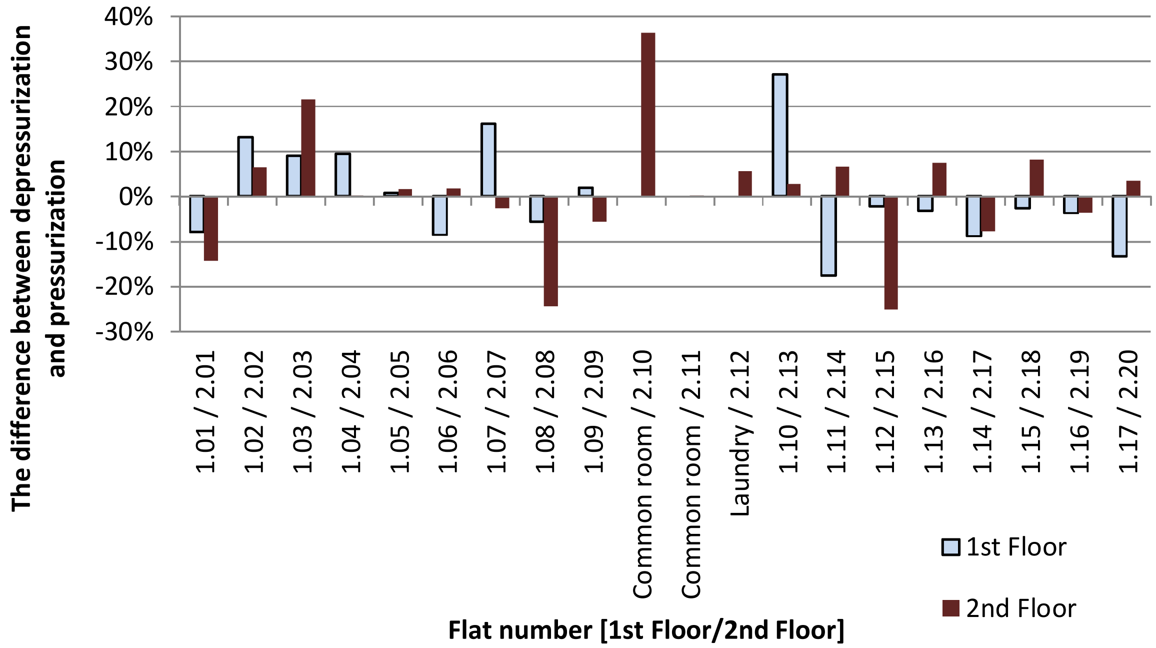

Figure 3: Negative values mean that the result from pressurization was larger than from depressurization

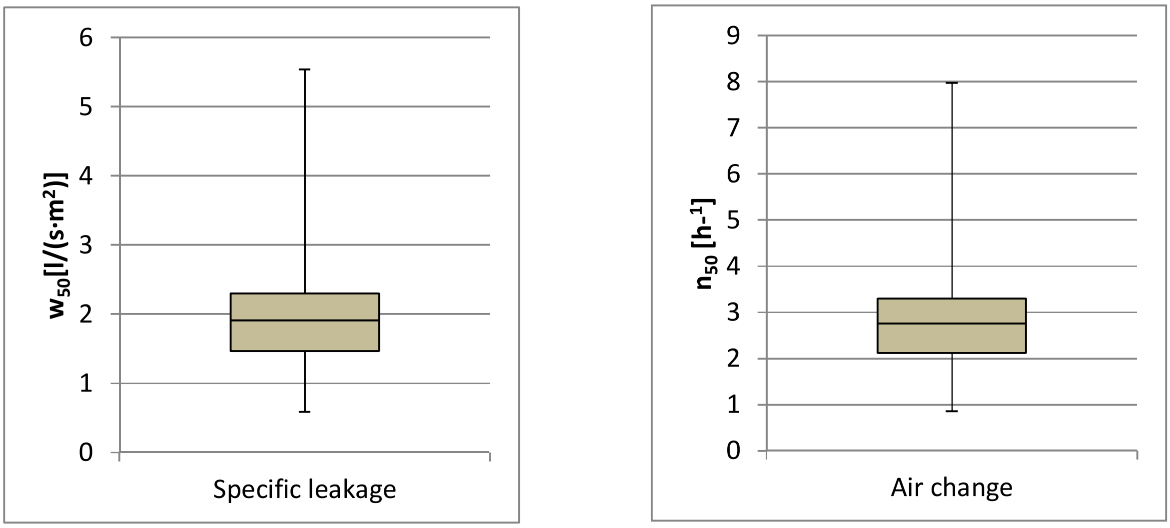

Figure 4: Distribution of overall results of blower door test

The combined specific leakage in all the tested units is presented in Figure 5. When testing the correlation between the first and second floor by means of Pearson's correlation test, we found a positive correlation of 0.53 at 5% level of significance between the single room flats which are above each other.

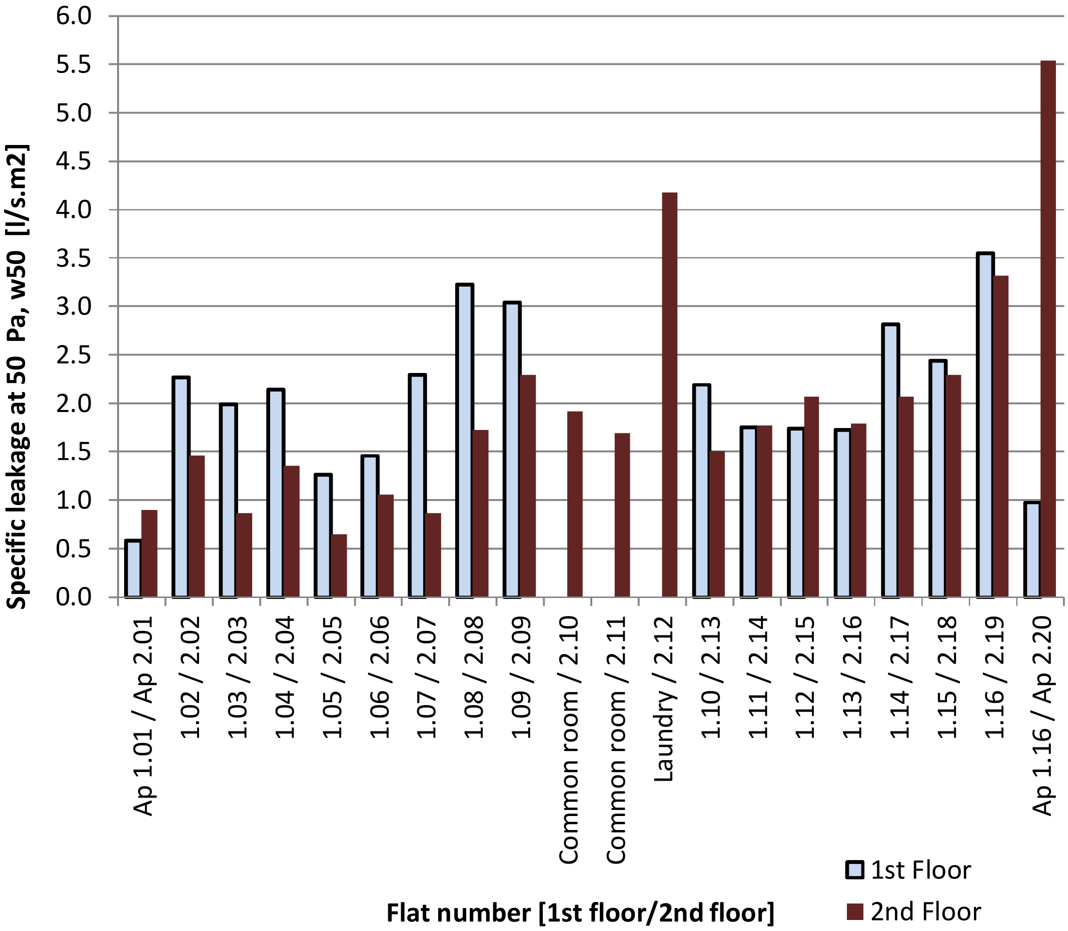

Figure 5: Combined results of testing all the units within the student accommodation

Comparison between flats inside and outside the atrium

The two sample t-test yields a P-value of 0.17 based on what the null hypothesis that there is no difference in airtightness between flats inside and outside the atrium cannot be rejected.

Flats outside of the glazed atrium		Flats behind the glazed atrium	
Mean	1.98	Mean	2.51
Median	1.89	Median	2.29
Standard Deviation	0.68	Standard Deviation	0.81
Variance	0.47	Variance	0.65

Table 2: The statistics of w_{50} [$l/(s \cdot m^2)$] measured in flats inside and outside the glazed atrium

Single room vs. double room flats

The mean specific leakage of the four double room flats is 2.00 l/(s·m^2), which is not different from the mean specific leakage of the single room flats: 2.06 l/(s·m^2) (Table 3). However, excluding the abnormally high specific leakage of the double room flat no. 2.20, gives a mean leakage of 0.82 l/(s·m^2), which is significantly smaller than the mean specific leakage of the singe room flats (P-value of one tailed t-test < 0.01).

	Single room flats	**Double room flats**	**Double room flats without no. 2.20**
Mean	2.06	2.00	0.82
Median	1.99	0.94	0.90
Standard Deviation	0.72	2.37	0.21
Variance	0.51	5.59	0.04

Table 3: The statistics of w_{50} [l/(s·m^2)] measured in single and double room flats

1st vs 2nd floor

There is no significant difference in air tightness between the units in the first and second floor (two sample t-test P-value = 0.82) even when the worst flat (2.20) is excluded (P-value = 0.33).

	1st floor	**2nd floor**	**2nd floor without 2.20**
Mean	2.09	2.02	1.84
Median	2.14	1.78	1.77
Standard Deviation	0.79	1.10	0.75
Variance	0.63	1.22	0.56

Table 4: The statistics of w_{50} [l/(s·m^2)] measured in all units in 1st and 2nd floor

Flats that were tested twice

	Flat 2.05	**Flat 2.12**	**Flat 2.20**
1st measurement	0.65	4.18	5.36
2nd measurement	1.99	3.63	5.54
Difference	206%	13%	3%

Table 5: The results of w_{50} [l/(s·m^2)] in units which were measured twice

Test on balcony door

	Flat 2.05		
Blower door sitting in:	**Front door**	**Balcony door**	**Difference**
Specific Leakage	1.99	0.85	57%
Uncertainty	0.03	0.09	

Table 6: Comparison of main entrance door and balcony door

Discussion

Overall results

The tests have shown, that the average specific leakage of the building is 2.05 $l/(s \cdot m^2)$ which would not fulfill the Danish requirement of 1.50 $l/(s \cdot m^2)$. Nevertheless 27% of all flats in the building had specific leakage lower than the requirement. This enhances the importance of large portion of flats in one building (even when they are identical) being tested when relevant results are sought.

The positive correlation between the single room flats above each other could be explained by the horizontal direction of the construction. The degree of dependence is however very low.

The reasons for poor air tightness are several. The lack of the installation gap between vapour barrier and inner surface plays a large role since all the installations have to penetrate the vapour barrier when entering the flats. Another reason is lack of overlapping flaps in corners where the vapour barrier connects to the concrete walls and floors/ceilings (see Figure 6).

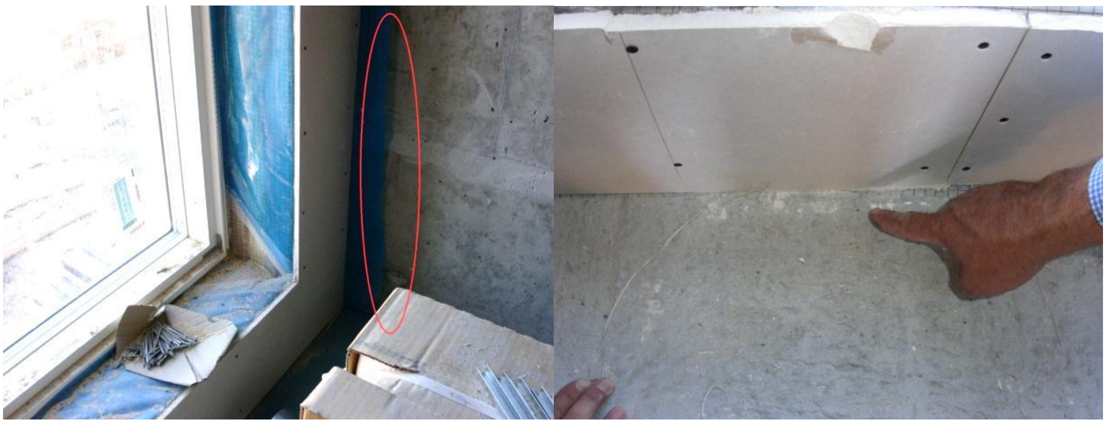

Figure 6: Left: Correct connection with overlap; Right: Missing overlap

Additionally an extra focus on air tightness had not been a part of the building tradition in Greenland until very recent years. Which can explain the insufficient consideration of its importance during construction and design phase.

We assume that if the blower door test was done during the construction phase, many errors would be explored and fixed which would have positive effect on the final air tightness.

Comparison between flats inside and outside the atrium

We have not found any evidence that the air tightness of flats inside the glazed atrium is significantly different from the rest of the building.

Single vs. double room flats

The reason why the double room flats have better air tightness than the single room flats (with one notable exception) is the vapour barrier area/total area ratio which in single room flats is 2x higher than in double room flats which gives higher risk of leakages.

There is probably some larger penetration of the vapour barrier in the flat number 2.20 which causes that high specific leakage. It is suggested to repeat the test together with smoke generating device in order to detect the leakage.

Flats that were tested twice

The 206% difference between first and second test of the flat number 2.05 can only be explained by a procedural mistake whereas the other two differences (13% and 3% in flats 2.12 and 2.20 respectively) are probably caused by combination of systematic and random errors.

Test on balcony door

The results show that the specific leakage when tested with the blower door equipment in the balcony door is smaller than the leakage obtained from the test in the front door by 57%. It may imply that there is significantly higher air leakage through the balcony door than through the front door. To justify this hypothesis, repeated measurements and also measurements in other flats need to be done.

Conclusion

The air tightness of all 37 flats in the building was measured with the result which does not meet the current Danish requirements. There is however no such requirement in Greenland.

Bringing awareness of the necessity of air tightness to all parties involved in construction process is of very large importance.

Performing the blower door test during the construction phase is a way to avoid errors as well as shoddy work.

When the actual air tightness of buildings is to be determined, large portion of the whole building rather than just small sample needs to be tested.

In order to test the validity of measurement procedure multiple measurements of specific leakage of randomly selected flat should be carried out.

During the experiment period (03 - 13 Aug.2012), the weather varied from day to day (sunny, cloudy, rainy). For further studies, these factors should be considered.

More tests should be carried out to compare the specific leakage when tested both on the balcony door and on the front door.

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THE RELATIONSHIP BETWEEN PERMEABILITY AND INFILTRATION IN CONJOINED DWELLINGS

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Abstract

The importance of adventitious air leakage under normal operational conditions and its reduction in order to save energy is highlighted by the relevant building standards of many countries. This operational leakage is often inferred via the measurement of air permeability, a physical property of a building that indicates the resistance of its fabric to airflow. A building's permeability is the measure of airflow rate through its envelope at a constant pressure differential of 50 Pascals. However, operational pressure differences are dynamic and typically an order of magnitude lower than 50 Pascals. Thus there is much uncertainty when using a value of permeability in an attempt to predict operational air leakage.

Powerful simulation tools can model the ventilation rates found in a building in great detail, yet these complex modelling tools contrast with the much simpler tools that are used frequently to estimate annual energy consumption for space heating in dwellings. For example, some building codes assume a simple fixed relationship between air permeability measured at 50 Pascals and mean background infiltration during the heating season; the so-called *rule-of-20*.

This paper evaluates afresh this rule-of-thumb. Firstly, a theoretical model of adventitious air leakage for a dwelling is presented. Secondly, the predictions of the model are compared against those of CONTAM, and AIDA, validated airflow analysis tools, for an identical building and environmental conditions. Thirdly, the model is used to predict the mean infiltration rate and the corresponding energy required to replace heat lost via air operation infiltration during the heating season for an apartment and a terraced house located in 14 different UK cities. Finally, the predictions of the model are used to develop a relationship between the adventitious air leakage under pressure, operational infiltration, and energy consumption during the heating season. The relationship is used to discuss the validity, accuracy, and applicability of the *rule-of-20* and its use by simple modelling approaches such as the UK's Standard Assessment Procedure.

Keywords

Infiltration, permeability, energy, dwelling, modelling, CONTAM, AIDA

Introduction

The ingress of cold air through adventitious openings can be a significant component of a dwelling's heating load. In the UK, for example, this has been recognised by a relevant standard for new dwellings [1]. However, measuring infiltration is technically difficult, invasive, and expensive. Accordingly, infiltration is often inferred from a measurement of permeability, the airflow through the fabric of a building, made at a steady high pressure difference, normally 50Pa, when the effects of wind and buoyancy forces are effectively eliminated [2]. Permeability is often scaled by the volume of the building or an area, such as envelope area in Finland or the UK, where it is known as the air leakage index (ALI), or in Denmark where permeability is scaled by heated floor area [2]. Because operational pressure differences are dynamic and normally an order of magnitude lower, at around 4Pa [2], the metric of permeability is only a physical property of a building that indicates the resistance of its fabric. Thus there is much uncertainty when using a value of permeability in an attempt to predict operational air leakage. The airflow rate at 50Pa, $\dot{Q}_{50}$ (m^3/s), must be converted to an infiltration rate, $\dot{Q}_4$ (m^3/s), at 4Pa, and although there are several approaches[3] for converting $\dot{Q}_{50}$ to $\dot{Q}_4$ the most common *rule-of-thumb* for dwellings[4] is given as

$$\dot{Q}_{50}/\dot{Q}_4 = 20. \tag{1}$$

Equation (1) is often known as the *rule-of-20*, *Sherman's ratio*, or the *leakage-infiltration ratio* [4]. The figure of 20 must not be viewed as fixed and should be scaled according to a variety of factors such as dwelling height, shielding, air leakage path size, and climate [4]. In the UK, the Standard Assessment Procedure (SAP) is the government's method for assessing and comparing the energy and environmental performance of dwellings used to make energy and environmental policy decisions. As a starting point SAP applies Equation (1) (using a fixed value of 20) to obtain an initial rate of air leakage from measured permeability. It then adds extra air leakage if chimneys, flues, and fans are present in a dwelling. This revised figure of air leakage is scaled if local shielding and mechanical ventilation are present. Other building codes make similar assumptions [5].

However, the relevant literature reveals that little attention has been given to any scaling that should be applied to take account of the permeability of party walls. Measurements of airflow through party walls separating a series of terraced houses and apartments have indicated that such flows can be a significant component of total air leakage rate – up to 30% [6]. In the UK, for example, ~80% of the housing stock shares at least one wall with another dwelling [7]. This paper thus addresses this issue via a modelling based approach.

In this paper, a conjoined dwelling, such as an apartment, is assumed to be joined to four immediately adjacent apartments and a semi-infinite number of other apartments in both the vertical and horizontal planes. In the horizontal plane each dwelling is a mirror image of its adjacent apartment, whereas in the vertical plane each dwelling is identical to that located above and below it. Under operational conditions, and with all purpose-provided openings sealed, one does not expect to observe airflow between adjacent dwellings through permeable party walls because they are all assumed to experience identical environmental conditions and thus have the same internal pressure. Therefore, airflow is only expected through external façades. Conversely, when undertaking a blower door test in a conjoined dwelling of interest one cannot expect adjacent dwellings to be undertaking a similar test simultaneously and so two limiting assumptions about the permeability of party walls can be made: (A1) party walls are permeable and so airflow to adjacent dwellings through them is observed; or (A2), party walls are impermeable and so no airflow to adjacent dwellings is observed. Accordingly, this paper asks the questions: what are the consequences of these two limiting assumptions of permeability and how do they affect Equation (1)? To answer them, a theoretical study is undertaken using a simple but useful model of infiltration.

INTERIM: A 2D INTEGRATING INFILTRATION MODEL

In the absence of knowledge of the location of air leakage paths (ALPs), we start by assuming that a wall is uniformly porous. The modelling of wind driven infiltration using an envelope flow model is simple because a single flow path, representative of all ALPs, is placed at an arbitrary height on each façade. Modelling buoyancy is more problematic, but guidance on the number and location of ALPs is given by the AIVC [8] which states that "*the simplest approach would be to assign a high positioned and low positioned leakage path to each façade*." However, they also note that "*we have found that 11 vertical holes, equally spaced, are required to model the stack flow though a uniformly porous wall to an accuracy of 3-4%*", although no evidence is given showing why 11 ALPs is an optimum number. The greatest error occurs when buoyancy forces are introduced into an infiltration model and so we propose a framework in which the pressure difference across each section of the thermal envelope of a dwelling are estimated explicitly and the resulting airflow rates integrated over the whole envelope to give a total ventilation rate. This approach offers a coherent starting point to investigate infiltration and so is utilized here. We directly apply the work of Lowe [9] whose 2D Integrating Infiltration Model is herein known as 'INTERIM'. Full details of the model are given in by Lowe in reference [9].

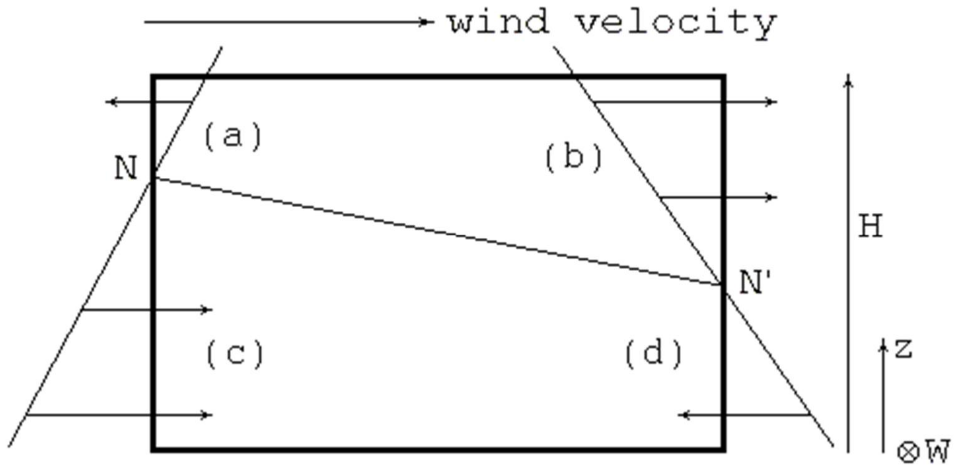

Figure 1: Vertical cross section through a dwelling showing stack pressure gradients on the windward and leeward façades and airflow modes: (a) windward exfiltration; (b) leeward exfiltration; (c) windward infiltration; (d) leeward infiltration. Line NN' is the neutral plane within the dwelling whose vertical deviation is caused by the action of wind around the dwelling. W is the dwelling width extending into the page.

A dwelling can be treated as a single-zone space by assuming that its rooms are interconnected and all internal doors are open[2]. Then, mass conservation ensures that the net mass flow rate $\dot{M}_{net}$ (kg/s) of air through the thermal envelope of a dwelling of height H (m) is zero, and is given by:

$$\dot{M}_{net} = \int WEF(|\Delta p|)\varepsilon(\Delta p)dz = 0 \tag{2}$$

where W is the dwelling width, E is the dimensionless relative leakage area, F is a flow function (kgm^{-2}s^{-1}), Δp (Pa) is the pressure difference across an infinitesimal section dz (m) of the thermal envelope in the vertical plane, and the flow direction function $\varepsilon(x) = 1$ if $x>0$ or -1 if $x<0$. The model assumes that the roof and ground floor are airtight and so infiltration only occurs through two opposite façades, and that each façade is uniformly porous. Figure 1 shows the stack pressure gradients on the windward and leeward façades and the neutral points (N and N') where there is no airflow through the envelope. The heights of N and N' (above ground) are affected by the action of the wind around the dwelling. Air flows into the dwelling below the neutral points and out above them, giving up to four airflow modes: (a) windward exfiltration; (b) leeward exfiltration; (c) windward infiltration; (d) leeward infiltration.

The flow function of Equation (2) has the form

$$F = a(|\Delta p|)^b \quad (3)$$

where b is the flow exponent with a value in the range of 0.6-0.7 [8], although it is often taken as 0.5 to simplify the analysis when a corresponds to $(2\rho)^{0.5}$. The permeability of a building is normally recorded at a pressure differential of 50Pa and under these conditions Equation (2) becomes

$$\dot{M}_{50} = EaA_{50}(50)^b \quad (4)$$

where A_{50} (m^2) is the area of the envelope able to transfer mass at 50Pa. When permeability assumption A(1) is applied $A_{50} = A_{env}$, the area of the dwelling envelope. When permeability assumption A(2) is applied $A_{50} = A_{exp}$, the total area of the exposed façades. Equation (4) is used to calculate E for the whole dwelling.

MODEL VALIDATION

INTERIM is used to answer the questions posed by this paper by predicting infiltration through the thermal envelope of a number of dwellings. Therefore, it is important to have confidence in the predictions of INTERIM and so they are compared against those of established envelope flow models. The first is CONTAM, a validated multi-zone ventilation and pollutant transport model [10], and the second is the AIDA algorithm, a simple single-zone ventilation model [8]. Both models assume a power law relationship between volume flow rate of air through the i^{th} of j ALPs and the pressure difference across it

$$\dot{Q}_i = C_i(\Delta p)^b \quad (5)$$

where C_i ($m^3 s^{-1} Pa^{-b}$) is a flow coefficient. Full descriptions of the models are given in their respective references and so are not repeated here. However, all of the models discussed here assume that energy and mass conservation is observed, flow characteristics are constant in the mean, the zone is perfectly mixed, and internal air velocities are negligible and do not affect the internal hydrostatic pressure [2].

To help compare the predictions of the models the dimensions of an archetypal apartment are used [11], see Table 1. The apartment has a floor area and height of $54.6m^2$ and 2.6m, respectively, two exposed façades oriented north-south each with an area of $20.3m^2$, an envelope area of $186.2m^2$, and an air leakage index (ALI) of $10 m^3/h/m^2$, the maximum permissible for a new UK dwelling [12]. Accordingly, using permeability assumption A(1), $E=1.63\times10^{-4}$ and a standard flow coefficient for each exposed façade is calculated to be $C=10\times2.6\times7.8/(50^{0.66}\times3600)=0.0043\ m^3 s^{-1} Pa^{-b}$, where the flow exponent b=0.66, a typical value for ALPs[8]. Windward and leeward façade pressure coefficients, c_p, are 0.603 and −0.452, respectively, and are specifically for a long wall [13]. Air density is $1.21kg/m^3$. Predictions are made for two conditions: wind only, and buoyancy only.

To model the wind only scenario using CONTAM and AIDA, a single ALP is placed at the centre of each façade and u is varied from 1 to 5m/s. When compared to INTERIM for all wind speeds, the predictions of CONTAM are 0.23% lower at all wind speeds, whereas the predictions of AIDA are 0.04% higher. These models predict wind pressure in the same way and so one would not expect to see big differences between their predictions. Variation may be attributed to the different numerical solving techniques and rounding errors.

Dwelling Parameter	Apartment	Terraced House
Width, height, depth (m)	7.8, 2.6, 7	6.2, 5.6, 10.5
Envelope area, A_{env} (m^2)	186.2	317.24
Total exposed façade area, A_{exp} (m^2)	40.56	69.44
Air Leakage Index ($m^3/h/m^2$)	10	10
ACH_{50} (h^{-1})	13.1	8.7
Relative leakage area $E_{A(1)}$, $E_{A(2)}$	1.63×10^{-4}, 7.49×10^{-4}	1.63×10^{-4}, 7.46×10^{-4}
Wind scaling height (m)	5.4	5.6

Table 1: Properties of an archetypal apartment [11] and terraced house [14].

The buoyancy only scenario is also modelled using CONTAM and AIDA where 2 to 11 equally spaced ALPs are placed at heights $z=0$m to $z=H$m at intervals of $H(j-1)^{-1}$ metres (where recall j is the number of ALPs) The internal temperature T_{int} (°C) is 19°C, a mean of recommended internal temperatures for a UK dwelling in winter[15], and the façade flow coefficient for each path is the façade flow coefficient divided by the number of paths present. When compared to INTERIM, for ΔT=10°C, the predictions made with 2 paths using CONTAM are 71% higher, whereas the predictions of AIDA are 68% higher. This overestimation by the modelling tools in relation to INTERIM is expected because the distance between the paths is the maximum possible and is equal to H. Therefore, increasing the number of paths systematically to 11, and reducing their separation, decreases the difference between the predictions of CONTAM and AIDA and those of INTERIM, see Figure 2. When compared to INTERIM for a temperature difference of 10°C, the predictions made with 11 paths using CONTAM are 8.8% higher, whereas the predictions of AIDA are 5.9% higher. Although more exhaustive testing would be beneficial, this inter-model comparison demonstrates reassuring agreement between their predictions.

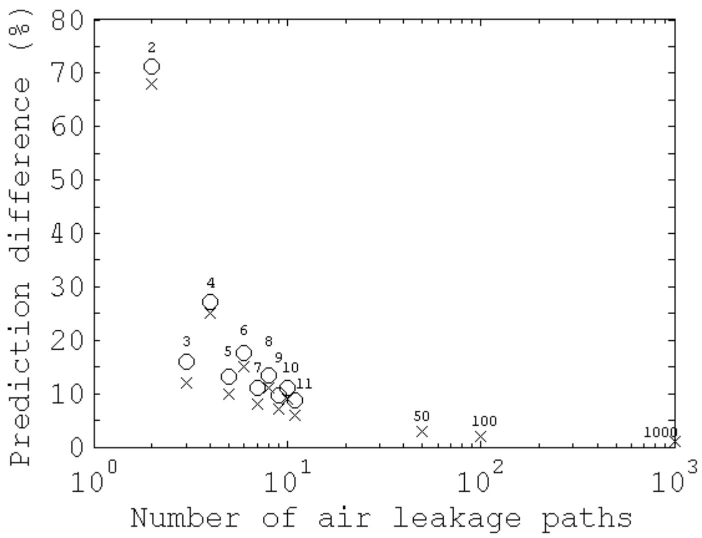

Figure 2: Percentage difference between the predictions of CONTAM and AIDA and INTERIM for a varying number of ALPs. ×, AIDA; ○, CONTAM; Number of ALPs. Wind velocity, 0 m/s; ΔT=10°C; H=2.6 m.

Based on the increased confidence in the predictions of INTERIM and as an interesting aside, we ask the question: what is the optimum number of ALPs when modelling infiltration using an envelope flow model? For this study, the data input of ALPs into CONTAM is done manually whereas data input into AIDA is automated. Using AIDA the number of ALPs on each façade is increased successively to 50, 100, and 1000, and its predictions are reduced to 2.6%, 1.8% and 1.22%, respectively, above those of INTERIM. This analysis suggests the difference between the predictions of the models reduce as the number of paths located on each façade approaches infinity asymptotically, but with diminishing returns, see Figure 2. However, for all practical purposes, 11 paths is close enough to infinity for a reasonably accurate prediction of buoyancy driven infiltration using a conventional envelope flow model such as CONTAM or AIDA.

Figure 2 shows that an odd number of ALPs gives better agreement than an immediately higher even number. An odd spacing places an ALP at the neutral height where the pressure difference across it and airflow through it is zero. Thus, the porosity of the wall reduces and better agreement is achieved, albeit artificially. Increasing the number of paths reduces the effect of this anomaly.

MODEL APPLICATION

The simplicity of the INTERIM model means that calculation time is significantly less than that for a CONTAM or AIDA model with a large number of ALPs. INTERIM is thus a useful tool for undertaking the simulations necessary to investigate the infiltration one might expect to find in a conjoined dwelling subjected to varying climatic conditions. The CIBSE Test Reference Year (TRY) weather data set [16] is a synthesised typical weather year suitable for analysing the environmental performance of buildings in the UK. Data exists for 14 locations, both coastal and inland, varying in latitude from 50.35°N to 55.95°N and longitude from 6.22°W to 1.36°E. Accordingly, these data are applied to the archetypal apartment (now considered to be located on the 1st floor) between 1st October and 1st March, thus simulating the heating season when purpose-provided ventilation is at a minimum. The rate of heat loss (W) via infiltration is given by

$$H(t) = \dot{M}_{inf} c \Delta T \tag{1}$$

where c is the specific heat capacity of air is ($c=1\,\mathrm{kJ\,kg^{-1}K^{-1}}$) and ΔT (K) is the difference between the internal and external air temperatures. ΔT is evaluated with internal air temperature $T_{int}=19$°C when external air temperature $T_{ext} \leq 16$°C. Otherwise, following Lowe [9]

$$T_{int} = T_{ext} + 3e^{-(T_{ext}-16)/3} \tag{2}$$

to account for the tendency of T_{int} to increase at the beginning and end of the heating season as T_{ext} rises. Equation (7) employs a *base temperature* [15] of 16°C; this is chosen because the heating system of an average UK dwelling begins to operate when $T_{ext} \leq T_{int} - 3$°C[17]. Accordingly, the rate of heat loss is not recorded when $T_{ext} > 16$°C because it is assumed that the heating system is off. Heat loss (kW) is estimated over periods of $t=1$ hour and so it is easily converted to the total energy lost by operational air leakage (kWh).

Wind speed is scaled for an urban environment using the power law formula with a coefficient of 0.35 and an exponent of 0.25[18]. Façade wind pressure coefficients are varied according to the wind direction using the distribution described previously. The relative leakage area is varied according to the two permeability assumptions so that under A(1), $A_{50}=A_{env}$; and under A(2) $A_{50}=A_{exp}$. Therefore, $E_{A(1)}=1.63\times10^{-4}$ and $E_{A(2)}=7.49\times10^{-4}$, respectively. All other variables are identical to those given in Table 1.

Table 2 gives the predicted mean, median, and standard deviation (σ) infiltration rate in air changes per hour (ACH) in an archetypal apartment during the heating season for the two limiting permeability assumptions in each city and overall. Also given is total heat loss (kWh) for each city and the overall mean value. For this example, if permeable party walls are assumed, the infiltration rate is below 0.5ACH, which is recommended by many European countries as a threshold ventilation rate above which some negative health effects reduce [19]. Under these circumstances, additional purpose-provided ventilation would be required. If impermeable party walls are assumed, the opposite is true, highlighting the importance of the assumption about the behaviour of party walls. Table 2 also shows when party walls are considered to be permeable the ratio of airflow rates at pressure to those under operational conditions is much greater than that given in Equation (1), whereas when party walls are considered to be impermeable the ratio is very close to that given in

Equation (1). This suggests that Equation (1) was originally formulated from measurements made in dwellings that either had no party walls or impermeable party walls, and required little scaling. A rough sensitivity analysis of the model shows that rotating the apartment through 90° increases average infiltration rates by 7% and so the simulations obtained here stand.

Location	**Assumption A(1): Permeable party walls**				**Assumption A(2): Impermeable party walls**			
	mean ACH	**median ACH**	**σ ACH**	**total heat loss**	**mean ACH**	**median ACH**	**σ ACH**	**total heat loss**
Belfast	0.16	0.13	0.11	470	0.74	0.60	0.52	2156
Birmingham	0.14	0.10	0.10	385	0.63	0.45	0.47	1767
Cardiff	0.15	0.12	0.11	401	0.68	0.55	0.49	1839
Edinburgh	0.14	0.10	0.12	421	0.66	0.45	0.55	1931
Glasgow	0.15	0.09	0.12	441	0.68	0.44	0.56	2025
Leeds	0.10	0.07	0.07	283	0.46	0.32	0.33	1299
London	0.12	0.09	0.09	305	0.57	0.39	0.42	1401
Manchester	0.14	0.10	0.11	395	0.66	0.47	0.51	1812
Newcastle	0.11	0.08	0.09	326	0.52	0.36	0.39	1496
Norwich	0.15	0.11	0.12	415	0.69	0.50	0.55	1904
Nottingham	0.13	0.10	0.09	391	0.60	0.46	0.42	1794
Plymouth	0.20	0.15	0.16	442	0.90	0.69	0.76	2030
Southampton	0.08	0.06	0.05	216	0.37	0.29	0.25	991
Swindon	0.16	0.12	0.13	471	0.75	0.57	0.58	2161
TOTAL	**0.14**	0.10	0.11	mean 357	**0.64**	0.44	0.52	mean 1640
$\dot{Q}_{50}:\dot{Q}_{4}$	**94.4**				**20.6**			

Table 2: Predicted infiltration air changes per hour (h^{-1}) and total heat loss (kWh) during heating season in an archetypal apartment for two limiting permeability assumptions. Permeability, 10m3/h/m2; A_{env}:A_{exp}, 4.59.

Location	**Assumption A(1): Permeable party walls**				**Assumption A(2): Impermeable party walls**			
	mean ACH	**median ACH**	**σ ACH**	**total heat loss**	**mean ACH**	**median ACH**	**σ ACH**	**total heat loss**
Belfast	0.12	0.09	0.07	879	0.53	0.40	0.32	4015
Birmingham	0.10	0.08	0.06	748	0.46	0.34	0.28	3419
Cardiff	0.11	0.08	0.07	746	0.49	0.37	0.30	3408
Edinburgh	0.11	0.08	0.07	823	0.49	0.34	0.34	3760
Glasgow	0.11	0.08	0.08	867	0.50	0.35	0.34	3960

Leeds	0.08	0.07	0.04	582	0.36	0.30	0.19	2657
London	0.09	0.07	0.06	599	0.42	0.32	0.26	2736
Manchester	0.10	0.08	0.07	754	0.48	0.34	0.31	3443
Newcastle	0.09	0.07	0.05	646	0.39	0.31	0.23	2950
Norwich	0.11	0.08	0.08	786	0.50	0.35	0.34	3591
Nottingham	0.10	0.08	0.05	753	0.44	0.34	0.25	3439
Plymouth	0.14	0.10	0.11	813	0.63	0.45	0.48	3713
Southampton	0.07	0.06	0.03	473	0.30	0.27	0.14	2162
Swindon	0.12	0.08	0.08	876	0.53	0.38	0.36	4000
TOTAL	**0.10**	0.07	0.07	mean 690	**0.47**	0.34	0.32	mean 3150
$\dot{Q}_{50}:\dot{Q}_4$	**85.4**				**18.7**			

Table 3: Predicted infiltration air changes per hour (h^{-1}) and total heat loss (kWh) during heating season in an archetypal terraced house for two limiting permeability assumptions. Permeability, $10 m^3/h/m^2$; A_{env}:A_{exp}, 4.57.

INTERIM is now used to assess the infiltration rate of a terraced house[14], using the properties given in Table 1 and CIBSE weather data. In a similar pattern to that of the apartment, the mean infiltration rate during the heating season is predicted to be $0.1h^{-1}$ when party walls are considered permeable, and $0.47h^{-1}$ when they are not, see Table 3. The leakage-infiltration ratios are predicted to be 85.4 and 18.7, respectively. Rotating the terrace through 90°C increases the infiltration rate by 5%. Accordingly, these predictions for an archetypal terrace house confirm the patterns of infiltration behaviour identified by the analysis of an archetypal apartment.

Consideration of Equation (4) demonstrates that the predictions made by INTERIM for the two party wall permeability assumptions are related by a simple ratio of the two effective leakage areas $E_{A(2)}$: $E_{A(1)}$, and by the exposed façade area to envelope areas A_{env}:A_{exp}; they both give the same value. Accordingly, the predictions made assuming permeable party walls can easily be scaled to identify those for impermeable part walls. For example, converting from the predicted mean ACH for the apartment for permeable party walls (see Table 2) to that for impermeable party walls is $ACH_{A(2)}=ACH_{A(1)}(A_{env}:A_{exp})=0.14(186.2/40.56)=0.64h^{-1}$. This means that Equation (1) can be amended according to one's knowledge of party wall permeability. The ability to scale infiltration rate means that it is also possible to scale predictions of total energy loss.

There are several consequences of these findings. If permeability assumption A(1) is true and party walls are indeed permeable, then conjoined dwellings do not experience the rate of operational infiltration predicted by Equation (1). Accordingly, annual energy lost via operational air leakage is also less than one might expect, see Tables 2 and 3. The payback period of retrofitted energy efficient measures (required to mitigate greenhouse gas emissions) designed to increase the air tightness of a conjoined dwellings would increase dramatically. The lower than expected airflow rates could also have health consequences by allowing the build-up of pollutants from internal sources, such as fine particulate matter, moisture, carbon monoxide, and radon. However, if permeability assumption A(2) is true and party walls are already impermeable then a sensible energy efficiency measure is the tightening of exposed façades. Although the dwelling types and weather data applied here from the UK, the findings can be applied by the policy makers of any country with a large number of conjoined dwellings and for those building codes that apply Equation (1) in some form.

Conclusions

This paper presents an analysis of infiltration rates in conjoined dwellings based on two limiting assumptions of party wall permeability at high pressure. The first assumption assumes that party walls are permeable, and in this instance the leakage-infiltration ratio is predicted to be significantly greater than that used by building codes to evaluate the energy and environmental performance of dwellings. The second assumption assumes that party walls are impermeable and here the leakage-infiltration ratio is predicted to be close to that used in practice. With this knowledge, it is now possible to amend the leakage-infiltration ratio for a given application, and to use it to make informed decisions on the implementation of energy efficiency measures. These findings have significant energy and health implications and should be of great interest to the policy makers of any country with a large number of conjoined dwellings. Finally, the paper also provides evidence for AIVC guidance on the modelling of infiltration using envelope flow models where none existed previously.

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CONSTRUCTION AND SET-UP OF A FULL-SCALE EXPERIMENTAL HOUSE FOR VENTILATION STUDIES

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Abstract

This paper reports on the construction, experimental set up and infiltration characteristics of a purpose built full-scale experimental house. The building has been designed as an experimental platform for measuring the moisture removal effectiveness of active and passive ventilation systems with indoor and outdoor climate conditions seen in New Zealand.

The two bedroom building was purchased as a pre-fabricated shell and moved onto the testing site. The inner wall lining was then air tightened following the Canadian "airtight drywall" approach to achieve less than 1 N_{50} (air changes per hour under a pressure difference of 50Pa). We then installed ventilation ports in walls, floor and ceiling so that the airtightness can be adjusted between 1 and 10 N_{50} to cover the current range of new housing in New Zealand. The building is equipped with temperature, relative humidity probes and multi-tracer gas equipment to track inter zonal air and moisture flows.

Early work has measured infiltration rates at four levels of airtightness, some of which are compared to infiltration rates calculated using a zonal model of the building.

Keywords

Ventilation, infiltration, full-scale, moisture removal

Introduction

The New Zealand Building Code offers an acceptable solution to home ventilation [1, 5, 6] that allows homes to be naturally ventilated through openable window and door openings greater than or equal to 5% of the floor area. Such a simple passive approach has been satisfactory given the temperate climate in New Zealand but this is potentially now not the case for the following reasons:

- The airtightness of new houses in New Zealand has increased over time, even though there is no airtightness requirement in the building code. The average airtightness of houses built pre-war is around N_{50} = 19 ACH and this reduced to N_{50} = 9 ACH for houses built 1960-1990 when large area sheet materials replaced strip lining and flooring. For houses built between 1990 and 2010 the average N_{50} = 4.5 ACH [4, 5, 6]. These changes are a natural consequence of building design and material selection but they have closed down natural ventilation paths that may have added useful ventilation.

- A recent survey of ventilation rates in homes built since 1994 [4] showed that the infiltration minimum is often supplemented by opening windows but that a proportion are exhibiting moisture problems because windows are kept closed for security and privacy. Clearly window opening cannot always be relied on for ventilation.

- Mechanical supply-only ventilation systems have become a popular retrofit solution to indoor moisture in New Zealand homes but with relatively simple controllers, they are not optimised for energy efficiency.

This paper reports on early steps towards trialling a range of ventilation options in a new full scale ventilation research building at BRANZ. Its purpose is to study the effectiveness of ventilation solutions in removing contaminants (particularly moisture), along with their ability to adapt to an occupant that opens windows. The work forms part of a wider WAVE (Weathertightness, Air Quality and Ventilation Engineering) programme at BRANZ. One of the aims of WAVE is to provide guidance on suitable ventilation options that are optimised for moisture control, energy efficiency and the airtightness of the house.

Our intention is to trial ventilation systems similar to those investigated by Yoshino et al. [7] as well as Liu and Yoshino [8] who have studied the performance of different ventilation systems in a full-scale two storey house at a fixed airtightness level without monitoring moisture removal or other contaminants. The effect of moisture buffering and ventilation as studied by Lengsfield et al. [9] and Hasegawa et al. [10] will be of particular interest to our research. Moisture production levels of various domestic activities we intend to simulate are going to be used according to Aizawa et al. [11] or Pallin et al. [12].

The experimental building

The building shown in Figure 1 was constructed as a pre-built shell in 2007 and recently transported on to the research site. The single storey house has a floor area of 91 m^2 and a volume of 206 m^3. The volume of the roof cavity is approximately 45 m^3. The house is a traditional timber frame construction that is clad with painted fibre-cement weatherboard directly fixed over a flexible wall underlay. The gable roof has corrugated iron cladding on timber trusses. The floor is made of particle board which is sealed with polyurethane. The walls and the ceiling are insulated to the requirements of the New Zealand building code [13] with fibre glass. All inner wall surfaces and the ceiling are lined with gypsum based plasterboard which received 3 coats of an acrylic paint.

In order to study ventilation effectiveness at airtightness levels that are present in a large part of the New Zealand housing stock we fitted the house with sealable ports that penetrate the envelope. The ports are located in the floor, the walls and the ceiling connecting the living area to the subfloor, the cavity of the outer walls and the attic, respectively. Our intention was to reach an airtightness level as low as 1 N_{50} (all ports sealed) and an upper level of about 9 N_{50} (all ports open). The pre-fabrication and the fact that it was going to be transported to its location on the research site made it necessary to achieve the airtightness through detailing of the indoor wall linings which were installed after the building reached its destination. We decided to implement the Canadian "airtight drywall" approach. To avoid air leakage from the outer walls through the inner walls into the room we isolated the inner wall by means of applying a 3 mm thick closed foam tape to the corners where the inner walls join onto the outer walls of the building. For the electrical outlets we used flush boxes that have seals at the cable inlet and where the plasterboard butts on the box rim. To avoid air leakage through gaps between the floor and the ceiling boards the plasterboards were sealed using silicone caulking. Every penetration of the plasterboards for cables, lighting, access hatch to the attic and the like was sealed as best as possible.

Figure 1: The experimental building on site.

Characteristics of the Ports

In order to derive a model of the infiltration, we measured the pressure/flow characteristics of the ports by pressurizing the building. The ports were constructed from PVC tubing with an inner diameter of 38mm and 64mm. The ports were installed in the walls, the floor and the ceiling which has given rise to four different pressure/flow characteristics. These characteristics were determined by fitting a exponential function $Q = C(dP)^n$ to the measured data points. Figure 2 shows the measured data and the graph of the fitted model while the fit parameters are provided in Table 1.

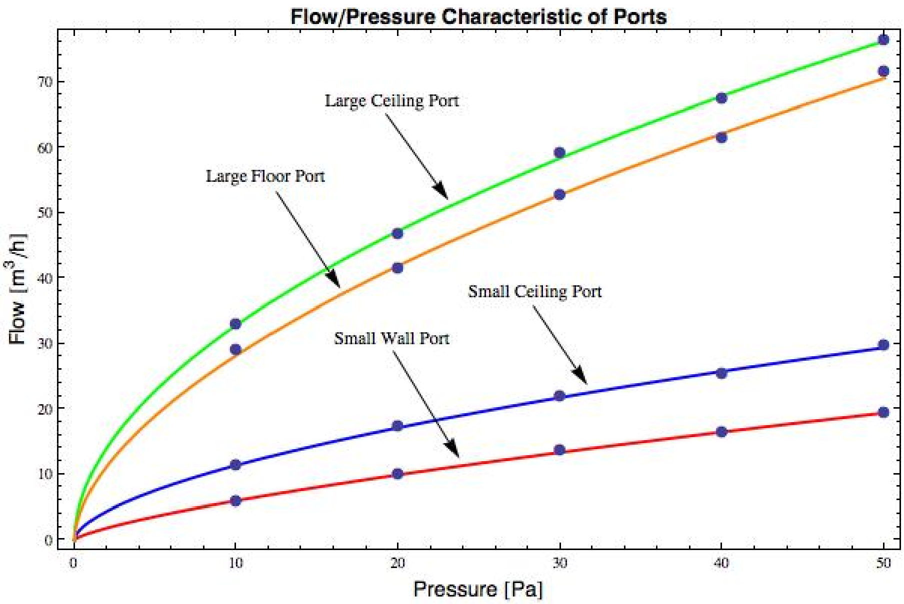

Figure 2: Measured data and fitted function for the flow characteristic of the various ports

The diameter of the port is the dominant factor determining the flow/pressure characteristics. The flow characteristic of the small ceiling ports and the wall ports show comparatively little differences taking into account that those ports lead on one hand into the large attic, while the wall ports lead into the confined space of the wall cavity. This indicates that the outer shell of the walls is not very airtight and that the airtightness level of 1 N_{50} achieved in the house is largely determined by the inner wall lining.

Port location/Size	Coefficient C	Exponent n
Wall Ports	1.1 ± 0.1	0.73 ± 0.02
Floor Ports	7.6 ± 0.5	0.56 ± 0.02
Small Ceiling Ports	2.9 ± 0.1	0.58 ± 0.01
Large Ceiling Ports	9.8 ± 0.4	0.52 ± 0.01

Table 1: Fit parameters of the power law pressure/flow model $Q = C(dP)^n$.

Instrumentation

The building is equipped with instruments that allow it to run infiltration and contaminant removal measurements in a semi automatic way. All operations are controlled by a computer which controls the indoor climate, the sampling of the tracer gas, the temperature and humidity sensors and writes the retrieved data into a database (see Figure 3). A database table is used to describe indoor climate parameters such as temperature and humidity. The house can be heated and the humidity can be increased but no cooling or dehumidifying is available at this point in time apart from what the installed ventilation system is providing. The airflow through the ventilation system into each zone is measured by means of pressure averaging tubes installed in the ducting.

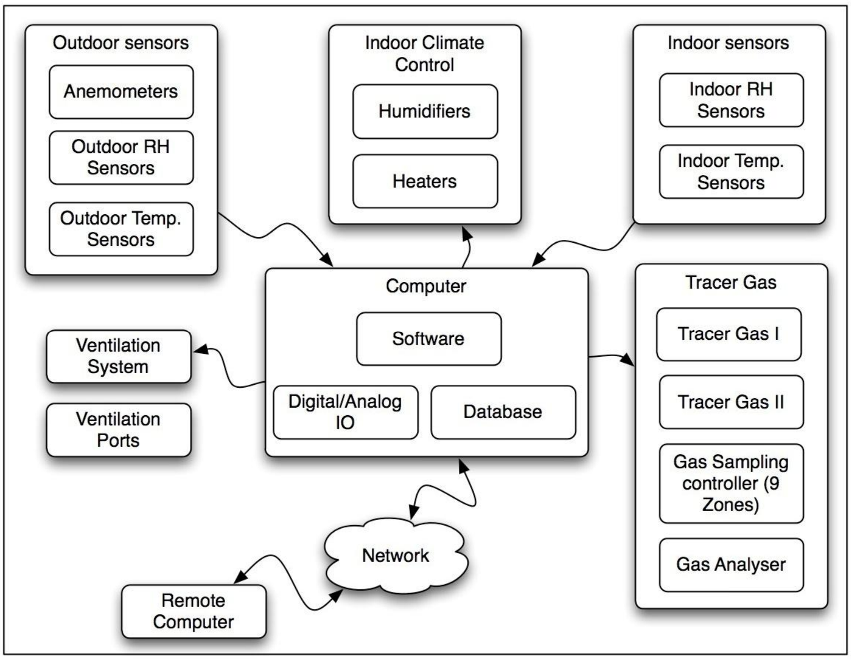

Figure 3: Instrumentation scheme used in the house.

The tracer gas injection rate is manually controlled at this point in time. Flow controllers used in gas chromatography are used to adjust the injection rate of the tracer gases from a few millilitres to hundreds of millilitres a minute. The flow controllers are kept at a few degrees above ambient temperature to minimise drift of the tracer gas injection rate. The flow rate is measured using simple bubble flow meters. An Innova 1412 photo acoustic gas monitor is equipped with filters to detect CO2, Freon, sulphur hexafluorid (SF6) and water with detection limits of 3.4 ppm, 0.02 ppm, and 0.006 ppm, respectively. The dynamic range of the gas monitor is typically 4 to 5 orders of magnitude. The target working concentrations of the tracer gas in the zones is usually at least 10 times the detection limit or, in case of CO2 10 times the background concentration. The tracer gases are sampled from the zones by means of a computer controlled manifold that can switch each of the possible 9 sampling locations onto the gas monitor. Each room, including the attic, is equipped with a number of sampling and dosing tubes. In the living area these tubes are located at approximately 1.5m off the ground. Before the gas monitor analyses the air sample it purges the tubes and the sampling chamber to avoid cross contamination. Measuring each location in turn takes about 10 minutes to process, thus allowing 6 samples to be taken from each location per hour. Wind velocities are obtained from the weather station located next to the house.

Infiltration Measurements

Before we can determine the performance of various ventilation systems, the infiltration characteristics of the house at different airtightness levels in the absence of a ventilation system had to be established. Our intention is to measure the ventilation effectiveness at the four airtightness levels of 1, 3, 5 and about 9 N_{50}. Various ports in the walls, the ceiling and the floor are opened to achieve these levels of airtightness. A ventilation port plan is used to make sure that only those ports are opened at a given airtightness level that allow for an even distribution of air leakage paths throughout the building. The injection rate of the tracer gas is adjusted in accordance with the set airtightness level to reach a tracer gas concentration of at least 10 times the detection limit, thus allowing for enough dynamic range and lower signal to noise ratio.

Figure 4 and 5 show the hourly averaged infiltration measurements of a single zone i.e., one tracer gas, over 2 - 4 days at different airtightness levels. The measurements were completed during a calm period with average wind speeds of only 2 m/s measured at 10 metres height.

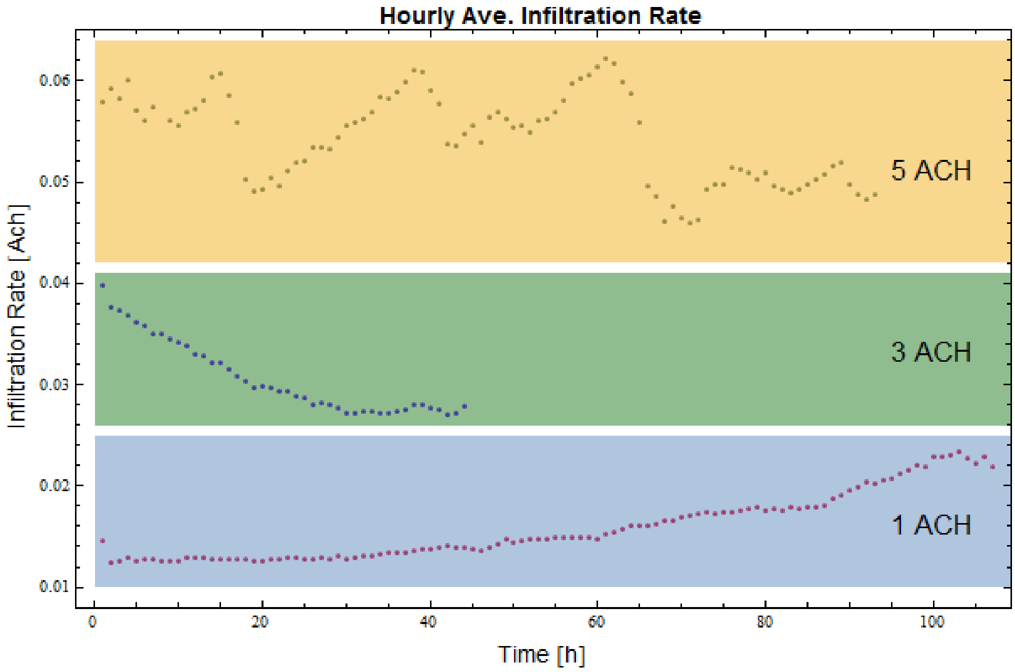

Figure 4: Single zone infiltration rate of the living area at different N_{50} airtightness levels. The graph for the airtightness level of 9 ACH has been moved to Figure 5 due to scaling.

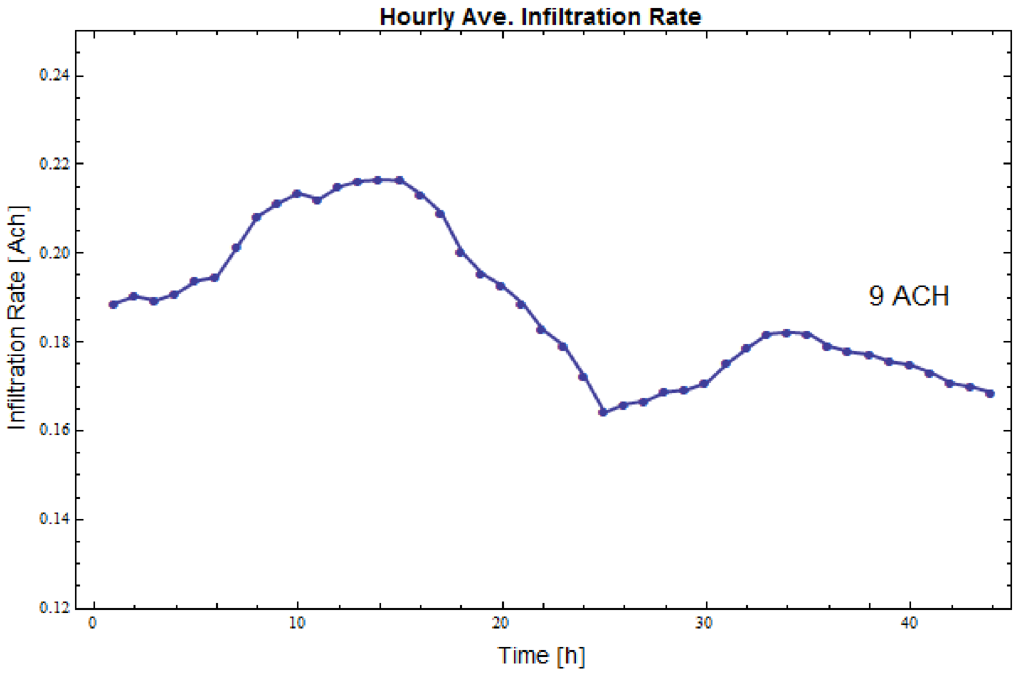

Figure 5: The graph shows the single zone infiltration rate of the living area at about 9 N_{50}. All ports are open at this level of airtightness but windows and doors are closed.

The hourly averaged infiltration rate of a short 2 zone infiltration experiment is shown in Figure 6. One of the bedrooms (Zone 2) of the house was filled with CO_2 while the remaining living area (Zone 1) of the house was filled with SF_6. Both zones were at an airtightness level of about 2 N_{50}. Only wall ports were open during this experiment, therefore, there was no cross infiltration between the two zones via the roof apart from through adventitious openings. Most of the inter zonal infiltration would have taken place through openings under the closed door. The average wind speed during this period was about 1.5 m/s at a height of 10 metres.

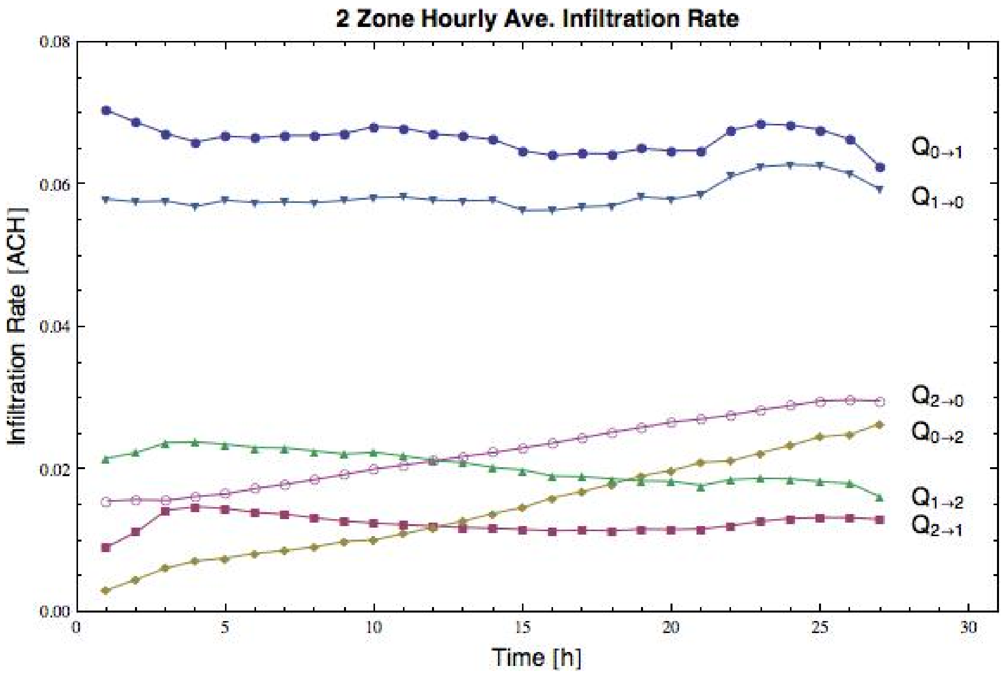

Figure 6: Infiltration rates for two zones - A bedroom (Zone 2) and rest of the house (Zone 1). Zone 0 refers to the outside of the building.

CONTAM Model

We have created a model of the infiltration characteristics using CONTAM. This model will be used later in the study to compare the measured performance with a ventilation system in place with what the performance would be without the ventilation system

At this point in time we have developed a single zone CONTAM [14] model using only the wall ports to simulate the ventilation in the living area of the test house. The pressure/flow characteristics of the wall ports (see Figure 3 and Table 1) have been used as parameters describing the flow paths in the model. Wind, outdoor and indoor temperature data were obtained from a weather station and the sensors in the test house. Pressure coefficient values for the building were derived from a wind tunnel measurements published by Tokyo Polytechnic University [15].

The tracer measurement was started on the 28th July and ran continuously till midnight of the 31st July. The hourly averaged simulated (dashed line) and the measured (continuous line) infiltration rate of the living area of the test house is shown in Figure 7. While the infiltration data is reasonable noisy it shows a good agreement between the simulation and the measurement. This indicates that the assumptions made in the model about the buildings pressure coefficients and the calculated pressure/flow characteristics of the wall ports are reasonable. Over time we will compare the simulation output of the model with other infiltration measurements to make the model more robust and show its validity under different wind and temperature conditions.

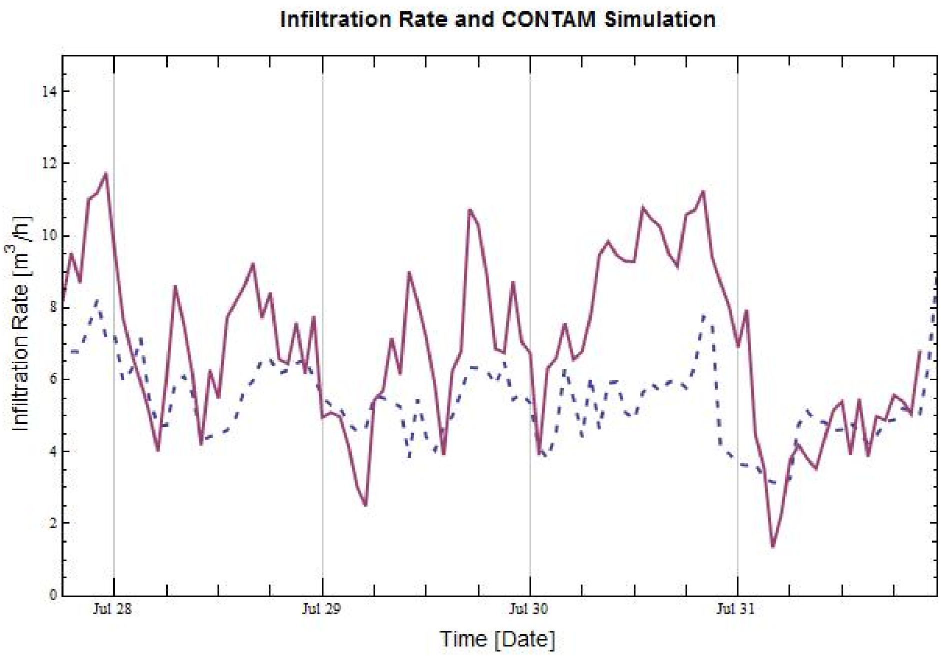

Figure 7: Good agreement is shown between the measured infiltration rate (continuous) and the rate simulated by use of a CONTAM model (dashed).

Conclusion

In this paper we have described the set up of a full scale experimental building to study the moisture removal effectiveness of ventilation systems and have presented initial measurements of infiltration data to characterise the building. The experimental setup can measure at up to 9 sample locations at a rate of 6 samples per hour. A single zone CONTAM model was developed and shows good agreement with a data set derived from an initial infiltration rate measurement.

Acknowledgements

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SWEDISH EXPERIENCE WITH AIR TIGHT TESTING: OVERALL SCHEME, TEST PROTOCOL AND PRACTICAL EXAMPLES

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Abstract

Starting already 1950 – i.e. for more than 60 years back in time – we have been using a probably quite unique quality assurance system in Sweden covering all aspects of building and installation technologies. Practically all buildings and their installations are performed according to the quality requirements in the AMA specification guidelines (General Material and Workmanship Specifications). The AMA requirements are made valid when they are referred to in the contract between the owner and the contractor.

The HVAC-part of AMA included requirements for tight ventilation ductwork systems already in the early sixties. Sweden has thus a long and unbroken tradition of demanding tightness of ventilation ductwork. During this long period, since 1966, the AMA tightness requirements have been raised in tact with technology improvements and increased energy costs.

But requirements and demands can be worthless unless they are controlled. The AMA requirements thus also include demands for tightness testing of the ductwork. The result of the tightness test has to be reported on standard protocol forms signed by the testing contractor.

And this has been shown to be very effective in raising the quality of ductwork. As e.g. shown in two EU-projects this long time focus on ductwork quality in Sweden has resulted in very low air leakage in normal Swedish duct installations.

And there are several reasons that justify the requirements for tight duct installations:

- Many studies have identified defective ventilation systems and insufficient airflows as a main reason for occurrence of sick buildings - the supply air needed to assure a good air quality should thus reach the areas where it is needed and not disappear along its transport through the building.

- The supply air flow has to cover the sum of total nominal air flow and the leak flow. With leaky ductwork this will lead to a considerable and costly increase of the needed fan power.
- Duct leaks can result in disturbing noise.
- When leaky supply and extract air ducts are installed above a false ceiling part of the air will take the simplest way, from the supply duct direct to the extract duct without bothering to pass through the connected rooms.

Swedish industries, building owners and authorities work together with the object to increase the quality of ventilation systems. Parallel with the voluntary AMA demands (i.e. voluntary until the contract has been signed) Swedish authorities 1991 thus started a compulsory system for ventilation control (OVK) in Sweden with aim to control and improve the function of ventilation installations. According to the ordinance (1991:1273) a control of the ventilation in most types of buildings has to be made before the installations are taken into operation and then regularly at recurrent inspections.

Keywords

AMA, Ductwork, Tightness,

TESTING OF DUCTWORK AIRTIGHTNESS: OVERALL SCHEME

AMA – a sixty year old system, easy and accepted tool for specifying quality

The future building proprietor and his consultant use the AMA system (General Material and Workmanship Specifications) as a tool to specify the requirements for a new project. AMA covers all aspects of building and installation works of various kinds – e.g. buildings, installations, roads, and tunnels – and is split up in several parallel main parts covering these aspects, from building foundations to HVAC and electrical installations. The AMA requirements are made valid when they are referred to in the project contract between the owner and the contractor.

It all started way back in 1950 when AMA was born with “House AMA” and “Pipe AMA”. During the following decades the group was extended with other AMA books for Ventilation, Ground works, Heating installations, Electrical installations and Refrigeration. Today these areas have been collected in four books, one of these is the HVAC AMA covering among many other aspects ventilation ductwork and e.g. protocol forms for reporting the result of tightness tests of ductwork.

Requirements in AMA are accompanied by advices in RA

Each of these AMA books (specifying the requirements) are accompanied by a parallel book (e.g. “RA – Advices and Instructions”) comprising advices to the consultant on how to specify and quantify systems and components. In many cases they also give advice on how to choose a quality level. These RA-books serve also as check list for how to write a complete specification where the demands on the tenderer/future contractor are clearly shown in a way enabling him to calculate the cost for his contract commitments.

A common AMA-rule states that these requirements shall be expressed in measurable terms combined with control methods with known (and possible low) measurement errors. Another AMA-rule is that the cost for fulfilling the demands shall be calculable for the tenderers.

The AMA books are shown in Figure 1.

Figure1: The AMA family (VVS = HVAC), 1998 edition.

Requirements are raised in tact with technical progress and when economically motivated

The level of the AMA quality requirements are based on a kind of "80/20"-type rule. They should be suitable for most of the applications ("80 %") while for the rest they are either too high (the project, e.g. a building, has a very short planned life span and thus does not need the normal AMA quality) or too low (for projects where a higher quality is needed, e.g. laboratories and hospitals).

The AMA quality requirements are lifted when possible by technology progress and when found profitable for the owner on a Life Cycle Cost basis. Proposed increased requirements are established after they have been referred for consideration to a large number of owners, manufacturers, contractors, consultants and other interested parties. Wherever possible, AMA refers to relevant national Swedish standards and European norms. Twice a year the AMA requirements can be updated through the AMA-nytt (AMA News) Journal and added to computer-based specification tool used by the consultants. AMA is published by The Swedish Building Centre, a non-profit organization).

The AMA system follows the project through all phases of the building project – from design (supplying advices to the designer), to tender documents with specifications (these include references to relevant AMA clauses and advices on how to quantify), to installation (stating quality requirements for material/components and workmanship e.g. for duct connections, insulation of ducts or soldering of copper pipes), testing (e.g. measurement methods, protocols, e.g. for tightness test of ductwork), and maintenance (e.g. labelling and marking of components, cleaning of ductwork).

AMA vs. regulations

AMA is a voluntary complementary to Swedish statutory rules, regulations and specified building standards laid down by the authorities. Even if AMA and the regulations have common interest areas in securing sustainability and low energy use there is a difference between the two - the statutory rules are normally mostly focussed on reducing the risk of injuries to workers and users while AMA (not having to deal with those aspects) is focussed on reducing property damages and LCC-costs.

The AMA demands on ductwork tightness

Specifying requirements on ductwork tightness has a long story in Sweden; it has been specified as part of building specifications since the AMA edition 1966.

As described the AMA quality requirements are raised when possible by technology progress and when found profitable for the owner on a Life Cycle Cost basis. This is also true for ductwork tightness requirements:

In AMA version 1966 two "tightness norms" A and B, were defined. They were to be spot checked by the contractor; minimum tested duct surface area was 10 m^2.

In AMA 1972 the requirements were transformed into two "tightness classes" A and B (same as the EUROVENT classes today). Class A was the basic requirement for the complete duct system in the air handling installation (i.e. including dampers, filters, humidifiers and heat exchangers). It was advised to raise the requirement to meet Class B when the system operates for more than 8 hours/day or the air is treated (cooling, humidification, high class filters etc.).

In AMA 1983 a new tightness Class C was added to be used round ductwork larger than 50 m^2. Class B was to be used for round duct systems having a surface area smaller than 50 m^2 and also for rectangular ductwork.

Class A was accepted for visible supply and exhaust ducts within the ventilated room (i.e. not hidden above false ceiling).

In AMA 1998 a new tightness Class D was added being 3 times tighter than Class C. The use is not specified. It is an optional requirement for larger circular duct systems and where leakage can lead to hazards.

In AMA 2007 also rectangular ductwork has to meet tightness class C.

In AMA 2011 the ductwork tightness requirements are the same as in 2007.

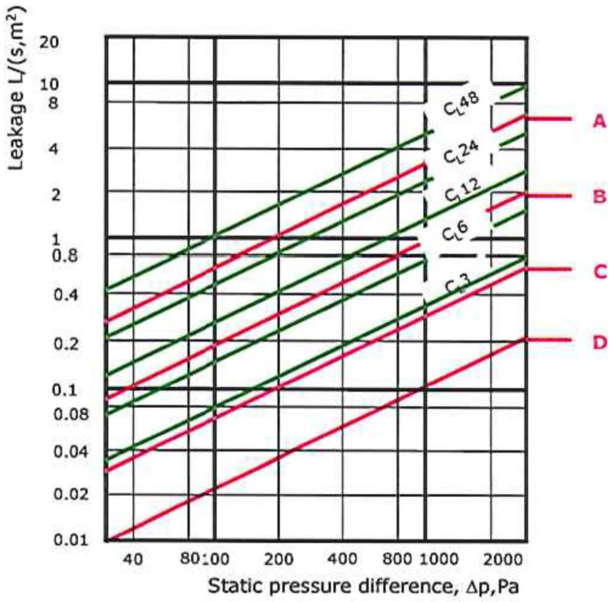

Figure 2: Eurovent Tightness Classes A – D and ASHRAE Classes C_L 48 - 3.

Often the duct manufacturers initially objected to these increased demands but as soon as one of them quickly announced that e.g.: “We can meet the new AMA requirements”, the rest of the gang was forced to follow.

Specify what you can control – and do it!

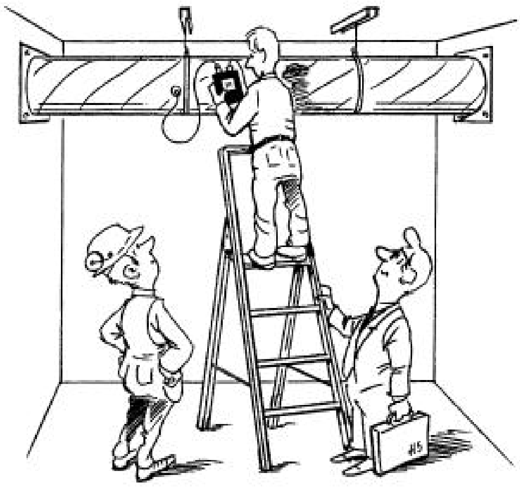

Figure 3: Express your demands in measurable units and measure it! The building owner’s consultant points out what part of the ductwork that should be tested by the contractor

A ductwork system should not be specified to be tight – instead the permissible leakage rate at a specified test pressure is stated – that is possible to measure! Unless otherwise specified the tightness classes are to be in accordance with AMA demands (as stated above). AMA also states the requirements for the testing of ductwork tightness.

The general AMA rules stated above are thus relevant for ductwork tightness: “Express your requirements in measurable terms and control that you have got it!” and the other: “The costs and risks for the contractor to fulfil the requirements in the contract should be possible to calculate”.

To ensure the quality of the duct system the leakage has to be verified; this is normally done either by the contractor himself or by a specialist engaged by the contractor. This is included in the contract and the cost is thus covered by the contractor. This test is undertaken as a spot check where the parts to be checked are chosen by the owner's consultant. For round duct systems 10 % and for rectangular ducts 20 % of the total duct surface normally has to be verified as specified in AMA.

Should the result of this test however show that the leakage is higher than allowed for the tightness class specified the contractor has first to tighten the leak points until the tightness requirement is fulfilled as verified by a new test of the same part of the ductwork – the contractor has consequently to redo his job until found OK! But in addition to this, another part of the same duct installation (e.g. another 10 % of a round duct installation) has to be checked. If this is also shown to be leakier than allowed the whole duct installation (i.e.100 %) has to checked and tightened until accepted.

And this increased testing, tightening and retesting can be costly for the contractor who is responsible for delivering an installation fulfilling the specification requirements. Quite naturally this has led to high quality tight ductworks – instead of risking this costly and time-consuming additional work the contractor aims to do a good job right away. Even though the tightness requirements have been raised during the past years, the new types of rubber gasket provided ducts and duct components have made the duct installation job easier, cheaper and more reliable than before.

The contractors do their best to avoid costly setbacks from inferior duct quality. The duct manufacturers are competing in inventing and marketing tight duct systems that are easy to install. Both circular and rectangular duct connections are provided with rubber gaskets that are very tight compared to older (and foreign) systems. New types of duct joints have reduced earlier laborious installation works.

In summary: the costs for the tests – the first 10 %, then another 10 % if not accepted and then at the end the whole system - is part of the contract and thus to be covered by the contractor. The mechanical contractor can either make the tightness test with his own personnel, provided he has equipment and skilled personnel to do that, or he can have it done by another specialized contractor. In both cases he has to cover the costs which can be quite considerable if the tests have to be repeated due to bad test results. The result of the leakage test shall be reported on AMA standard protocols and handed over to the owner.

Is it worthwhile to require and control the ductwork tightness? Yes!

There are several reasons that justify the requirements for tight duct installations:

Many studies of SBS, the Sick Building Syndrome, have identified defective ventilation systems and insufficient airflows as a main reason for the occurrence of sick building problems. The required supply air flow needed to assure a good indoor air quality should of course be delivered to the areas where it is needed and not be allowed to disappear along its transport through the building. This requires tight ducts!

In order to guarantee that the correct air flow is delivered to the room the supply air flow from the fan has to cover both the sum of the total nominal air flow and the disappearing leak flow. With leaky ductwork this will lead to a considerable and costly increase of the needed fan power (that has to be raised with up to third power of air flow increase).

Ductwork leak points can result in disturbing high frequency noise.

If leaky supply and extract air ducts are installed above a false ceiling part of the supply air will take the simplest way, from the supply duct with overpressure direct to the extract duct with underpressure without bothering to pass through the connected rooms.

And the AMA system has been shown to be very effective in raising the quality of ductwork. When compared to the result of tightness test of ductwork in Belgium and France as shown in two EU-projects this long time focus on ductwork quality in Sweden has resulted in very low air leakage in normal Swedish duct installations.

Comparison of the results from an EU project – Ductwork in Sweden was 25-50 times tighter!

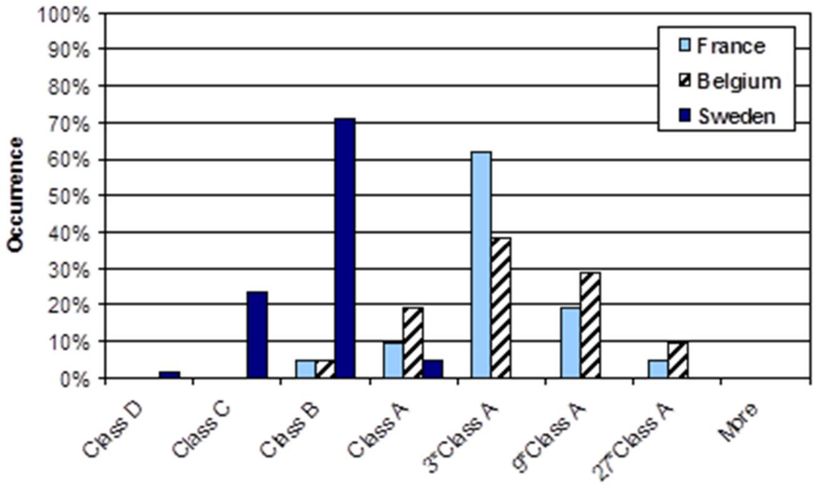

Figure 4: Comparison of the results from an EU project – Ductwork in Sweden was 25-50 times tighter!

As shown above duct leakage is detrimental to energy efficiency, comfort effectiveness, indoor air quality, and sometimes even to health. However, in most countries designers, installers, building managers and building owners, often ignore the benefits of airtight duct systems. Furthermore, as there are no incentives in most countries, over the years, this has (probably) lead to poor ductwork installations in a large fraction of the building stock.

In these countries ductwork installation is often undertaken using conventional in situ sealing techniques (e.g. tape or mastic), and therefore the ductwork airtightness is very much dependent upon the workers' skills..

The measurements and literature review performed within the EU-project SAVE-DUCT found that duct systems in Belgium and in France are typically 3 times leakier than EUROVENT Class A, see Figure 4. Typical duct systems in Sweden fulfilled the requirements for EUROVENT Class B and C and were thus between 25 – 50 times tighter than those in Belgium and France.

The answer to the question "Why this large difference between the countries?" is most probably that Sweden has required tight ducts, i.e. specifying how much they are allowed to leak at a certain test pressure, since the early sixties whereas in the two other countries tightness of ductwork is normally neither required nor tested.

Conclusion

Duct leakage is detrimental to energy efficiency, comfort effectiveness, indoor air quality, and sometimes even to health.

The Swedish long-time experience of quality approach to ductwork airtightness has shown that tight ductwork systems are cost effective and sustainable.

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PROPOSAL FOR UPDATING FRENCH REGULATION CONCERNING AIRTIGHTNESS MEASURING EQUIPMENTS' CALIBRATION

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Abstract

French standard for airtightness measurements is NF EN 13829. It is completed by French application guide GA P50-784, to set calibration rules more precisely, among other issues. This guide was published in 2010. To answer measurers' remaining questions, a Frequently Asked Questions web site was created by CETE de Lyon.

Today, some weaknesses of French GA P50-784 have been clearly identified. It was therefore planned to update it, taking into account the experience gained in the last few years in dealing with airtightness in France, measurers frequently asked questions and ISO 9972 standard requirements in revision.

This article presents the conclusions of a working group created in 2011, lead by CETE de Lyon, which was in charge of updating French philosophy about calibration rules by optimizing the compromise between calibration's precision and costs. It is also planned to improve precision requirements for low air flow rates measurements. The content of this article must not be considered as the future French regulation; it is only the final proposal of the working group.

Keywords

Airtightness, building, calibration

Introduction

Airtightness measurements in France are based on three complementary references:

- European standard NF EN 13829, published in 2001 [1] ;
- French application guide GA P50-784 of European standard, published in 2010 [2] ;
- On-line Frequently Asked Questions (FAQ) on CETE de Lyon's website.

First, NF EN 13829 details the protocol to be followed to measure airtightness. It also explains calculations which must be done to get the air-leakage flow rate at the considered pressure level, as well as the conversion of air-leakage flow rates into one single airtightness indicator : n_{50} [vol/h].

Then, GA P50-784 explains how to determine French legal airtightness indicator $Q4Pa_{surf}$ (also written Q4Pa_surf) and associated uncertainty. It gives sampling guidelines for grouped and collective housing. Calibration rules are also specified in this application guide. It is published under French Association for Normalization (AFNOR) copyright.

Finally, answers to measurers' Frequently Asked Questions can be found on CETE de Lyon's website. These answers are not based on any reference. They complete and precise NF EN 13829 standard and GA P50-784. Authorized measurers agreed by French Ministry in charge of Construction must follow the FAQ's specifications, in case of doubt on some issues dealt with in the standards.

Today, some weaknesses of French GA P50-784 have been clearly identified. It was therefore planned to update it, taking into account the experience gained in the last few years in dealing with airtightness in France, measurers Frequently Asked Questions and future ISO 9972 [3] standard requirements, which should replace NF EN 13829.

This article presents the first conclusions of a working group created in 2011, lead by CETE de Lyon, which is in charge of updating French philosophy about calibration rules. The content of this article just gives some elements of the final proposal of the working group and should not be considered as part of the future French regulation. It begins by reminding today's calibration rules; then, weaknesses of these rules are detailed; finally, tracks of progress are proposed.

Calibration rules applicable today

Calibration rules given in GA P50-784 are shown in Table 1.

Device	Measuring range	Required precision	Calibration or verification frequency	Authorized organisms
Barometer	900 – 1100 hPa	± 2 hPa	3 years	- Manufacturer - COFRAC accredited organism
Pressure-gauge	0 – 100 Pa	± 2 Pa	1 year	- Manufacturer - COFRAC accredited organism
Flowmeter	Unspecified	± 7 %	1 year	- Manufacturer - COFRAC accredited organism
Thermometer	-30 °C / +50 °C	± 1 °C	3 years	- In-house - Manufacturer - COFRAC accredited organism
Wind gauge	0 – 25 m/s	± 0,5 m/s	3 years	- Manufacturer - COFRAC accredited organism
Distance measuring equipment	0 – 20 m	± 1 cm	3 years or replacement for electronic devices	- In-house - Manufacturer - COFRAC accredited organism
Adjustable diaphragm	Unspecified	Unspecified	1 year	- Manufacturer - COFRAC accredited organism
Fixed diaphragm	Unspecified	Unspecified	5 years or less according to manufacturer specifications or in case of damage	- Manufacturer
Fan	Unspecified	Unspecified	5 years or less according to manufacturer specifications or in case of damage	- Manufacturer
Pipes' shape	Unspecified	Unspecified	Unspecified	- Manufacturer

Table 1: Calibration rules given by French application guide GA P50-784

The certificate delivered after calibration must describe the calibration protocol and state whether the device is in conformity or not. For non-measuring devices, like diaphragms or fans, it is only asked to report a list of tested components and associated corrections.

Main weaknesses

First problematic issue is precision and reliability of calibration: French application guide makes it possible to choose between sending measurement devices either to the manufacturer or to an external COFRAC accredited organism. COFRAC is the French Accreditation Comity, member of EA (European Accreditation) and ILAC (International Laboratory Accreditation). The manufacturer is not able to be as reliable as a COFRAC accredited organism.

Secondly, calibration is not mandatory for fans and associated diaphragms. It is only required to check shapes, rotation speeds and stability, without any precision criteria nor operation range.

Thirdly, full airtightness measurement systems cannot be calibrated at once. Components can only be calibrated separately. However, manufacturers observed in some cases that deviation measured on a full system could be greater than theoretical deviation calculated from known components' deviations.

Fourthly, systems for air-flow rate measurement have no specified measuring range. They can therefore be calibrated on a given range and then used on a wider range. This point creates difficulties to reach precision especially at low air-flow rates ranges, for which most of blowing-door technologies are usually not calibrated.

Finally, mandatory information given by the calibration certificate is not complete for the measurer to calculate uncertainty. For example, standard reference and calibration uncertainty, as well as devices' resolution, are not specified in the certificate.

Tracks of progress

The aims of the working group created in 2011 are :

- To ensure greatest precision of airtightness measurements;
- To consider any existing or future technology for airtightness measurement;
- To minimize practical and financial constraints for measurers.

Precision is particularly crucial for future controls of airtightness for dwellings built after January 2013. According to French Thermal Regulation (RT 2012), those buildings will be measured at the end of their construction and their airtightness will have to be below:

- 0.6 $m^3/h/m^2_{\text{cold surface}}$ at 4 Pa differential pression between indoor and outdoor for individual dwellings;
- 1 $m^3/h/m^2_{\text{cold surface}}$ at 4 Pa differential pression between indoor and outdoor for collective dwellings.

COFRAC was identified by the working group as the only way to get fully transparent and reliable calibration, with all information needed to calculate uncertainty given on the certificate. It was therefore decided that COFRAC calibration would become mandatory for all components of measurement systems, to ensure excellent precision, except for barometers (for atmospheric pressure measurements), thermometers and distance measuring equipments. Those equipments were considered as having lower impact on the final result than flowmeters, for example.

To enable calibration of all existing and future measuring systems, not necessarily using pressure-gauges as flowmeters, and also to ensure the consistency of the full acquisition chain, the group recommended that the systems should be calibrated without separating components. However, to limit practical constraints for measurers, who sometimes need to use flowmeters in association with many different fans, it was decided that the possibility of calibrating components separately would be preserved.

A two-possibility solution was therefore proposed:

- First, the full system has to be calibrated when sold to the customer, with a maximal tolerated error of 2 $m^3/h \pm 7$ %;
- Then, two choices are proposed :
    - Either the system is kept full every time it is used and can therefore be calibrated at once every year, with a maximal tolerated error of 2 $m^3/h \pm 7$ %;
    - Or system's components are not always kept together and must be calibrated separately, with frequencies and maximal tolerated errors reported in Table 2.

Device	Measuring range	Required precision	Calibration or verification frequency	Authorized organisms
Barometer	700 – 1100 hPa	± 2 hPa	4 years	- Category 1[3]
Pressure-gauge	{-100, -50, -10, 0, 10, 50, 100} Pa	1 Pa ± 1%[4]	1 year	- COFRAC accredited organism
Thermometer	-20 °C / +40 °C (3 steps on full range)	± 1 °C	4 years	- Category 1
Distance measuring equipment	0 – 20 m (0 – 100 m for telemeters)	± 1 cm		- Category 2[5]
Complete measuring	6 steps on desired range (3	2 $m^3/h \pm 7\%$	1 year	- COFRAC accredited organism

[3] Category 1: calibration or verification must be done in conformity to FD X 07-012 or FD X 07-011 (in-house, manufacturer or external organism).

[4] Percentage of measured value

[5] Category 2 : self-control with specific protocol and verification file.

system (full acquisition chain)	steps per configuration[6] if many)			
Pressure-gauge (flowmeter)	Desired measuring range	1 Pa ± 1%	1 year	- COFRAC accredited organism
Wind gauge	5 steps on desired range	0,5m/s ± 3%	3 years	- Manufacturer - COFRAC accredited organism
Fan and associated aperture or cone	6 steps on desired range (3 steps per configuration if many)	2 m^3/h ± 4%	1 year or 2 years (still to be discussed)	- COFRAC accredited organism

Table 2: Calibration rules proposed by the working group

Each component and the entire system must not be used out of the measuring range used for calibration. This ensures precision at low air-flow rates, for example, because systems which are not calibrated on low ranges can no more be used. For very airtight buildings measurements, specific systems should therefore be bought by measurers and calibrated on low air-flow rates ranges.

It was observed that new rules proposed by the working group were quite complex, compared to previous ones. However, they were considered as the only way to meet the three objectives the group had defined. It is still unknown whether one of the two possible solutions for calibrating systems (full system or component-by-component) will be more expensive than the other. This could make measurers prefer one solution than the other on the long term.

Points still to be discussed

First, frequency of calibration for fans must be precised: chosen period will be either 1 year or 2 years, depending on observed deviations on Building Services Research and Information Association (BSRIA, UK) database. It was decided that the period would not exceed 2 years in order to keep maximum competitiveness between the two possible calibration solutions.

As airtight door is never verified together with full measuring system, the group also imagined a service control procedure, which could become mandatory to check full system's consistency between two calibrations. A decision must still be made on this point.

[6] Configurations can be rings with different diameters, for example.

Then, after having found the air-flow rate range usually used for dwelling measurement, specific calibration rules should be defined for higher and lower air-flow rates, in order to guide calibration organisms' investments.

Afterwards, fans with uncommon diameter should not be forgotten in calibration rules. Specific rules should therefore also be defined for them.

Finally, as there is no French organism able to do COFRAC calibration for fans at the moment, it was planned to set a deadline for the regulation changes to be applicable, so that organisms have time to adapt. Suitable deadline should also let enough time to measurers to calibrate their equipments and get aligned with new rules. This deadline is still to be defined.

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FRENCH POLICY FOR SHELTER-IN-PLACE: AIRTIGHTNESS MEASUREMENTS ON INDOOR ROOMS

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Abstract

Accidental dispersion of toxic gas clouds may occur around industrial platforms or during hazardous materials transportation. In case of such a toxic risk, the best protection strategy is to remain inside a building and seek refuge in an airtight room identified as "shelter" until the toxic cloud has finally been swept off. This strategy called "passive shelter-in-place" also includes obstructing all external openings and turning off all mechanical ventilation systems

Following the AZF chemical accident (Toulouse, 2001, 31 deaths), a French law was adopted in 2003 that can compel public and private building owners to adopt such a shelter-in-place strategy. To prove that the shelter airtightness is sufficient and that the occupants will not be exposed to irreversible effects, the shelter's air leakage measurement is compulsory for buildings owners. Envelope leakage does not need to be measured.

This paper gives an overview and first analysis of collected airtightness measurements for these indoor shelters. More than 100 results have been collected, with information on the building use (one-family dwelling / multi-family dwelling / non residential), the required airtightness level, the volume, the floor area, the year of construction. The final goal of this database is to give a picture of the vulnerability of housing stock around industrial platforms.

The aim is to help local decision makers with information related to the cost and the extent of works to be done on buildings in order to protect people against toxic risk, e.g. to reach the expected airtightness requirement, regarding some criteria like building use, geometric characteristics of the shelter, year of construction.

These experimental data can also be used as inputs in multi-zone airflow and pollutant transfer model, when data on internal airtightness are needed to study inter-zone airflows.

Keywords

Air infiltration, air leakage, shelter-in-place, vulnerability, toxic risk, land-use, indoor air transfer, airtightness measurement

Introduction

Accidental dispersion of toxic gas clouds can occur around industrial platforms or during hazardous materials transportation. In case of such a toxic risk, two strategies can be implemented to protect people: shelter-in-place or evacuation [1]. In France, like in other countries, passive shelter-in-place has been found the best protection strategy. It consists in having people remain inside a building and seek refuge in an airtight room identified as 'shelter' until the toxic cloud has finally been swept off. Following the AZF chemical accident (Toulouse, 2001, 31 deaths), a French law adopted in 2003 established a land-use tool around all SEVESO II (high level) classified establishments [2]: the technological risk prevention plan (PPRT) [3]. Such a plan specifies protective construction works for future and existing buildings in case of toxic risk in the plant, which consist into the implementation of a shelter-in-place system against toxic risk.

On 14th August 2012, 182 PPRT have been established, 8 PPRT have not begun and 212 are under development.

Description of Shelter-in-place requirements on buildings

Shelter-in-place requirements are detailed in a guide we wrote up for the French Ministry in charge of PPRT plans development [4]. It is compulsory for a shelter-in-place system to achieve the protection of people during 2 hours against irreversible effects caused by a toxic cloud.

Firstly, a shelter-in-place system includes general constraints on the whole building and on a room used as shelter. These constraints do not depend neither on the toxicity of the products, nor on the intensity of the toxic cloud.

For instance, each building has to be equipped with a system that quickly stops all voluntary airflows, which supposes an emergency circuit breaker on ventilation systems and devices to close rapidly the air inlets and outlets. The room used as shelter must respect a minimum size per occupant (1 m^2, 2.5 m^3). The heating system must be adjustable from the room. Toilets are compulsory in the shelter for non-residential buildings, but not for dwellings.

Secondly, the shelter's airtightness level must guarantee that the concentration in the shelter remains lower than the irreversible effects threshold (SEI) during 2 hours, for the considered toxic cloud.

During the elaboration of the PPRT, different zones are defined along with the severity of the effects (irreversible, lethal 1%, or lethal 5% effects) and types of pollutants. For each zone, a conventional toxic cloud (60 min duration) can also be defined.

Then, the maximum attenuation rate on concentrations A (Eq.1) is calculated, defined as the ratio between the threshold in the shelter and the concentration of the conventional outdoor toxic cloud. As a result, the maximum attenuation rate depends on the toxicity of the products, and on the severity of the effects caused by the toxic cloud. In case of several toxic products, the lowest attenuation rate is selected.

$$A(\%) = \frac{SEI(2h)}{C_{outdoor}(1h)} \quad (1)$$

With this, it is possible to calculate the airtightness level of the shelter that will be able to guarantee this maximum attenuation rate. For shelter-in-place issues, we use as an indicator the air change rate at 50 Pa: n_{50} (Eq.2, [5]). Pressure codes like CONFINE can be used, under conditions described in the guide [4].

Since 2005, we have developed CONFINE [6,7] a software that calculates the minimum airtightness level required for a shelter in order to maintain the internal concentration under a given limit. With CONFINE, we assume that any building can be modeled as a 3-zones building with a default envelope airtightness level: Q_{4Pa_surf}, the airtightness indicator in French Thermal regulation (Eq.3, [8]).

$$n_{50} = \frac{q_{50}}{v} \quad (2)$$

$$Q_{4Pa\_Surf} = \frac{q_4}{A_{Tbat}} \quad (3)$$

$q_{\Delta P}$: volumetric airflow through envelope leakage defaults with an induced pressure difference ΔP, between indoor and outdoor ($m^3.h^{-1}$)

V: internal volume of the tested zone (m^3)

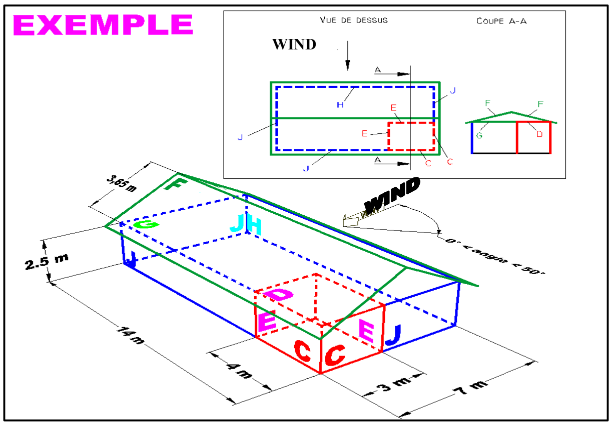
A_{Tbat}: total envelope area of the building, excepted ground floor area, according to the French thermal regulation (m^2)

Shelter-in-place airtightness requirements FOR dwellings

Airtightness requirement on an internal room envelope

The French Ministry for Ecology wished to avoid an airtightness calculation for each dwelling, which would result in an additional cost for individual owners. In this goal, we used CONFINE software to generate abacus, using “standard dwellings”, as presented hereafter. These abacuses deliver the shelter airtightness requirement (n_{50}) depending on the maximum concentration attenuation rate (Eq.1). They are includes in the guide [4] used by State departments responsible to design PPRT. As a result, PPRT-plans include, for each zone, airtightness requirements for dwellings, and not only the maximum attenuation rate, which is not directly applicable. Contrarily to non-residential buildings, there is no need to use modeling software such as CONFINE to define the shelter airtightness level of dwellings.

The “standard single-family dwelling” (Figure 1) has been considered in the abacus as a single level house, with a 98 m² ground floor and whose envelope airtightness level is estimated as the 95th percentile of the CETE airtightness database[7]: $Q_{4Pa\_surf} = 2$ m^3/h/m² (n_{50}=7.7 h^{-1}, considering V/A_{Tbat}=1.4 m).



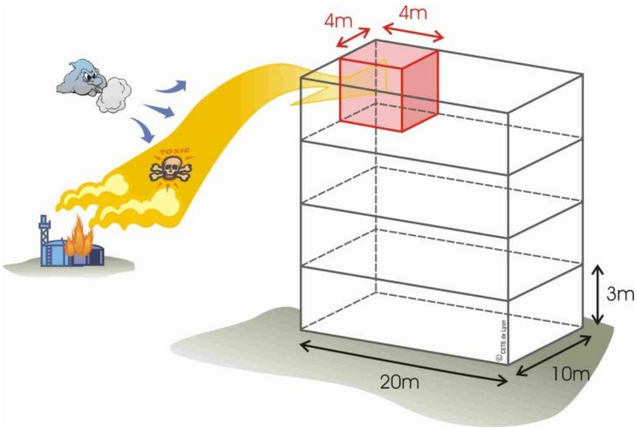
$V_{shelter}$ (m^3)	27
V_{attic} (m^3)	98
$V_{rest\ of\ the\ building}$ (m^3)	251
$H_{building}$ (m)	4.2
Slope of the roof (°)	25

Figure 1 and Table 1: Characteristics of the 3-zones “standard single-family dwelling”, with downwind shelter

The “standard multi-family building” (Figure 2) has been considered as a four-stories building, with an envelope airtightness level estimated following the 95th percentile of the CETE airtightness database on multi-family dwellings[8]: Q_{4Pa_surf}, = 3 m^3/h/m² (n_{50}=6.5 h^{-1}, considering V/A_{Tbat}=2.5 m).

[7] 217 single-family dwellings in 2007

[8] 190 multi-family dwellings in 2007



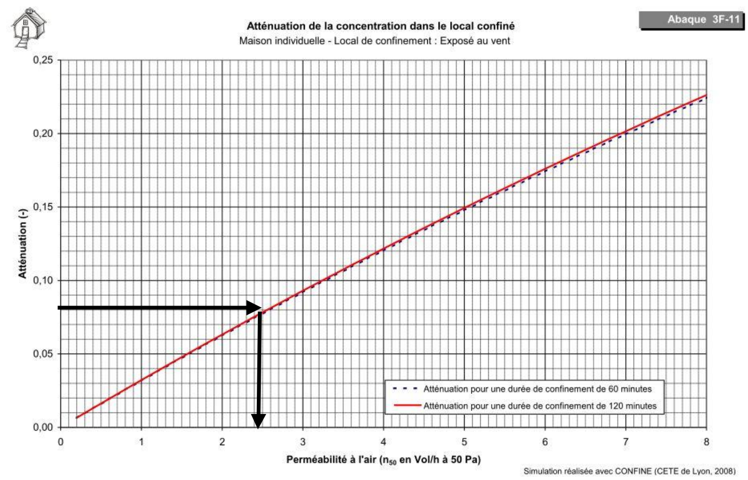
$V_{shelter}$ (m^3)	48
V_{attic} (m^3)	0
$V_{rest\ of\ the\ building}$ (m^3)	2352
$H_{building}$ (m)	12

Figure 2 and Table 2: Characteristics of the 2-zones "standard multi-family building", with upwind shelter

For both types of buildings, two configurations were studied depending on whether the shelter is down- or upwind.

Lastly, three wind velocities have been considered: 3-5-10 m/s.

As a result, we computed 12 abacuses (Figure 3), which are used by State services during technological risk prevention (PPRT) plans design.



	A = 8 %
	n_{50}
Upwind shelter, v=3m/s	2.5 h^{-1}
Downwind shelter, v=3m/s	> 8 h^{-1}
Upwind shelter, v=5m/s	1.3 h^{-1}

Figure 3 and Table 3: Example of use of "standard single-family dwelling" abacus for shelter airtightness requirement establishing

Measurement requirements

For every building, air leakage level of the shelter must also be measured after constructive works have been implemented, including works on ventilation systems.

As it was shown in Rolfsmeier et al.'s paper [9], there can be misinterpretations of the measurement protocol and analysis, with consecutive errors in the estimations of derived quantities that are used in the calculation method. As a consequence, the French Ministry for Ecology decided that the air leakage measurers will have to be authorized to perform such measurements, and has streamlined a procedure in this goal. This procedure described in a paper [10] concerns measurements in the field of low-energy labels and of the new French thermal regulation (RT2012). On September 2012, around 400 persons have been authorized.

In the PPRT plan, buildings owners are encouraged to work with those authorized measurers. A special measurement protocol has been developed and published [11].

In order to accompany the market transformation in this field, we have conducted a free training program for authorized measurers, including information on the PPRT context and the shelter-in-place strategies, and works to be realized on buildings. On September 2012, around 80 persons have been trained. The list of the trained professionals is maintained on a website[12] and largely distributed to State organizations and local authorities.

Collected data

Context

During the working out of each PPRT, shelter-in-place studies may be implemented by local State organizations, in order to get information on the vulnerability of the territory, and have an idea on the financial impact of the PPRT.

For selected dwellings and with their owners' agreement, a free-of-charge vulnerability diagnostic may be realized, supported by the Ministry for Ecology, including an air leakage measurement. In those cases, measurements are performed before any constructive work has been done. Thanks to these diagnostics we were able to collect data and to generate a small database.

Description of the database

In September 2012, data from 140 measurements performed between 2008 and 2012 on 95 single-family dwellings and 45 multi-family dwellings were collected.

For each dwelling, the database includes the location, the type of dwelling (single-family or multi-family), ground floor area and volume of the shelter, required and measured airtightness of the shelter. Year of construction and envelope airtightness level are sometimes given.

First analysis

Airtightness measurements on internal rooms give results from n_{50}=0.7 h^{-1} to 30.7 h^{-1}, with a median value of 6.1 h^{-1} and a mean value of 8.0 h^{-1}. A first analysis in terms of cumulative frequency shows that 95% of the tested rooms have an air leakage level under n_{50}=22 h^{-1}.

Figure 4 shows that it is much higher for single-family dwellings (n_{50}=22 h^{-1}) than for multi-family dwellings (n_{50}=17 h^{-1}). For 6 cases, we were able to compare the airtightness of the shelter to the envelope airtightness of the dwelling (Table 3). For one case only, shelter envelope is tighter than dwelling envelope. Internal rooms are rarely designed to be tight because there is rarely an energy issue, even if acoustics or IAQ problems could contribute to design airtight rooms. On the field, we often observe that high air leakage is due to a leaky internal wall: for instance wood intermediate floor without concrete slab.

We observe also that year of building's construction, volume and ground floor area of the shelter have no influence on its airtightness level.

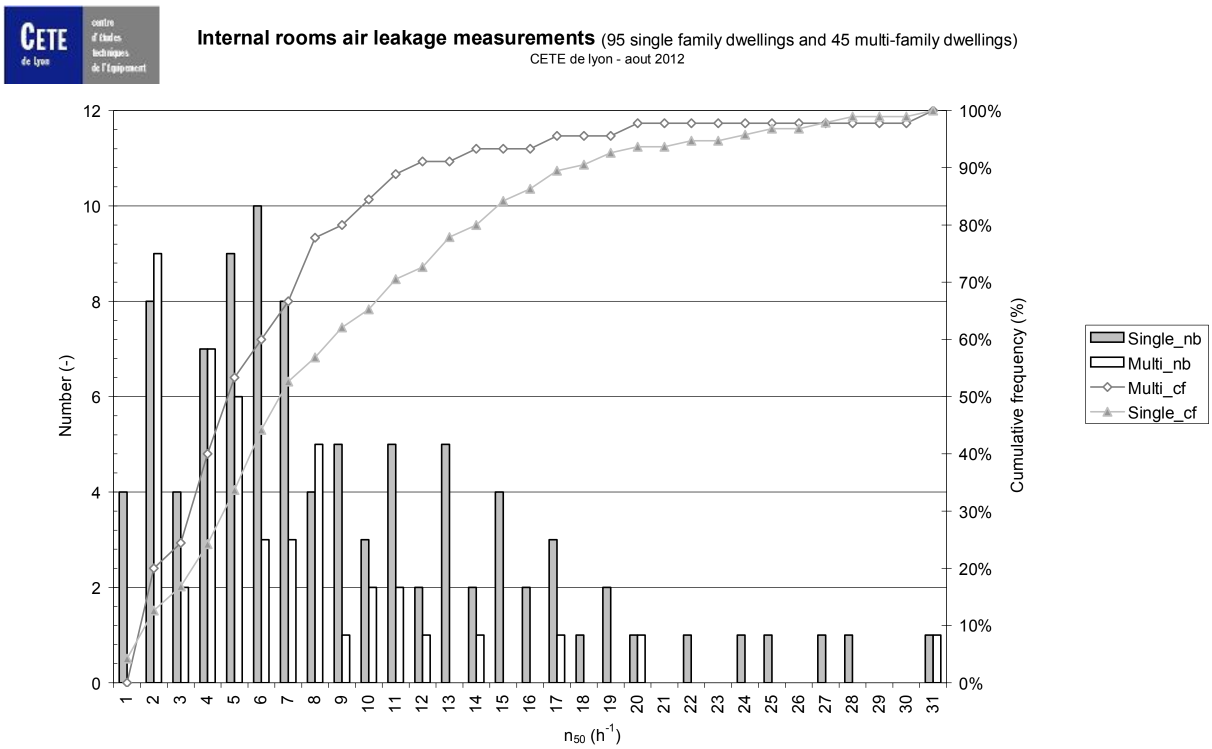


Figure 4: Internal rooms air leakage measurements on 140 dwellings. Cumulative frequencies.

Type of dwelling	n_{50} room (h^{-1})	n_{50} enveloppe (h^{-1})
Single-family	5.5	8.2
Single-family	6.9	5.0
Single-family	13.3	10.3
Single-family	15.8	8.0
Single-family	20	9.0
Multi-family	3.1	2.6

Table 4: Comparison between internal and envelope airtightness levels

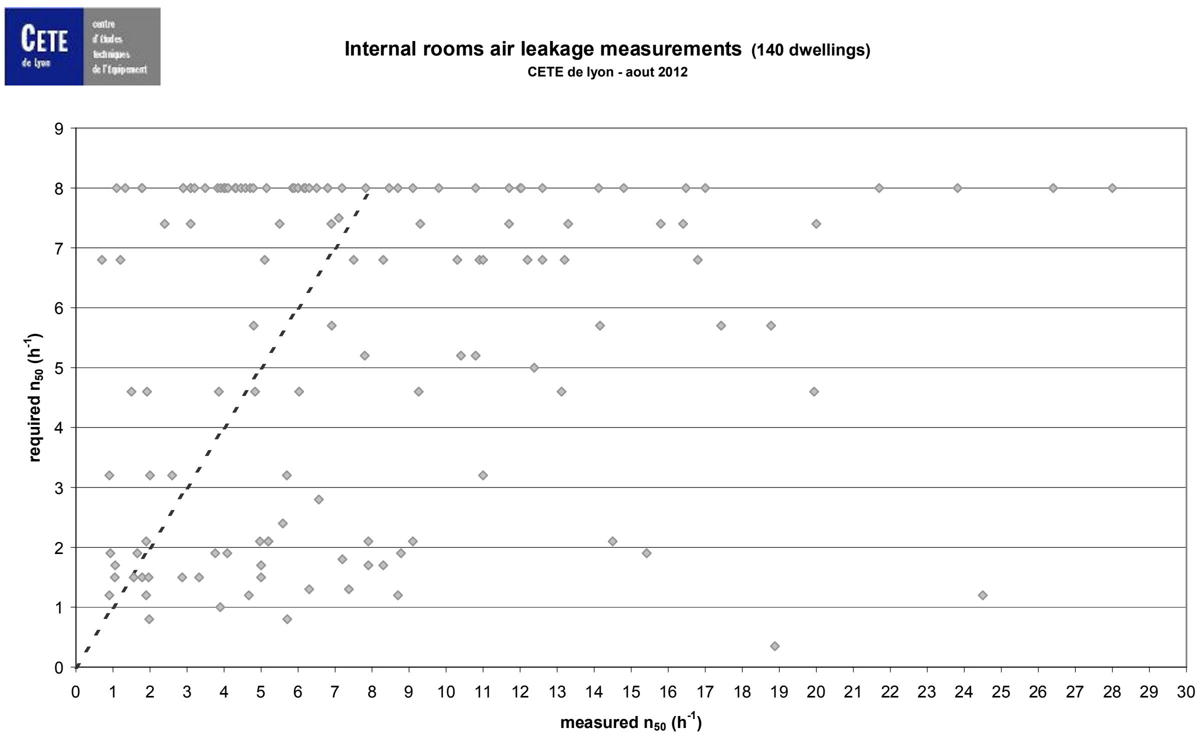


Figure 5: Internal rooms air leakage measurements on 140 dwellings. Difference between airtightness requirement and measurement

As a result, 60 % of the tested shelters have lower performance than expected (Figure 5). In those cases, private individuals have to perform constructive works in the room in order to achieve an airtightness level, which will guaranty their protection. On the other size, a significant number of shelters are tight enough (40%). In those cases, buildings owners would just have to do works to respect general constraints on the whole building and on the room used as a shelter (e.g. a system to quickly stop all voluntary airflows).

Conclusion

When all PPRT plans will be promulgated, we expect to have a database of about 1000 airtightness measurement of shelters. Later on, it will be more difficult to collect these data because each dwelling's owner will order its own measurement.

Analysis of this database allows us to estimate the territory vulnerability around Seveso facilities in France and overall cost consequences of this public policy.

This database is also a good opportunity to collect precise information about internal air leakage in dwellings. These experimental data can be used as inputs in multi-zone airflow and pollutant transfer model, when data on internal airtightness are needed to study inter-zone airflows.

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CHECKING "FABRIC FIRST" REALLY WORKS: IN-CONSTRUCTION TESTS USING THERMOGRAPHY

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Abstract

The UK Government strategy for all new homes to be built to zero carbon standards by 2016 is based upon a "fabric first" approach to design. This means prioritising energy efficiency improvements to the building envelope through: increasing overall levels of insulation; reducing thermal bridging; and making buildings more airtight. However, recent research has raised concerns about the standards that are actually achieved in the construction of new housing. More robust quality assurance procedures for construction work may be required to ensure that energy efficiency targets are met in practice. One potential approach is the use of thermal imaging (thermography) to inspect new buildings at different stages during the construction process. The effectiveness of this technique has been tested during the construction of two affordable housing projects in Swansea, UK. Thermal performance issues were identified at both of the schemes, including infiltration through the building envelope and poor insulation of ductwork for mechanical ventilation systems. The results of these two case studies illustrate some practical considerations for the application of the thermography technique and also shortcomings in the current approach to determining compliance with energy performance requirements in UK Building Regulations. This research topic will be of interest to housing developers, built environment professionals, thermographers and researchers interested in methods of investigating the thermal performance of new housing.

Keywords

Thermography, performance testing, construction process, low carbon housing, Building Regulations

Introduction

In the 'Building a Greener Future' policy statement of 2007, the UK Government announced proposals for all new homes to be built to “zero carbon” standards by 2016 [1]. These standards are to be based upon a “fabric first” approach to design, which means prioritising energy efficiency improvements to the building envelope through: increasing overall levels of insulation; reducing thermal bridging; and making buildings more airtight [2]. As the UK construction industry moves towards full implementation of the 2016 zero carbon target, a series of small-scale research studies have raised concerns that significant discrepancies can exist between the predicted energy performance of a new home as calculated at the design stage compared to the actual performance of the completed building – with evidence of significant under-performance in some cases [3]. This phenomenon is widely referred to within the industry as the “performance gap”. The extent of concern is such that, in a recent consultation on changes to Building Regulations in England, the Government acknowledged that *“the risk of wider scale underperformance cannot be ignored and that the potential performance gap could be very significant”* [4].

The main focus of this paper is the relationship between construction quality and performance testing in the delivery of low carbon homes in the UK. Specific consideration is given to the use of thermography as a quality control test for fabric energy efficiency and quality of workmanship during the construction of new housing. It is proposed that conducting tests at appropriate points during the construction process (or ‘in-construction testing’) will help support the management of construction quality and increase confidence that design targets for thermal performance will be achieved in practice [5, 6]. Moreover, it is advantageous if defects can be identified through testing within a reasonable timescale prior to completion, since remedial work can become increasingly costly and disruptive once a building is occupied. The practical experience of the authors has shown that some specific considerations apply to conducting thermographic surveys on a construction site. However, a literature review has identified a lack of detailed guidance on the effective application of thermography in this context (e.g. [7–12]). Having identified this gap in existing knowledge, an approach has been developed for in-construction tests using thermography. The main elements of the testing approach are shown in Figure 1.

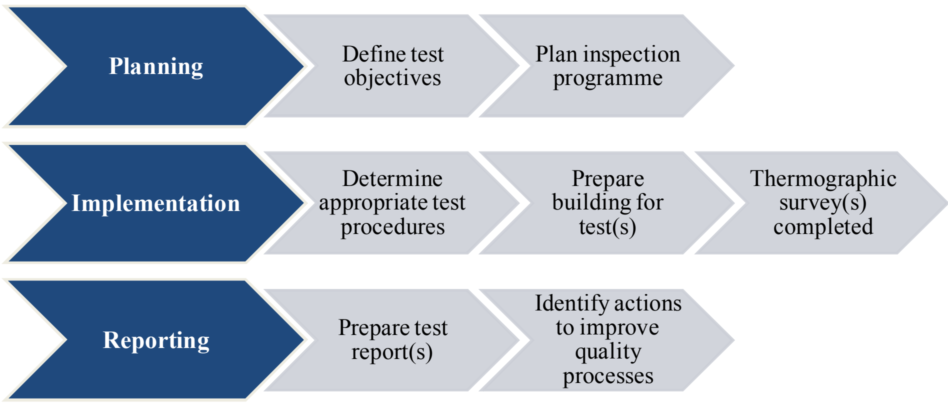


Figure 1: Main elements of the testing approach.

The content of the paper is organised into three main sections as follows:

1. Performance testing and UK Building Regulations
2. Examples of construction defects detected using thermography
3. Introduction to testing approach

Performance testing and UK Building Regulations

Levels of compliance with energy efficiency requirements are reportedly a "weaker area" of UK Building Regulations [13]. A report commissioned by the Department for Communities and Local Government 'Performance Testing of Buildings' [14] reviewed the scope for additional performance tests to check compliance with the requirements of the Regulations. The report concluded that: *"To be useful, pre-completion performance tests must be quick and inexpensive. They must not delay occupancy, or have to be carried out after occupancy when they may become impracticable"*. In a previous publication, Taylor et al. [5] argued that the 2016 zero carbon target will likely result in a significant shift in the procedures and practices of Building Control[9] and, furthermore, that new approaches to testing in-situ performance would need to be developed. In the next section of the paper, this argument is developed further with reference to two case studies where in-construction thermography tests revealed performance defects in low carbon housing projects. The tests conducted at these case studies illustrate the limitations of pressurisation testing as a means of verifying that construction quality is consistent with the predicted energy performance of a building.

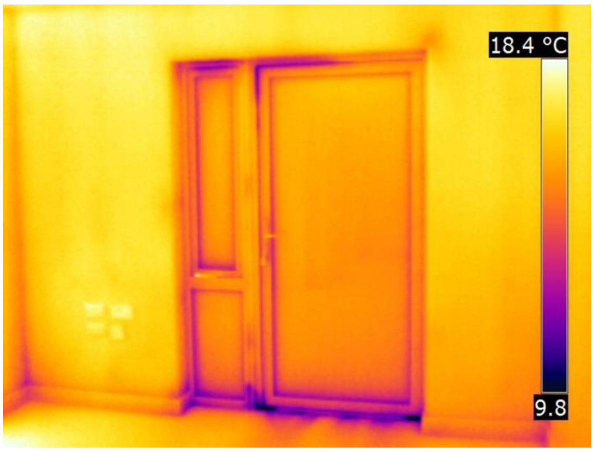
[9] In the UK, Building Control Bodies have the responsibility for checking compliance with Building Regulations.

Examples of defects detected using thermography

Case Study A test results

The environmental design strategy at Case Study A (a block of 69 flats in timber frame construction) was developed with an assumption that the building would be constructed to high standards of airtightness (achieving an air permeability of 3.0 $m^3/h.m^2$ at 50Pa). To determine if this level of performance was likely to be achieved in practice, one of the flats in the development was brought to a more advanced stage of completion so that a pressurisation test could be carried out at an early stage of the construction process. The result of this test showed a measured air permeability of 1.09 $m^3/h.m^2$ at 50Pa had been achieved – a significant improvement on the design target. However, masking tape was used extensively to seal around openings and sockets prior to the pressurisation test. The use of temporary seals in this way is not permitted according to the testing protocol that is specified in the Building Regulations: *"All external doors and windows should be closed (but not additionally sealed). This includes door thresholds"* [15]. A thermographic survey of the flat 14 months later showed extensive air leakage around the balcony doors as shown in Figure 2 below.

(a) Photograph taken of balcony doors in living room of test flat at time of thermographic survey



(b) Thermal image of balcony doors corresponding to photograph (a)

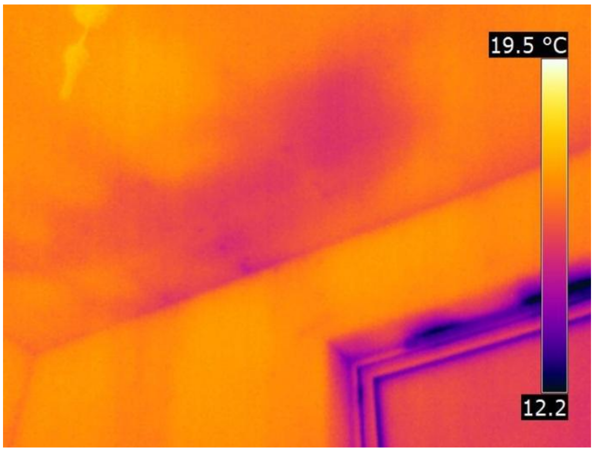
Figure 2: Thermal images of flat in Case Study B.

The masking tape applied around the balcony doors before the pressurisation test effectively concealed these locations of air leakage[10]. On this basis, the pressurisation test result is unrepresentative of actual performance and higher levels of infiltration may mean

[10] It should be further noted that the pressurisation test was not performed as part of mandatory testing and the test result was not used to determine compliance with Building Regulations.

that the energy performance of the flat is less than predicted. The wind pressures that caused the air leakage observed in Figure 2 can also result in other types of heat loss. In the same flat, a thermographic survey indicated a localised surface temperature decrease in the ceiling of one of the bedrooms. The area of the ceiling where this was observed corresponds with the location of an extract duct for the mechanical ventilation unit. It follows that a possible explanation of this thermal pattern could be wind penetration above ceiling level around a poorly-sealed or damaged duct air terminal. This type of defect would contribute to heat loss but does not constitute an infiltration mechanism. It would therefore not be detected by a pressurisation test (this is also the case for thermal bypass caused by "wind-washing" [16]).

(a) Photograph taken of the junction between the wall and ceiling above a window in one of the bedrooms of the test flat



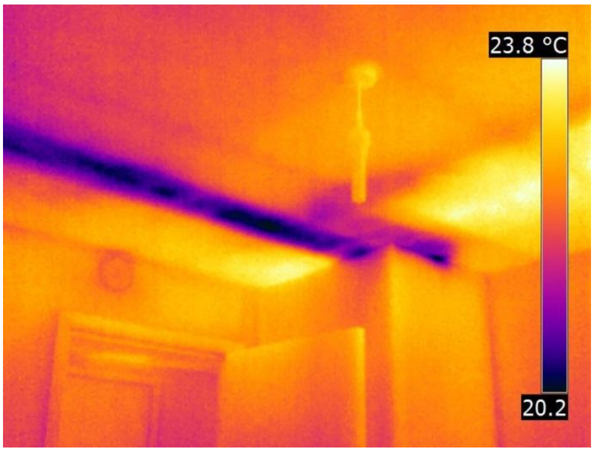
(b) Thermal image shows localised surface temperature decrease in ceiling area corresponding with the position of the extract duct for the mechanical ventilation unit

Figure 3: Wind cooling effect observed in ceiling below mechanical ventilation extract duct.

Case Study B test results

At Case Study B (a block of 32 flats, part new build and part refurbishment) the ventilation strategy utilised mechanical ventilation heat recovery (MVHR). A thermographic survey in one of the top floor flats indicated that the inlet duct for the MVHR unit was not correctly insulated as shown in Figure 4 below. Poor installation of the MVHR ductwork will reduce the energy performance of the dwelling.

(a) The reduced surface temperatures along the ceiling follow a linear pattern corresponding with the position of the MVHR unit ductwork



(b) The MVHR unit is located in a storage cupboard adjacent to this corner of the room

Figure 4: Insulation not continuous around MVHR ductwork.

Summary of case study results

The case study results illustrate how thermography can be used to identify: air leakage around window and door openings; wind penetration through the external leaf, or "wind-washing"; and poor insulation of ductwork. In these cases, low standards of workmanship and poorly performing building components were not identified by pressurisation testing. At Case Study A the effect of air leakage around window and door openings would not have been measured by pressurisation testing because the preparation of the building deviated from standard test protocols. Although one example cannot be considered representative of wider industry practices, it does indicate the sensitivity of pressurisation test results to correct site test procedures. The risk of making unrealistic assumptions about the airtightness of the building envelope based upon a pressurisation test result is not only important in the context of demonstrating compliance with Building Regulations – it also has implications for the design of heating and ventilation systems. This emphasises the importance of a holistic approach to environmental design; encompassing design, construction and maintenance practices. For designs that include provision for passive means of ventilation, current approaches to performance testing could be extended by carrying out pressurisation testing with vents sealed and then repeating the test with vents open to calculate an in-situ 'equivalent area' of the open vents. This approach could be use to verify design assumptions for background ventilation rates [14].

In-construction tests using thermography

The testing approach follows a process illustrated in Figure 1 comprising three main stages: planning, implementation and reporting. The main purpose of in-construction testing using thermography is to assess the continuity of insulation and identify air leakage paths in the test building. The testing approach is generally consistent with the requirements of BS EN ISO 13187:1998 for simplified testing with an infra-red (IR) camera [10] and is intended to be applicable to all dwelling types. However, practical experience has shown that some specific considerations apply to conducting tests effectively during the construction process and this is reflected in the test procedures outlined in the following sections of the paper. Firstly, it is useful to outline some general principles which help to determine the most appropriate approach to testing:

- Location of insulation layer(s) within the building structure

For assessing the continuity of insulation, it will be advantageous if the insulation layer is positioned close to the surface of the construction that is being inspected. Defects within the insulation layer will have two effects when the building is heated: increased heat loss and reduced internal surface temperatures [17]. This localised decrease in surface temperature is the basis on which defects can be identified using thermography. A defect appears more obvious during a thermographic survey when the insulation layer is located closer to the inspected surface because the contrast between the thermal pattern of the defect and the surrounding structure is enhanced. To verify that the insulation layer has been correctly installed, if follows that the optimal time to survey the building is once the insulation layer has been fixed and covered over, but before any finishes have been applied. Surveying the building at a later stage of the construction may involve additional re-work if partial deconstruction is required to repair a defect.

- Completion of airtightness layer during the construction process

The airtightness of the building envelope is ideally tested early once the build has been completed up to the airtightness layer and windows and doors are in place (or at least can be temporarily sealed) [18]. Thermography can be used to identify the location of leaks within the envelope if testing is carried out in conjunction with a fan pressurisation test. It may also be useful to conduct tests when the building is exposed to strong prevailing winds (without mechanically pressurising the building). In this case, wind pressures will cause air movement through any leaks in the envelope and it may also be possible to observe "wind-washing" effects. Testing under these conditions may enable the identification of defects that are more significant in terms of the actual performance of the building in use.

Planning

Certain forms of construction will be more amenable to thermographic testing. This is illustrated with reference to three external wall construction types given in Table 3 below. These forms of construction were selected on the basis that they have been developed to reflect good practice in fabric energy efficiency and represent the main construction types often specified in UK housing.

Construction type	Type code	Description
Timber frame	TF01	140mm fully filled timber frame, sheeted externally, air barrier/vapour control layer and insulated lining internally. Service void and plasterboard. Clear cavity with brick outer leaf.
Cavity masonry	MV01	100mm block inner leaf internally plastered. 150mm fully filled insulated cavity. Brick outer leaf.
Light steel frame	SF01	70mm fully filled light steel frame, sheeted both sides, air barrier/vapour control layer. Service void and plasterboard. Partially filled insulated cavity with brick outer leaf.

Table 3: Energy Saving Trust Enhanced Construction Details [19].

- **Timber frame external walls (TF01):** An initial thermographic survey to check the continuity of insulation would ideally be carried out once the insulated lining is fixed to the timber frame (enclosing the insulation between the studwork). The purpose of this initial survey would be to confirm that the insulation between the studwork has been correctly installed before the insulated lining is covered over with plasterboard. Either an internal or external survey would be effective for this first test. However, an internal survey is likely to be more appropriate since it allows greater flexibility with respect to the timing of the test[11] and the external envelope may also be obscured by scaffolding. At this stage of the construction process the building heating systems would not have been installed and commissioned and so an alternative method of heating the building would need to be adopted for the test. A second survey would usefully be carried out in conjunction with a pressurisation test to identify locations of air leakage through the building envelope once the heating, plumbing and electrical services have been installed (to check the effectiveness of sealing around the building services).

- **Masonry Cavity external walls (MV01):** An initial thermographic survey to check the continuity of insulation within the cavity is ideally carried out once the building is weathertight but before a parge coat is applied to the internal face of the inner leaf. Either an internal or external survey would be effective for this first test. If any defective areas of insulation are identified then repair work may necessitate partial deconstruction of the inner or outer leaf. A longer heating period would be required in comparison to the testing of timber frame structures because of the thermal mass of the block inner leaf. Once the plasterwork has been applied to the internal leaf (this effectively acts as the airtightness layer), a second survey would be usefully carried out in conjunction with a pressurisation test to identify air leakage.

- **Light steel frame (SF01):** As with the timber frame external wall type, an initial survey would ideally be carried out to check the continuity of insulation between the

[11] The best conditions for external surveys are found during the night, sometime after sunset, when the effects of direct solar radiation on the surface temperature distribution of the external envelope can be discounted.

studwork once the sheeting has been fixed to the internal face of the steel frame (before it is covered over with plasterboard). Thermography will be less effective for checking the continuity of the insulation within the cavity since any discontinuities in this insulation layer will be difficult to detect from either an internal or external survey. This is because the intermediate layers of the external wall structure will reduce the effect the defect has on the internal and external surface temperatures. In this case, supervision of the construction process becomes increasingly important to ensure the insulation is securely fixed back to the inner leaf to prevent air from circulating around the insulation. A second survey would usefully be carried out in conjunction with a pressurisation test to identify air leakage.

Implementation

The interpretation and reliability of thermographic testing is facilitated by a stable pattern of heat flow through the building envelope and a sufficiently large difference between internal and external temperatures so that surface temperature variations are detectable. Pearson [8] recommends a minimum temperature difference of 10°C between internal and external temperatures for thermal performance surveys. Wahlgren & Sikander [18] state that a temperature difference of at least 5°C is acceptable for surveys to identify air leakage. Prior to testing, the building may be heated using either electrical fan heaters, radiant heaters or the building heating system (if this has been installed and commissioned). A decision tree for selecting the most appropriate approach is given in Figure 5 below. However, experience indicates that a useful daytime temperature difference can be obtained through solar gain alone for internal surveys and thus in some circumstances it may be possible to identify defects in the building envelope without providing supplementary heating.

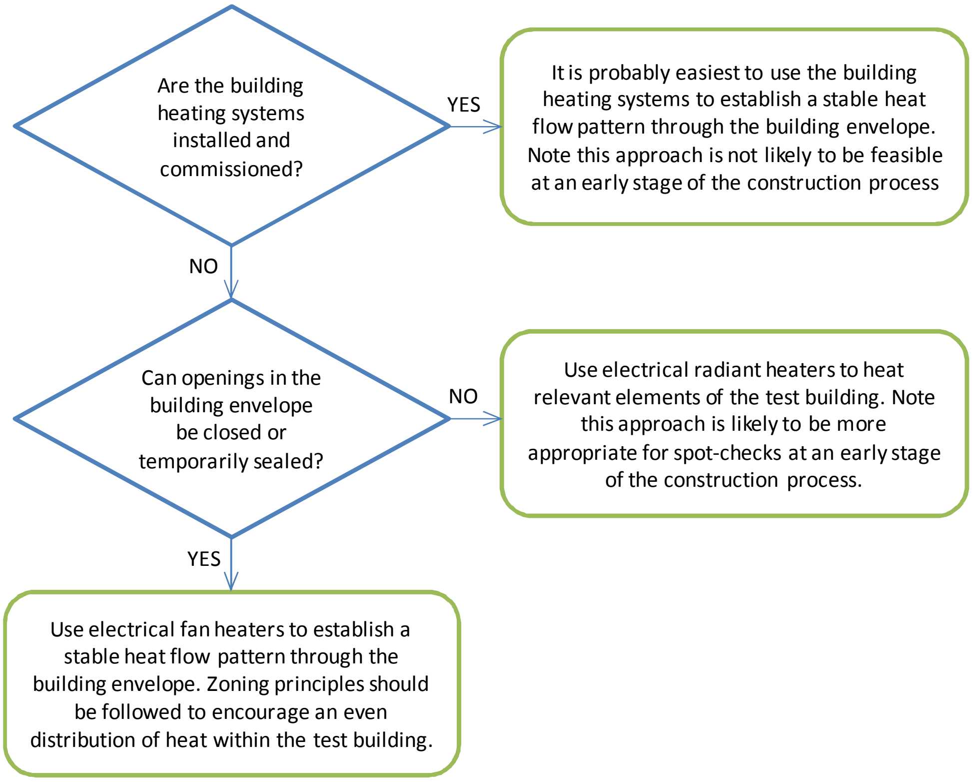


Figure 5: Decision tree for selection of heating method.

In outline, testing consists of two stages as follows:

- **Pre-test requirements:** to prepare the building for testing, including a walkthrough of the test building and the installation of heaters and other equipment (if required).
- **Site test procedure:** the process of examining thermal patterns on the internal and/or external surfaces of the test building.

The pre-test requirements are as follows:

1. Select a heating approach using the decision tree in Figure 5.
2. It is preferable to commence heating of the test building at least 24 hours before the inspection. However, a shorter heating period may be adopted if it is not possible to obtain access or permission to operate the heaters outside of normal site working hours. In this case, the number and/or power output of heaters may need to be adjusted to compensate for the reduced heating period.

   If using electrical fan heaters:

- Install 110V electrical fan heaters in the test building[12]. The power output and number of heaters required will depend upon the configuration of the building. The placement of circulation fans in appropriate locations to encourage air movement may assist with achieving a more even temperature distribution.
- *If using electrical radiant heaters:*
- Install 110V electrical radiant heaters in the test building. It may be necessary to adjust the distance of the radiant heater from the target building element and also the angle of inclination of the heater element to the building surface to achieve an even heating profile. The IR camera can be used to assist with this process. Care should be taken not to point the IR camera directly at the radiant heater when it is switched on as this may damage the detector.
- *If using building heating systems:*
- Adjust the heating controls in the test building according to the instructions provided by the manufacturer.

3. Prior to switching on the heaters, all external doors, windows and trickle vents should be closed. Internal doors should be fully opened and restrained (if necessary) to encourage an even distribution of heat within the test building.
4. If the inspection personnel are on site before the heaters are to be switched on then this may be an appropriate point at which to conduct a walkthrough of the test building. The walkthrough presents an opportunity to record visual images, taking note of any factors that may influence heat flow through the building envelope (e.g. service penetrations), and review health and safety issues with the site manager and/or other responsible person(s).
5. If a meteorological station is located in close proximity to the test building then this may be a convenient way of noting the local weather conditions during the 24 hours preceding the survey. Temperature and humidity sensors may also be installed in appropriate internal and external locations if required. All surfaces to be inspected during the survey must be dry and therefore any precipitation in the 24 hours preceding the survey is likely interfere with surveys of the external facade of the test building.

The **site test procedure** is as follows:

1. The external air temperature, external relative humidity (RH) and wind speed should be recorded at the start of the survey using a suitably calibrated environment

[12] Note the Health and Safety Executive (HSE) recommends a reduced low voltage 110V supply system for all portable electrical equipment used on construction sites in the UK. Further information is provided in BS 7375:2010 Distribution of electricity on construction and demolition sites – Code of practice.

meter (with thermometer, hygrometer and anemometer functions). The air temperature and relative humidity inside the test building should also be recorded. Ideally, these measurements should be repeated at the end of the survey.

2. Thermal patterns should be examined using the IR camera on the internal surfaces of the test building and/or all aspects of the external facade (unless radiant heaters are used, in which case only the relevant element of the building envelope need be inspected). Particular note should be taken of windows and any joints in the construction (e.g. wall-ceiling junctions). Any areas of special interest and any thermal irregularities should be studied in detail. Written or audio notes should be taken to accompany the thermal images recorded during the inspection to aid the interpretation of results.

Reporting

The results of the survey should be presented in a report including a description and interpretation of the thermal images recorded during the survey, and preferably accompanied with corresponding visual images. Recommendations for the detailed content of the report are given in Pearson [8] and BS EN 13187:1999 [10].

Conclusions

The UK Government expects carbon savings to be delivered by increasing the energy efficiency of new housing to zero carbon standards. However, a growing body of evidence for a potential "performance gap" suggests that planned carbon savings may not be delivered in practice. Underperformance poses a reputational risk to the UK construction industry, as Government carbon reduction targets may be undermined and householders may not benefit from the expected savings in their energy bills. This paper has developed an argument for extending current industry practices for in-situ performance testing of new housing to help address these risks. A testing approach using thermography to check the continuity of insulation and locate air leakage in the building envelope is outlined in the paper. Existing literature on thermography does not provide detailed guidance for the effective implementation of testing during the construction process. The testing approach, which is being developed as part of a PhD research programme at Cardiff Metropolitan University, seeks to address this gap in existing knowledge. The main benefit of 'in-construction testing' is that defects can be identified at an early stage of the construction process when it is likely to be easier and less costly to carry out any remedial work that may be required. Therefore, thermography is potentially a useful complement to pressurisation testing, and the use of both techniques together could provide a more representative assessment of fabric energy efficiency and quality of workmanship in residential construction projects.

Acknowledgements

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LESSONS LEARNT FROM THE REGULATORY QUALITY MANAGEMENT SCHEME FOR AIRTIGHTNESS IN FRANCE

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Abstract

From January 1st 2013 on, the French energy performance regulation will demand that the airtightness level is justified and that airtightness of a building should be below 0,6m^3/h/m² at 4Pa for single family housing and 1m^3/h/m² for multi-family dwellings, resulting into an important growth in the airtightness market. It is the role of the State to accompany this market evolution and to supervise the quality of airtightness measurements used for the EP calculation. This is why it has been decided that there are two possibilities to justify the airtightness level of a building. Either the constructor makes a systematic measurement of their building or the constructor proves they have a quality management approach so that more than 85% of their production reaches the wanted airtightness.

In order to ensure the quality of the quality management schemes for airtightness, a specific committee on delegation of the French Ministry in charge of Construction has been created. Its goal is to authorize constructors to justify an airtightness level by a quality management scheme. The CETE de Lyon is in charge of this committee.

This paper deals with the role and preliminary results of the committee and discusses the advantages and issues raised by such authority, as seen so far, thanks to the experience gained by the CETE de Lyon on these matters. Preliminary results show an improvement in the airtightness levels reached by authorized constructors in comparison to levels reached without any quality management approach. Flaws in the control process and biased tests show several possibilities for the State to improve the frame of this authorization.

Keywords

Envelope airtightness, quality management

Introduction

With the future obligation to prove a certain level of compliance with the French Energy Performance Regulations, airtightness has got a key role in the construction field. Indeed, the application of the 2012 EP regulation demands that buildings comply with an airtightness level below 0,6m^3/h/m² at 4Pa for single family housing and 1m^3/h/m² for multi-family dwellings. To prove the compliance, a constructor has two choices. Either they make a systematic measurement of their buildings or they prove by hand of a quality management scheme for airtightness that their production has the wanted airtightness. Until December 31st 2012, a 85% compliance of the building production is accepted.

This paper deals with the role of this committee and discusses the advantages and issues raised by such authorities. This paper also presents the results of a state driven control campaign. This paper will hence try to give some answer to the question: is it worth it to implement such a procedure for quality management schemes?

Regulatory quality management scheme

Context

As described in Leprince 2011, quality management process for airtightness of buildings has been set up in order to improve air tightness treatment during all design and construction stages and in order to spread good practice among professionals.

The French 2005 energy performance regulation introduced the possibility to use an airtightness value lower than the default value in the EP-calculation. This possibility is given only if a measurement proves the lower airtightness value or if the constructor follows a State authorized quality management procedure for airtightness, without systematically performing a test.

Soon, the 2012 energy performance regulation, applicable from January 1st 2013 for housing, makes the airtightness test compulsory. The quality management scheme gives the applicants the possibility to reduce the amount of compulsory tests at commissioning since only a fixed amount of dwellings, representative of the production has to be tested. It gives also the possibility to make energy performance calculations with an airtightness factor lower than the regulatory 0,6 m^3/h/m².

Requirements

Applications are sent to a specific committee dealing with the quality management procedure in airtightness. Any application has to include basic requirements linked to quality management approach, tests on a sample of the production and training documents focusing on airtightness destined to co-workers and craftsmen. Furthermore, some documents have to be submitted to the committee, among others:

- Identification of the chain of liabilities: who does what and when
- Description of the approach applied to the company
- Description of the design characteristics of the buildings on which the quality management approach applies
- Results of tests on a sample of the buildings production proving that more than 85% of the tests are below the target airtightness value. After January 1st 2013, all dwellings built hence 100% of the sample has to comply.

The 2012 quality management process will also require all documents produced in the frame of the quality approach for randomly selected buildings.

Self declared results obtained by approved companies in 2011

So far, the committee received follow ups from a dozen of applicants implementing a 2005 quality approach. The follow ups included bar charts of all measurements performed internally. The following figures are the results of the very first analysis performed on this data.

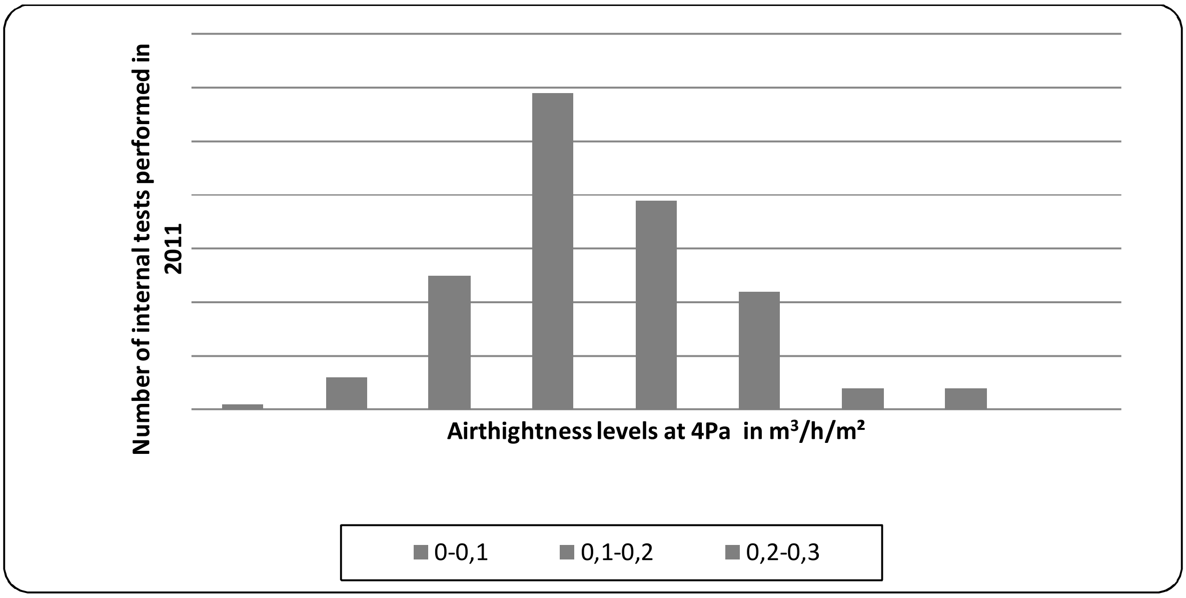

Figure 1: Bar chart of all self-declared results (follow-up 2011) N=160

Figure 1 presents a sum up of all self-declared test results made in 2011 by all constructors that had been authorized in 2010. Obviously, the results in Figure 1show that every single building tested by these 14 constructers scored below the Q_{4Pa_surf} target of 0,8 $m^3/h/m^2$. The bar chart also shows a normal distribution.

Controls by state technicians

The results presented in Figure 1 are based on measurements performed by State authorized testers, commissioned by the applicants. Noteworthy is that these testers are not necessary independent of the applicant. Indeed, applicants get advice from ISO9001 bodies working in the field of airtightness that audit the applicants and most likely also test the production of the applicant. The independence of the measures is therefore not guaranteed.

To avoid such a bias, the committee started in 2011 a control campaign. Every year, each applicant is asked to hand in a list of all buildings expected to be delivered in the coming year, including date of commissioning, name and address of the client. If the applicant is reluctant to give the demanded information, the applicant might see his agreement suspended.

Then a state technician performs control tests on randomly selected buildings. The amount of buildings tested aims at covering more than 5% of all buildings delivered. As of September 2012, 74 control measurements have been performed, whereas 99 had been planned. It represents so far 3,7% of the yearly production of all constructors. Further tests are still expected.

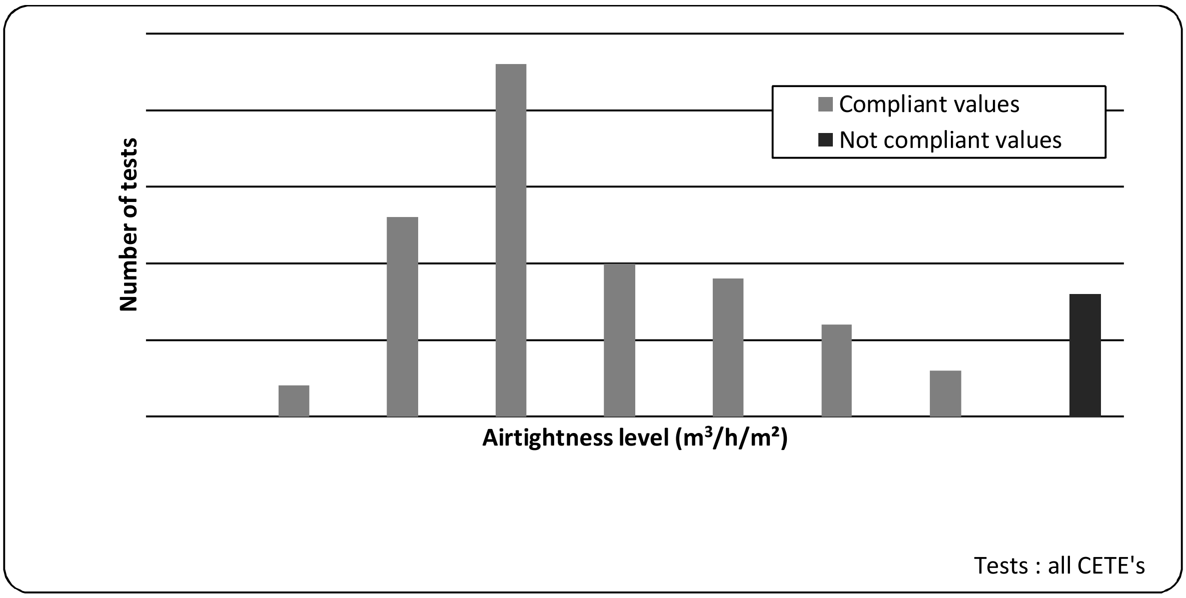

Figure 2: Bar chart of airtightness levels from the control campaign, compliance to the target level

Figure 2 shows a bar chart of all airtightness values measured by State technicians. From Figure 2 can be inferred that if most of the tests show a result lower than the target airtightness level, a few are above the wished Q_{4Pa_surf} of 0,8m^3/h/m². In the dwellings showing a higher airtightness measure, the leaks are mainly located around water and gas ducts, around boxes integrating roller shutters and window frames. Other leaks are due to a misunderstanding of the constructor of the moment of commissioning. Indeed, some constructors leave the possibility to the client to do a part of the building works themselves, for example installing toilets or a wood-burning stove. So when the dwelling is handed in to the client, these elements are not installed. Since they do have an influence on airtightness, it explains part of the high airtightness results obtained. This specific point is then contradictory to the constructor's goal to guarantee an airtightness level of the building in normal use conditions.

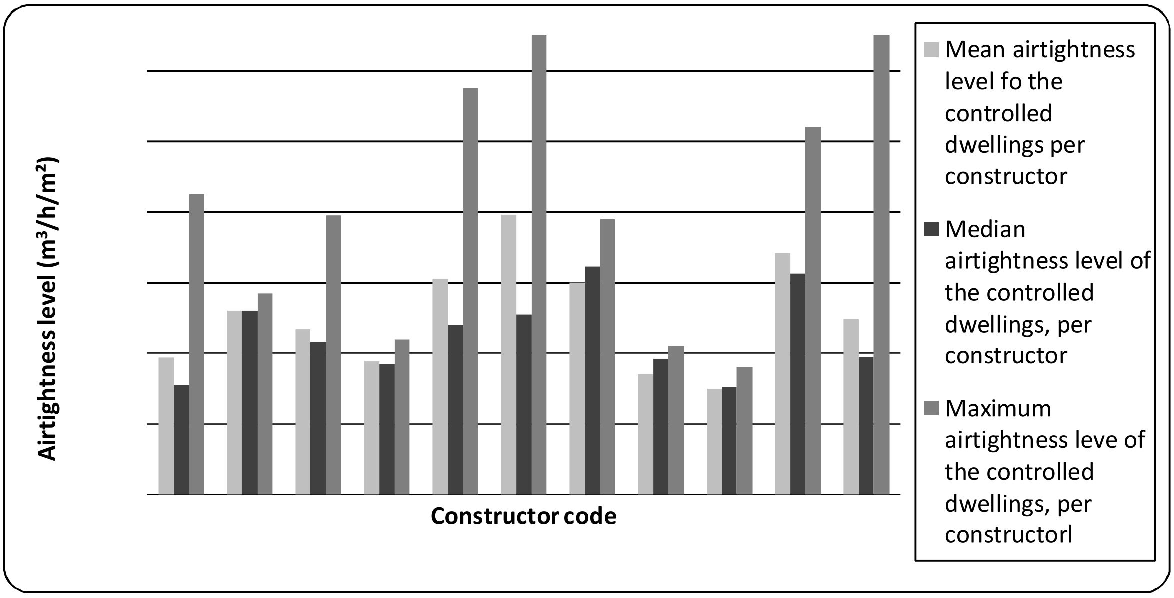

Figure 3: Bar chart of the mean, median and maximum airtightness values from the control campaign, per constructor [Maximum value of constructor 6 is above 1m^3/h/m² and is out of the scale of the chart]

Mean and median values showed in Figure 3, all under the 0.8 m^3/h/m², corroborate the results implied from Figure 2. However, this means that some constructors have been controlled with frequent too high airtightness results, whereas other constructors comply at 100% to the target level. A particularly problematic point in this chart is that one of the constructors showed control results above 1.3m^3/h/m², which is above the default value of the Energy Performance Regulation 2005 and which is a specific requirement to be respected.

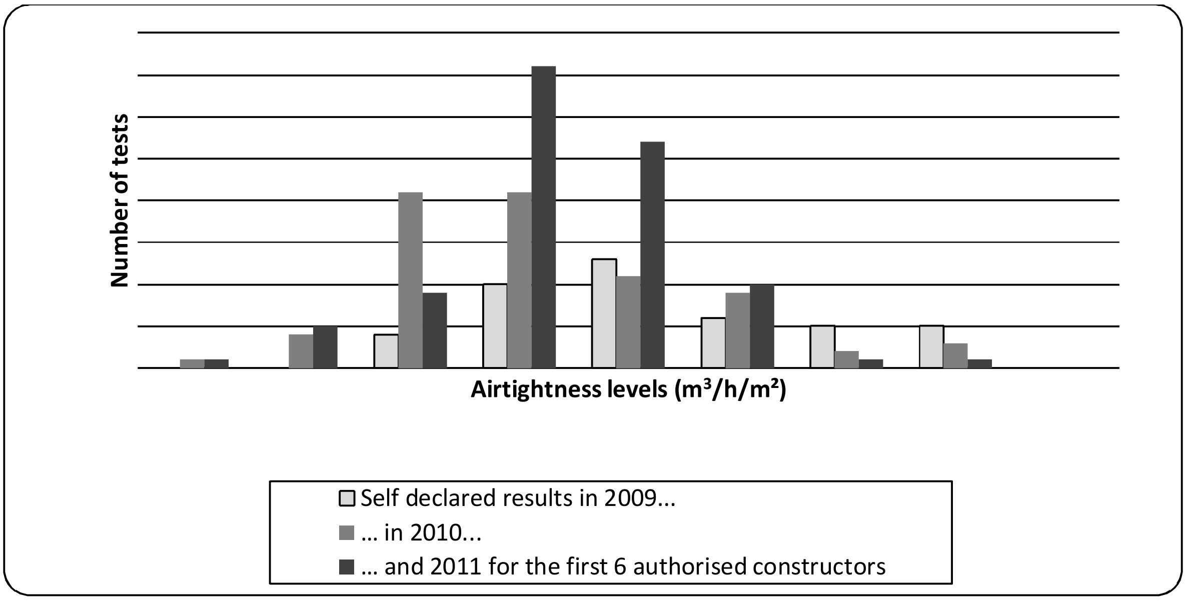

Figure 4: Bar chart of the self-declared results for constructors that have at least a 2-years' experience (follow-ups from 2009/2010/2011 or 2010/2011)

Figure 4 shows the self-declared results of the constructors that have had more than two follow-ups since beginning. It can be implied that results of 2010 and 2011 are better than results of 2009, but that the latest follow-ups show higher results than in 2010. This means that there is a certain improvement in the general airtightness level, but also that the efforts are probably not being pursued when the target level, 0.8m^3/h/m² is reached. These early conclusions still have to be confirmed with next year's follow-ups.

Discussion

As already mentioned above, buildings are not always completely finished when the keys are handed to the owner, for example clients take in charge bathrooms or chimney. As a consequence, testers should not seal the holes left because they have to comply to the norm NF EN 13829 and its implementation guide, which demand to leave the holes open, hence there are probably some improper measurements done internally, which gives a bias in the results showed by the constructer.

The committee discussed this point and decided that it is still the liability of the constructor to justify the level of airtightness at commissioning, even when holes are left open. The committee will therefore expect the following requirements to be fulfilled. If works are to be done in the house by the client, the constructor has to prove that those works are not a threat to the airtightness, and a test is performed after the works by the client. On the contrary, if the works are a threat, the test will still be done after all works are finished. Hence the constructor is expected to give a specific training about air permeability to the client so that they will not deteriorate the airtightness.

As a consequence, the committee advises the constructors to inform in early stages their clients that their house has had a specific airtightness treatment and that there have to be precautious if they do not want to ruin the work done.

Another bias seen in the control tests performed by the state technician is that the controller is given name and address of clients with approximate date of commissioning by the constructor. The controller randomly selects buildings to test, but still relies on the constructor to visit the construction site. It has been seen that some controlled buildings have been “prepared” for the venue of the controller, with among others fresh foam material filling in vacant spaces for toilets. The test is done in the conditions the building has been delivered, but the real final airtightness value will be higher than what is measured, since the foam material is not meant to remain.

To improve the efficiency of the controls, it has been suggested that they should focus on buildings with sensible spots. We identified among others wooden intermediate floors or mechanical ventilation as quite difficult to apprehend from an airtightness point of view. A proposal is to give the focus on these types of characteristics, expecting that the rest of the buildings production complies with the target airtightness level. Plus, the committee witnesses a growth in the number of applicants and with the application of the 2012 energy performance regulation. In only a few months, the number of applicants for the 2012 version has already exceeded the number of total amount of 2005 applicants. It will then become difficult for control testers to measure more than initial goal of 5% of the production of all these constructors. It then makes sense to focus on sensible construction types.

Seeing that constructors having a quality management process succeed more easily to reach a target airtightness value, it raises an issue concerning other constructors. Every building will soon have to comply with the Q_{4Pa_surf} of $0{,}6 m^3/h/m^2$ but it is feared that without proper preparation especially in early design stage, it might be difficult for average constructor to obtain such airtightness results.

Finally, let us note that controls are informative. But what if in the future, controls show more applicants that do not comply with their own target? Some questions remain: will the company lose immediately its agreement, will they be warned for a year, or will they have to hand in more documents? The balance between understanding and harsh decisions is yet to be found.

Conclusion

With the January 1st 2013 deadline approaching, it is of the greatest importance to prepare the market for lowered requirements in airtightness of buildings.

With the increase of applications received the committee, it is to be understood that more and more constructors see the importance of treating airtightness by hand of a quality management scheme, which is in a way a success knowing the initial purpose of this authority. From the results of this first analysis, the self-declared tests as well as the control tests show that in general, constructors gain advantage of such a scheme, for they reach satisfying airtightness levels, even for the 2012 version of the quality management requirements.

At the same time, it is feared that companies that have their authorization for long do not make any effort anymore to continuously improve their scheme, which is the opposite of what was hoped for. Plus, knowing the difficulty of testing the building at the exact moment of commissioning makes the committee doubt about the good faith of some self-declared tests and makes it a necessity to communicate to all authorized constructors about what is testing at commissioning. On this point at least, the committee will be highly vigilant for the coming follow-ups.

ACKNOWLEDGMENTS

The sole responsibility for the content of this publication lies with the authors. It does not necessarily reflect the opinion of the Ministry.

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AIR LEAKAGE CHARACTERISTICS OF DWELLINGS IN HIGH-RISE RESIDENTIAL BUILDINGS IN KOREA

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Abstract

Reliable airtightness data is needed to calculate the estimate of air infiltration and the thermal loads for building energy efficiency and indoor comfort. While useful information on air leakage in low-rise dwellings does exist, there is little data available on dwellings in increasing high-rise residential buildings (particularly ones with central core plan). In this paper, we conducted airtightness measurement using fan pressurization method for about 350 dwellings in 4 high-rise residential buildings in Korea. The results were compared to airtightness requirements for high performance buildings or several airtightness ratings. The measured results show that average ACH50 was 2.3, and the ACH50 value was within the range of 2~5 which are level of 'quite tight' on the basis of ASHRAE airtightness ratings. The results of the building component test show that the most leak parts of dwelling are the internal walls between residential units.

Keywords

Airtightness, Air leakage distributions, High-rise residential building, Fan pressurization method

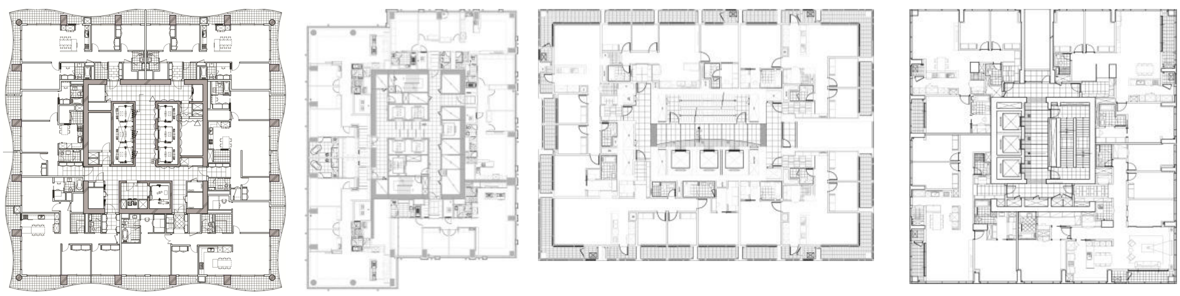
Introduction

Most residential buildings located in the United States, Canada, and Europe are low-rise dwellings. Many studies have been conducted on the airtightness level of low-rise dwellings. Sherman and Chan(2004) reviewed various airtightness research and practices. This report reviews the most important publications relating to the building airtightness. Many studies in this report mainly presented the data on airtightness of single-family house. Measurement methods of the airtightness of single-family house and the airtightness standard for each nation were also suggested. On the other hand, most residential dwellings in Asia are constructed as a multi-family house and high-rise buildings where many units are adjacent to each other. Most Asian countries including South Korea lack airtightness standards and data. In addition, the measurement data or standards for low-rise dwellings of the United States, Canada, and Europe are not applicable. Therefore, airtightness data of high-rise residential buildings should be investigated to provide an airtightness standard.

This study presented the airtightness data and air leakage distributions of dwellings in 4 high-rise residential buildings in South Korea. Fan pressurization method with blower door was used to measure the airtightness value of about 350 dwellings, and the measurement results were compared with the standards of each nation. The airtightness of building components that form units of residential buildings—such as envelope, internal walls between dwellings units, and floor—were investigated.

Test building descriptions

The core was located at the centre of all the tested buildings, and hallways and each unite were on the surrounding plane. In addition, the floor structure was a flat slab, and walls between units and hallways were dry walls. Thus, compared to concrete walls, it is difficult for joints to be air tightly constructed in dry walls, which degrades airtightness. The exterior wall was a curtain wall type for buildings A and B and a punched window type for buildings C and D. The construction outline of the targeted building are summarizes in Table 1.



Building A Building B Building C Building D

Figure 1: Building Plan

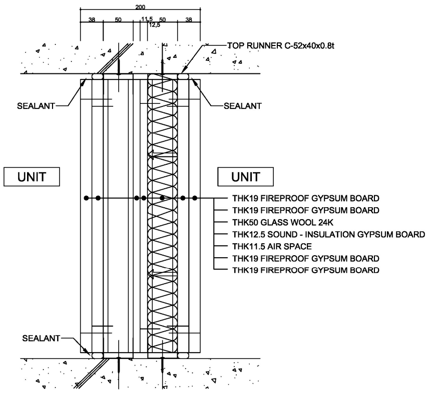


Figure 2: Structure of Dry Wall

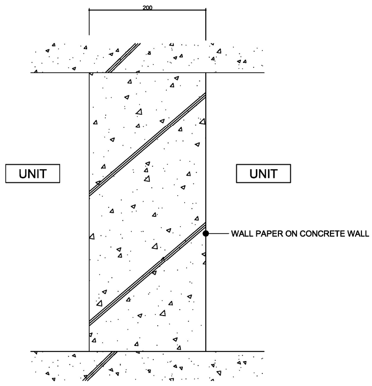


Figure 3. Structure of Conctre Wall

Classification	**A**	**B**	**C**	**D**
Building site	Incheon, SOUTH KOREA			
Construction	Flat Slab			
Number of stories	2 basements, 47 stories	2 basements, 42~49 stories	2 basements, 12~28 stories	2 basements, 11~33 stories
High	161.1	174.6	-	108.8
Building use	Multi-unit dwelling, commercial facility, neighbourhood living facility	Multi-unit dwelling, commercial facility, neighbourhood living facility	Multi-unit dwelling	Multi-unit dwelling
Exterior wall	Curtain wall type	Curtain wall type	Punched window type	Punched window type

Table 1: Test building summaries.

Measurement method

The test conditions presented by the ATSM standard were followed to measure the airtightness of the unit and building components such as envelope, internal walls between dwelling units, floors, and ventilating equipment.

In order to measure the airtightness of a dwelling unit, a blower door was installed in the entrance door at each dwelling unit, and the pressure difference was controlled at 5–10-Pa intervals for measurement. In order to prevent the influence of the airtightness of adjacent units on the building, large openings (windows and doors) of units located above and below were left open so that the situation can be set based on ambient conditions. Building components were distinguished as envelope, internal walls between dwelling units, floors, and ventilating equipment for their air leakage distributions. In order to measure the airtightness of envelope, the airtightness data of envelope was measured two times (built condition and no air leakage condition). When the difference in the amount of air leakages is calculated before and after airtight processing, the airtightness of envelope could be identified. Airtightness of the ventilation equipment was measured with same.

To measure the internal walls between dwelling units and floors, two blower door sets were placed on either side of the measurement target. Then, pressurization and de-pressurization methods were conducted on the measured unit and adjacent units. If the pressure difference between the two dwelling units stayed at ±0 Pa, then air leakage did not occur from the measurement target. The amount of air leakage without air leakage through internal walls was measured. Finally, airtightness data of the internal walls were determined by the differences between in whole airtightness value of the dwelling unit and measured value without air leakage through internal walls.

Measurement result

Analysis on airtightness of unit dwelling of each building

Measured ACH50 results for 350 dwellings of high-rise residential buildings are displayed in Figure 4, and the mean values for each building are marked. ACH50 range was about 1.9–3.8 for building A, 2.6–5.2 for building B, 1.4–3.8 for building C, and 1.4–3.7 for building D. Each the mean value was calculated as 3.1, 3.9, 2.5, and 2.3 ACH50 respectively. Thus, building D was the most airtight followed by buildings C, A, and B in order. Since the ground structure, internal walls between dwelling units, and ventilation types of the buildings were similar, the exterior wall was considered to be the factor with the greatest influence.

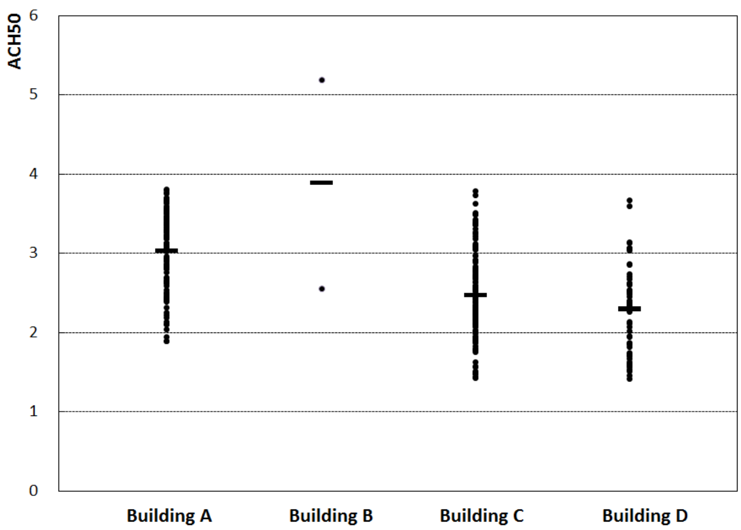


Figure 4: Results of airtightness for each building (ACH50)

When the four test buildings were evaluated according to the ASHRAE ventilation standard for residential buildings, they showed “airtight” or “quite airtight” level, which was sufficient airtight according to the standards of European nations such as Norway, the Netherlands, and Switzerland. However, the airtightness results were evaluated as insufficient airtight that is based on the standards for energy-conservative buildings such as the passive house of Germany and R-2000 of Canada. Figure 5 shows a comparison of airtightness of each nation’s standard and the test buildings in this measurement study.

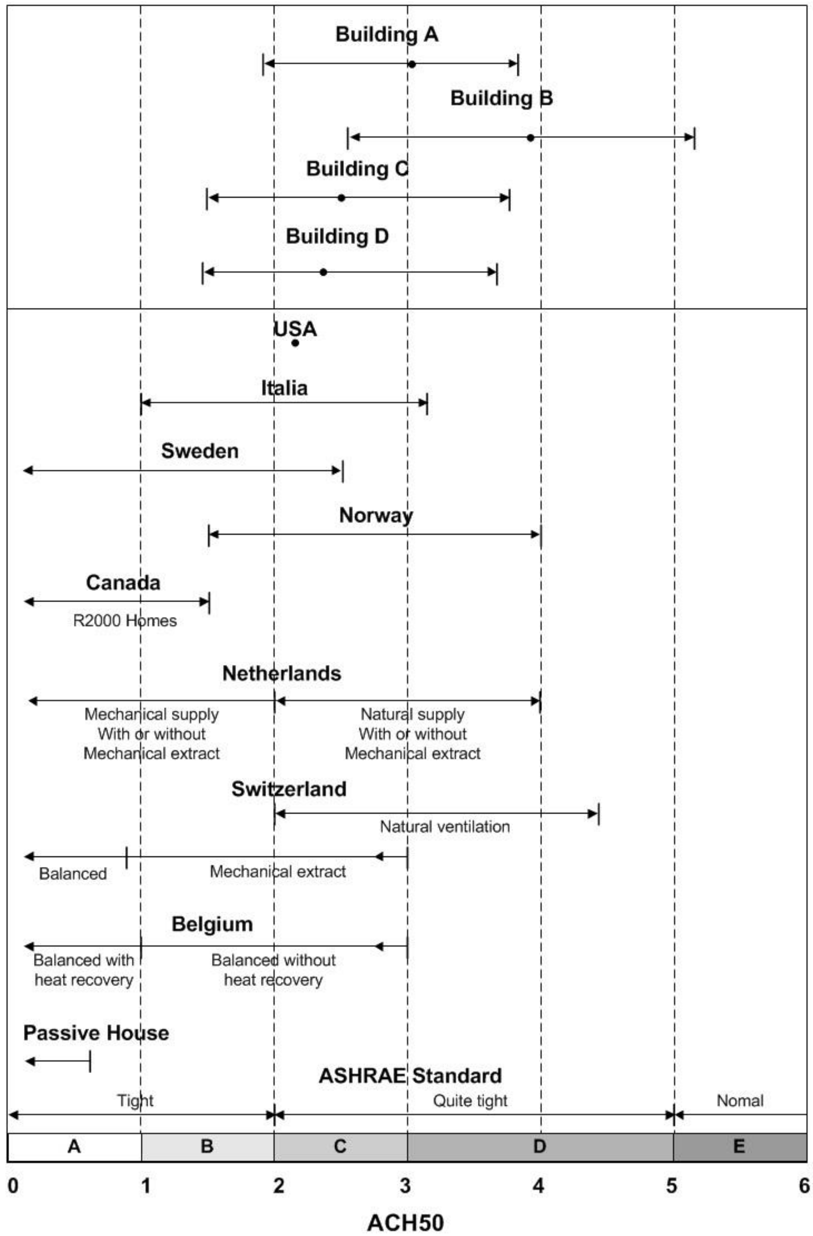


Figure 5: Comparison between measurement data and standard of each nation

Airtightness distributions of building components

The airtightness distribution of building components was measured for building A. Nine dwellings were targets for measurement in building A. Two dwelling types with general plans and one side facing the ambient were selected. Table 2 presents detailed information on the measured dwellings.

	Floor area (㎡)	Floor height (m)	Unite envelope area (㎡)	Volume (㎥)
Type 1	103.85	3.1	342.71	321.94
Type 2	132.53	3.1	418.17	410.84

Table 2: Test dwelling information

The airtightness measurement results were calculated as the air leakage distribution ratio for each building component and are summarized in Figure 6. The test residential units took up the highest amount of air leakage with 30%–58% of the overall amount of air leakage. Because of the trend of lighting structures of high-rise residential buildings, they were mainly constructed with dry walls. Thus, a great deal of air leakage occurred between wall joints or joints where columns and slabs came in contact with walls. The envelope took up 5%–30% of the overall air leakage of residential units. In addition, 3%–32% of air leakage occurred because of floors. Smoke inspection results showed that air leakage occurring from continuing curtain wall frames to adjacent dwellings. As a heat exchanger ventilation system was installed in the dwellings, the amount of air leakage coming through the ventilation equipment was 3%–19% of the overall air leakage of dwellings. The remaining 7%–30% of air leakage was considered to come from the entrance door of the each dwelling unit, equipment penetration, and electrical pipes. Further studies are needed to identify of specific air leakage areas as well as the air leakage distribution ratio.

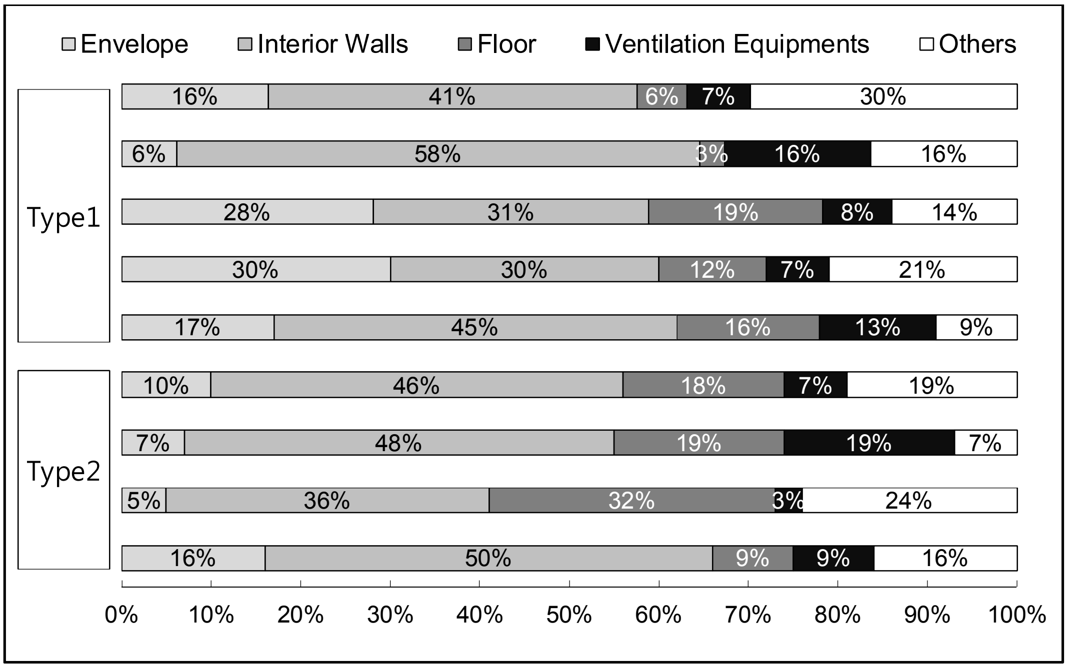


Figure 6: Infiltration (air leakage) distribution ratio for each building component

Conclusion

The airtightness data of 350 dwellings in 4 high-rise buildings in Korea was about 1.4–5.2 ACH50. Building A had an average ACH50 of 3.1, building B had an average ACH50 of 3.9, building C had an average ACH50 of 2.5, and building D had an average ACH50 of 2.3. The airtightness of the four test buildings was at the level of "quite airtight" and satisfied the standards of European nations such as Norway, the Netherlands, and Switzerland. By measuring the airtightness of building components of each dwelling and by calculating the air leakage distribution ratio to identify leaking parts where airtight-constructions are needed, the air leakage distribution ratio was determined to be the highest (31%–58%) for the internal walls between dwelling units. This is considered to be properties of high-rise residential buildings constructed with dry walls, and airtight construction is needed at internal walls between dwelling units.

Acknowledgements

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ASSESSMENT OF THE AIRTIGHTNESS AND AIR EXCHANGE IN POLISH DWELLINGS – MEASUREMENT EXPERIENCES AND PROBLEMS MET

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Abstract

Indoor environment quality in buildings strongly depends on the proper ventilation. Still a large amount of single- and multifamily buildings are equipped with the natural ventilation system.

When the air exchange in the building is estimated, the main uncertainty concerns the air tightness of the given object. This parameter is used as the input data when the ventilation air flows in building are simulated, and therefore a reliable determination of the air tightness is essential.

The method of determining of the air tightness consists of the measurement of the air flows through the investigated flat or house for the given pressure difference. The procedure and techniques are well- known and the measurement is realized by so-called blower door.

The paper presents the course and results of experiments performed in several flats in different multifamily buildings as well as in the single-family house.

Keywords

airtightness, air exchange, ventilation, blower door

Introduction

Airtightness of the building envelope is an essential parameter for assessment of the energy demand, for it determines the amount of air infiltration to the building, and therefore the amount of heat required for heating. Modern technologies and materials used in construction, allow the walls of the buildings for significant reduction of heat loss through transmit ion, however at the same time, due to tight windows, they limit the possibility of proper ventilation.

Large share of the housing stock in Poland are multi-family dwelling houses, ventilated by the natural duct ventilation based on the stack effect. This method of ventilation, cheap to run, results from existing regulations, which allow the system to be used in buildings up to 11 storeys. The system of natural duct ventilation is common in domestic single-family housing. More and more often passive single-family houses, as well as houses using renewable energy sources and mechanical ventilation systems are built.

Measurement of building airtightness can be used to verify the design assumptions, to allow comparisons with other buildings and to estimate the air infiltration.

The paper presents the results of the measurements of the airtightness in two types of dwelling houses: multifamily (two buildings) and single-family (one building). In addition the results of the measurement of exhausted air flow of the analysed multi-family houses and the air exchange simulation calculations on a model of one of the buildings, in which the results of previous measurements were used as an input, are presented.

Polish requirements regarding building ventilation

Polish regulations are based largely on European standards, both for ventilation air flows and airtightness of buildings and flats. The selection of the ventilation method is based on Polish standard PN-83/B-03430/Az3 [1]: in buildings up to 11 storeys, both residential and public, gravitational ventilation can be used, whereas in higher buildings mechanical ventilation is required. In the case of dwelling houses, Polish standards set removed air flows on the following levels: 70 m^3/h for the kitchen, 50 m^3/h for the bathroom and 30 m^3/h for the separate lavatory. The minimum air change rate in dwellings should be 0.5 h^{-1} [2].

The airtightness of the building envelope (or the airtightness of the dwelling), measured by the n_{50} index, should be in accordance with PN-EN 12831 standard [2] (Table 1).

Building	**Airtightness requirement at 50 Pa pressure n_{50}, h^{-1}**		
	high airtightness	medium airtightness	low airtightness
Single family buildings	<4	4-10	>10
Multifamily dwelling houses	<2	2-5	>5

Table 1: Air change rate according to PN-EN 12831 standard

Airtightness and air exchange measurements

The study aimed at: the measurement of the airtightness of the building envelope or its part, the evaluation of the ventilation air flow as well as the identification of uncontrolled air flow paths.

The measurements of the building airtightness were conducted in accordance with PN-EN 13829 standard [3], based on the fan pressurization method with the use of blower door device. The standard recommends measurements according to the method A or B. The main difference lays in the fact that heating and ventilation systems in method A are in the same condition as during regular utilization, while all intentionally made openings in the building envelope in method B should be closed. All the airtightness measurements in the research presented in this paper were carried out in accordance with method B.

Before performing the measurements of airtightness, areas were thoroughly examined in order to eliminate possible leakages, other than window leaks. All of the intentionally made openings in investigated areas were closed: windows, exterior doors, inlets of ventilation and exhaust ducts. All the interior doors were open.

Auxiliary measurements were performed prior to conducting the experiment: floor area, height and volume of the room were calculated; air temperature inside and outside the building, air pressure and wind speed were measured.

Figure 1: The test stand for the measurement of the apartment airtightness in multifamily house

Subsequently, the device producing, depending on the flow direction, under pressure or overpressure in examined room, was installed in the door opening (Fig. 1). Airtightness of the joints in door opening was inspected, then the device measuring air pressure and the computer with an appropriate software were installed.

The measurements of the air flow and the air pressure difference between the zone and the environment at intervals of 10 Pa and in the range of 30 ÷ 70 Pa, were performed after the device initiating movement of the air was turned on.

The main result of the study was a flat or building leakage curve (separately for pressurization and depressurization) in the form of the formula:

$$\dot{V} = C \cdot \Delta p^{n} \tag{1}$$

where:

$\dot{V}$ – leakage air flow rate, m^3/h

C – flow coefficient, $m^3/h \cdot Pa^n$

Δp – pressure difference induced by ventilator, Pa

n – exponent.

Additionally, the air flow V_{50} and the air change rate n_{50} for the air pressure difference of 50 Pa, were obtained.

Prior to airtightness tests in every analysed apartment in multifamily houses, the flows of the air blown out through ventilation ducts were measured with the use of barometer. Moreover, meteorological data, according to the local weather station, for the day and hour were recorded.

Multifamily dwelling houses

The measurements were performed in two multifamily dwelling houses: 5 and 11 storeys, equipped with gravitational natural ventilation. The buildings were built several decades ago. Gravity pipes are located in kitchens, bathrooms and separate lavatories in the case of 2-storey building (in each case one exhaust grille). There are several types of windows in buildings, both: relatively new, quite tight PVC windows with seals, as well as wooden windows made several decades ago. None of the windows is equipped with air inlets.

There are leaks in the form of cracks in building construction and poorly sealed verticals of central heating in apartments (Fig. 2). Serious leakages into the corridor in the place where gas pipes pierce to counters were noticed in some apartments of 11-storey building.

Figure 2: The examples of leakages in the walls and ceiling of the apartments

In the 5-storey building, the measurements concerned three apartments: two on the 2nd storey (M1 and M3) and one on the 5th storey (M15). The selection was random and depended on the consent of the tenants to carry out measurements. Similar situation occurred in the case of 11-storey building, where the measurements were performed in apartments on the groundfloor (M4) and one on the 10th storey (M55).

It was necessary to seal some components of the electrical installation, as well as culverts of central heating verticals and culverts of gas installation. Grilles' outlets were also plugged. Large and hard-to-reach openings, caused by the culverts for exhaust pipes to the individual gas water heaters, were detected in bathrooms in 11-storey building. Due to the fact that bathrooms are interior rooms, without windows and external walls, they were isolated by sealing the door for the period of measurements (Fig. 3). Hereby, problems with all leakiness in these rooms were avoided.

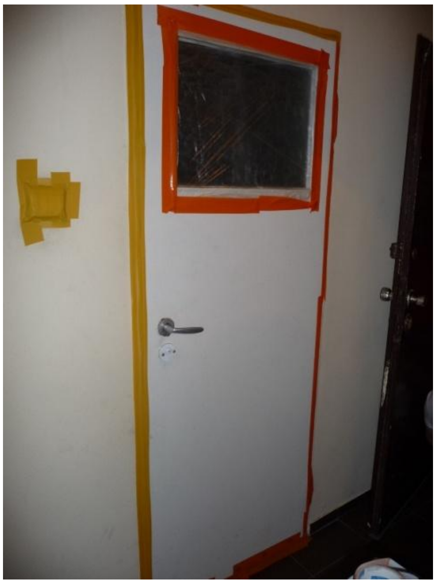
Figure 3: Method of sealing of bathroom's door in the flat of the 11-storey building

The results of pressurization tests are presented in Table 2. Knowing the length of the window leakages and a flow coefficient *C* generated by the program, window airtightness factor *a* was calculated.

The value of an index generated by the program should be about 0.67. If it is different, much lower than 0.67, it may indicate the presence of uncontrolled air flows through the envelope of a zone.

Unfortunately, during the study, it was not possible to seal the zones enough to obtain a desired value of *n*, therefore, to calculate airtightness factor *a*, the index of a flow characteristics (*n*) was corrected to a value of 0.67. With the use of spreadsheet, corrected values of flow coefficient *C* were obtained. Dividing the flow coefficient *C* by the length of the window cracks, the values of airtightness coefficients a were obtained and summarized in Table 2.

Building	**Flat**	**Type of window**	**V_{50}, m^3/h**	**n_{50}, h^{-1}**	**Airtightness factor *a*, m^3/m·h·Pa^{0,67}**	**Air flow measured in air outlets (required air flow), m^3/h**
5-kond.	M1 (2st storey)	old	**415**	**3.3**	1.16	32 (120)
	M2 (2st storey)	new	**232**	**1.5**	0.54	92 (150)
	M15 (5th storey)	old/new	**715**	**3.8**	1.37	105 (150)
11-kond.	M4 (1st storey)	old/new	**320**	**2.7**	0.57	15 (120)
	M55 (10th storey)	new	**132**	**1.5**	0.32	10 (120)

Table 2: The results of the measurements of the airtightness and ventilation air flow

Single family building

The measurements were performed in 2-storey building with a cubage of 570 m3. The building is equipped with a mechanical ventilation system providing required ventilation air flow. All windows are in very good condition, relatively new and tight.

Figure 4: The example of leakiness in the building

Before the measurements, the inspection of rooms was conducted to search and seal potential leakages. Air intake and exhaust air device, as well as fireplace doors were detached (Fig. 4). The results of pressure tests are: V_{50}=983 m^3/h, n_{50}=1.73.

Analysed building is tight, obtained factor n_{50} describes the building with high degree of envelope tightness in terms of PN-EN 12831 [2] standard. In the case of the building with mechanical ventilation, this coefficient can be considered as satisfactory.

Assessment of the air infiltration

One of the goals of the study was to estimate of the air change rate in the analysed buildings. Knowledge of the characteristics of airtightness and the total length of the leakages in the windows made it possible to calculate the rate of air infiltration.

In addition to measurements related to building ventilation, numerical simulations of ventilation air flow on the model of the analysed 5-storey building were carried out. Each flat and corridor was modelled as a separate zone, resulting in a total of 30 zones. Calculations were performed using the CONTAM [4] software for the meteorological data recorded by the local weather station. The air infiltration coefficients, calculated on the base of airtightness measurements, were used with the assumption of their repeatability in the same type of windows in other flats in the building. Air flow simulations were carried out for the period of the heating season. Fig. 5 presents the course of air infiltration variability on the day of measurements in three analysed apartments. Fair compatibility of the results of measurements of the air flows exhausted from two apartments with an air infiltration can be noticed. Differences do not exceed 12%. In the case the 3rd apartment, large (3-fold) difference may result from substantial contamination of the ventilation grille, so that the air flows largely through apartment's door to the staircase, which is not included in the measurement.

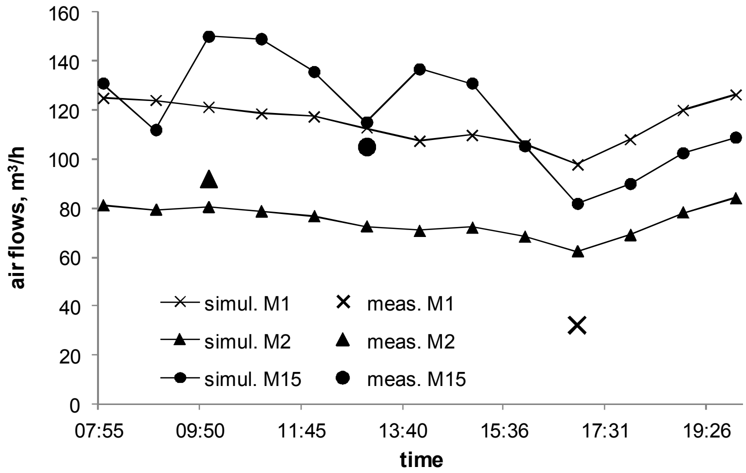

Figure 5: Air infiltration in analysed flats – simulation versus measurement

Conclusions

The obtained results of measurements of airtightness are within the ranges specified in the standards. The measurements indicate high airtightness of apartments with new PVC windows. The value of n_{50} does not exceed 2 h^{-1}.

The study confirmed that many uncontrolled leakages, which impede measurements and increase their uncertainty, exist in old multifamily houses. Uncertainty as to the results may also result from the fact that the measurements were performed in completely random houses, not including possible connections to the neighbouring houses.

Ventilation air flow, measured directly in the exhaust grille, is small and substantially deviates from the Polish Standard (with one kitchen and one bathroom required air flow is 120 m^3/h). The maximum measured air flow for this type of housing was 32 m^3/h. The ventilation air flow decreases with increasing storey. Unfortunately, the amount of gravitational ducts on the highest storeys of the buildings has not been increased. However, it should be noted, that the given air flow was measured only in the exhaust grilles, without taking into account the air flow through the apartments doors to the building staircase.

Acknowledgements

The work is part of the project financed by the National Centre for Research and Development (NCBiR) agreement SP/B/4/77113/10 and was also supported by the Polish Ministry of Science and Higher Education – statutory research BK-364/RIE-1/2011.

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POSTULATE FOR AIRTIGHTNESS LIMITS IN LARGE BUILDINGS

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Abstract

DIN 4108-7 requires a limit of $q_{50} \leq 3.0$ m³/m²h for the air permeability of large buildings [1]. Even stricter limits with respect to q_{50} can be found at DGNB (German Sustainable Building Council) [2] and in the Swiss MINERGIE Standard [2].

It is the objective of this presentation to develop awareness of this topic in the audience and to give recommendations as to which limits can be applied to new building projects.

Theoretical considerations and experience from measurements lead to the conclusion that a volume-based limit of n_{50} is not a suitable target value for large buildings. Because of the changing surface-area-to-volume ratios (SA:V-ratio) in large buildings, it makes sense to require an envelope-based limit, especially since there are requirements for limiting air permeability for building component joints and service apertures. Existing limits and results from airtightness measurements are presented. The presentation will also outline the main points of the approach to achieving airtightness as planned.

Keywords

Air permeability q_{50}, limits (table), roll-up doors, loading bridges, smoke extraction for elevators

Introduction

Airtightness tests of large buildings such as office buildings, schools, homes for the elderly, warehouses, and production halls are fortunately becoming increasingly common in Germany. They are frequently performed in order to meet the requirements or exploit the benefits of building airtightness as defined in the German Energy Savings Regulation [4] or conducted because of increased public awareness as to preventing waste of energy. Another reason is the ever higher number of quality certificates required.

Photos:

Left: www.hammersen.de

Right: www.sanidetectif.be

Figure 1: Two buildings with an internal building volume of 200,000 m^3 each. The building on the left with a V_{50} = 2,600 m^3/h is very airtight. The building on the right has a V_{50} = 86,500 m^3/h.

Limits and Measured Values

Air change rate n_{50} at 50 Pascal

The German Energy Savings Regulation [4] limits the air change rate n_{50} of a building to the following values when conducting an airtightness test according to European Standard EN 13829 [5]:

$n_{50} \leq 3.0\ h^{-1}$ for buildings without a ventilation system and

$n_{50} \leq 1.5\ h^{-1}$ for buildings with a ventilation system

According to the German Energy Savings Regulation [4], the energy balance for non-residential buildings is calculated according to the series of German Industrial Standards DIN V 18599 [6]. Based on the project experience of Mr. Moritz Wagner, Dipl.-Ing., of Büro IFB Sorge (Nuremberg), the following can be stated with the DIN V 18599 assessment:

- Considering an airtightness test usually has a positive effect on the annual primary energy requirement.
- For common types of buildings, the reduction comes to 10-15%.

The German Industrial Standard DIN V 18599 [6] allows for applying the measured n_{50}-value as a rated value. The standard rated value according to DIN V 18599 for buildings without ventilation systems is $n_{50} \leq 2.0\ h^{-1}$ and for buildings with ventilation systems is $n_{50} \leq 1.0\ h^{-1}$. Figure 2 shows that the real measured values often amount to $n_{50} \leq 0.5\ h^{-1}$. By using the real measured n_{50}-values, improvements in the energy balance beyond the standard rated values can be expected.

It is important to determine this value according to Method A in German Industrial and European Standard DIN EN 13829 [5].

The experience from testing large buildings has shown that the limits of the German Energy Savings Regulation and German Industrial Standard DIN V 18599 [4,6] are usually met and to some extent the measured values remain far below them. The following diagram shows a compilation of the air change rates at 50 Pascal (depressurization tests) of 82 buildings measured by a series of testing teams. The smallest building has an internal volume of approximately 1,300 m^3, the largest one of approx. 520,000 m^3.

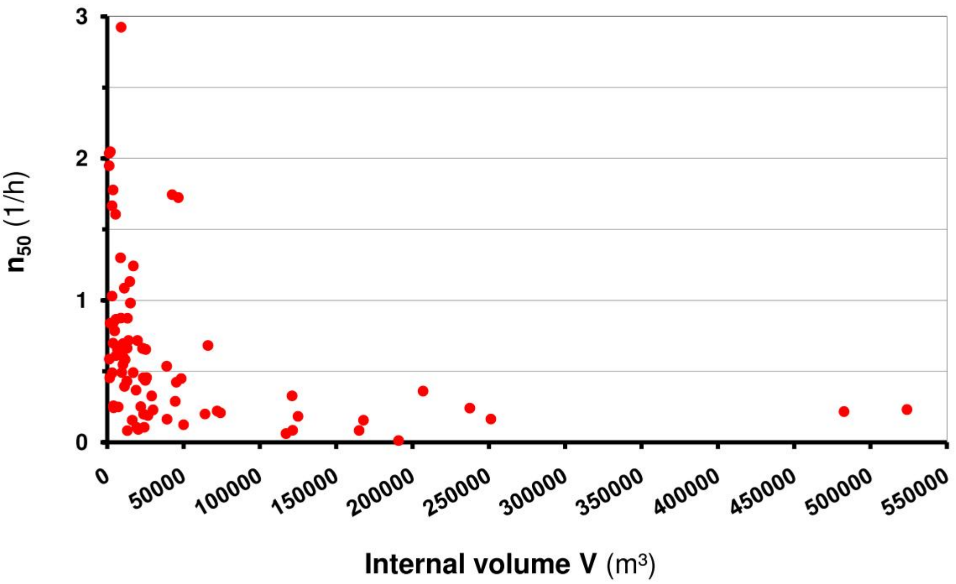

Figure 2: Air change rates n_{50} (82 depressurization tests) of large buildings

The air change rates of all buildings are below 3.0 h^{-1}. Almost 90% of the air change rates are even lower than 1.5 h^{-1}.

What is the reason for these seemingly excellent results for the air change rates at 50 Pascal? Is the quality of the building envelope of large buildings so much better than that of single-family homes? Or are there other reasons?

The air change rate n_{50} is a volume-based indicator. It is calculated by dividing V_{50}, the leakage flow determined at 50 Pa, by the internal building volume V:

$n_{50} = V_{50} / V$

This results in large buildings achieving better (lower) air change rates than single-family homes because they have a smaller SA:V-ratio (surface-area-to-volume ratio), which means that a “large” volume is enclosed by a relatively small building enveloping area containing the leakages.

Examples for SA:V-ratios:

Type of building	SA:V-ratio(1/m)
high-rise building	from 0.2
apartment building/multiple family home (MFH) (3 to 4 floors)	approx. 0.3 to approx. 0.6
center row house (2 to 3 floors)	approx. 0.5 to approx. 0.7
single-family home (SFH)	from 0.8

In this context, the air change rate n_{50} does not yet provide any information on the quality of the building envelope. An evaluation can only be conducted when the air change rates of the same quality of the airtight layer are related to the SA:V-ratios.

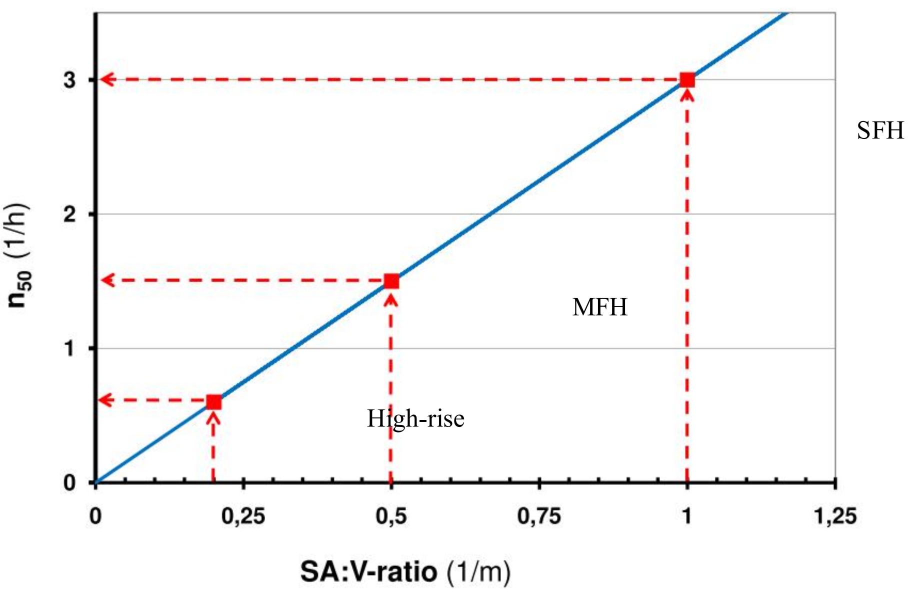

Figure 3: Air change rates of the same quality of the airtight layer related to the SA:V-ratio

The diagram shows the example of three buildings: a single-family home (SFH) with a SA:V-ratio of approx. 1 m^{-1}, an apartment building/multiple-family home (MFH) with a SA:V-ratio of approx. 0.5 m^{-1}, and a high-rise building with an SA:V-ratio of 0.2 m^{-1}. The single-family home at 50 Pascal is supposed to have a maximum air change rate of n_{50} = 3.0 h^{-1}. Assuming that the multiple-family home and the high-rise building feature just as many leakages per square meter of enveloping area, the airtightness test of the multiple-family home would determine an air change rate of n_{50} of 1.5 h^{-1} at 50 Pascal and that of the high-rise building a rate of 0.6 h^{-1}.

Conclusion

The air change rate of large buildings should always be evaluated in relation to the SA:V-ratio of the building.

Air permeability q_{50} at 50 Pascal

To better compare the quality of the building envelope of different buildings, an additional indicator can be used: the air permeability q_{50}. German Industrial Standard DIN 4108-7 [1] in its version of January 2001 also requires limiting the air permeability for buildings with an internal volume of > 1.500 m³ to $q_{50} \leq 3.0$ $m^3/(h \cdot m^2)$.

The air permeability q_{50} is calculated by dividing the leakage flow V_{50} at 50 Pascal by the respective building enveloping area A_E:

$$q_{50} = V_{50} / A_E$$

It indicates how many cubic meters of air per hour at a building pressure differential of 50 Pascal flow over one square meter of building enveloping area.

The following diagram shows the air permeability q_{50} of 42 depressurization tests.

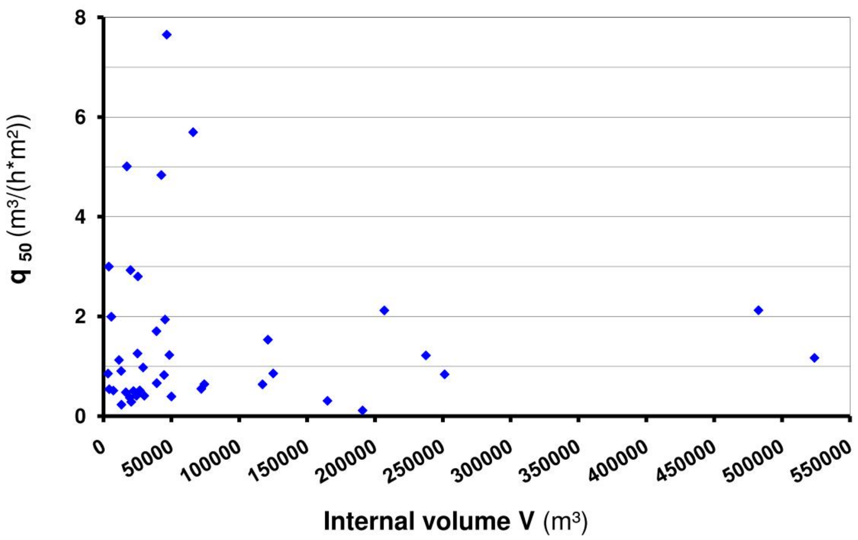

Figure 4: Air permeability q_{50} (42 depressurization tests) of large buildings

90% of the buildings meet a $q_{50} \leq 3.0$ $m^3/(h*m^2)$. 70% remain below a $q_{50} = 1.5$ $m^3/(h*m^2)$.

At an international level, limits for buildings larger than 1,500 m^3 have already been formulated:

- Minimum standard 4108-7 $q_{50} \leq 3.0\ m^3/(h \cdot m^2)$
- Minimum standard DGNB $q_{50} \leq 2.5\ m^3/(h \cdot m^2)$ (German Sustainable Building Council)
- Improved standard DGNB $q_{50} \leq 2.0\ m^3/(h \cdot m^2)$ rule of technology (German Sustainable Building Council)
- Swiss MINERGIE Standard $q_{50} \leq 1.25\ m^3/(h \cdot m^2)$ soon rule of technology
- Optimum standard $q_{50} \leq 0.6\ m^3/(h \cdot m^2)$ state of the art

Rule of technology means that these values are already met today by applying the generally used techniques and working methods. Since awareness in practice has been increasing, the authors estimate that the rule of technology will very soon shift towards a $q_{50} \leq 1.25\ m^3/(h \cdot m^2)$.

State of the art means that it is possible to achieve these values by applying special diligence. This usually implies quality assurance during the construction phase. The authority for public buildings in Luxemburg already applies a limit of $q_{50} \leq 0.6\ m^3/(h \cdot m^2)$ for new school or office buildings. For halls, the q_{50} is adjusted depending on the quality of the roll-up doors.

Suggestions for quality improvements

To purposefully achieve good quality in the airtight building envelope, an airtightness concept for the building should be developed as early as the planning phase, as is the case for single-family homes. The airtight layer as well as the thermal building envelope have to completely enclose the entire heatable volume. Selecting sufficiently airtight materials, planning details diligently and avoiding unnecessary penetrations are requirements for successful implementation later.

Based on the testing experience to date, improvement is needed for, for example, post-and-rail façade structures, smoke extraction in elevators, roll-up doors and movable loading bridges.

Post-and-rail façade structures

Figure 5 gives an example of early airtightness testing of a post-and-rail façade structure.

Figure 5: A sample façade with connected casing allowed the airtightness of the façade component and the connecting joint to be tested before construction. In this case, improvements and a second airtightness test were necessary.

Smoke extraction in elevators

Smoke extraction in elevators is intended for cases of fire. It is mostly an aperture at the elevator head. In case of fire, these apertures serve as smoke extractors from the shaft. Elevator doors in many cases are only authorized if smoke extraction apertures exist. If these apertures remain open all year, they cause ventilation heat loss or, in air-conditioned buildings, ventilation cold losses in summer. Flap valves that will only open as needed are now available on the market. In some cases, the smoke extraction apertures also serve to cool the elevator drive motor. Should this be the case, the function of the smoke extractor shutter can be combined with switch-on/switch-off temperature for cooling the motor.

Installation shafts frequently also feature smoke extraction, and thus also have to be equipped with flap valves.

Roll-up doors

Roll-up doors are used in many larger projects, e.g., warehouses. Table 1 shows the airtightness of roll-up doors: "Airtightness classes 0 to 5 for roll-up doors according to German Industrial and European Standard Din EN 12426 [7]." The indicated values correspond to the q_{50}-value in German Industrial Standard DIN 4108-7 [1]. A roll-up door of the airtightness class 4 with an air permeability of 3 $m^3/(h \cdot m^2)$ corresponds to the limit stipulated in DIN 4108-7.

Class	Air permeability(AP) at a pressure of 50 Pa $m^3/(h \cdot m^2)$	Value defined
0		No value defined
1	24	
2	12	
3	6	
4	3	
5	1.5	

Table 1: Airtightness classes 0 to 5 for roll-up doors according to DIN EN 12426 [7]

Movable loading bridges

Different loading-bridge systems are in use for loading and unloading trucks.

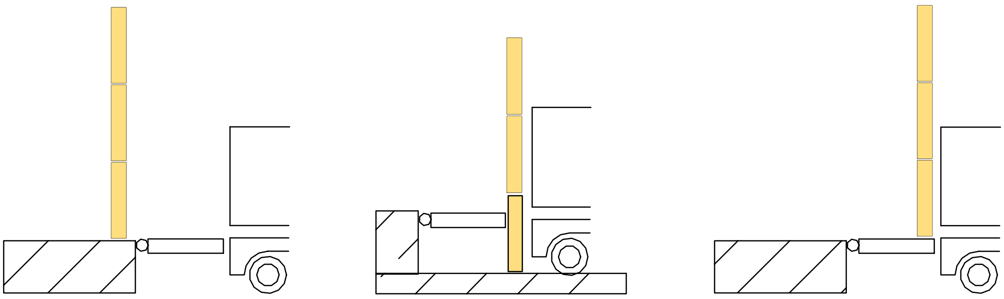

Figure 6: The loading bridge on the right has an effect on the airtightness since it forms part of the building envelope.

For loading bridges that form part of the external building envelope, the two-centimeter joint between the loading bridge and the floor has a critical effect on airtightness. Attention must be paid to sealing this joint (Figure 7). The authors are not aware of any airtightness targets for movable loading bridges.

Figure 7: Detail, movable loading bridge with integrated sealing. A clearly visible air leakage only remains at door level [8]

Test example

Figure 8: New school building in Luxemburg, cafeteria building “Public” with integrated BlowerDoor MultipleFan measuring system.

Building envelope = 15,000 m^2

Internal building volume = 45,000 m^3

Target value: $q_{50} \leq 1.25\ m^3/(h \cdot m^2)$

Test results: $V_{50} = 7{,}000\ m^3/h$, $q_{50} = 0.5\ m^3/(h \cdot m^2)$, $n_{50} = 0.15\ h^{-1}$

Figure 9: During the BlowerDoor test in the building “Public”

Conclusion: The authors recommend discussing the target values for large buildings as pertains to setting a target value for newly planned large buildings of $q_{50} < 2.0$ m^3/(h·m^2) in calls for tender and stricter requirements, e.g., determining a target value of $q_{50} \leq$ 1.25 m^3/(h·m^2) for office buildings.

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AIRTIGHTNESS AND VENTILATION OF NEW ESTONIAN APARTMENTS BUILT 2001-2010

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Abstract

The performance of ventilation and airtightness of building envelope was studied in field measurement in lately built apartment buildings in Estonia. The buildings were selected with different building envelope and with ventilation system. The mean air leakage rate at the pressure difference of 50 Pa in the entire database was 1.7 $m^3/(h \cdot m^2)$. The mean air change rate at the pressure difference of 50 Pa from entire database was 2.3 h^{-1}.

Ventilation airflows in apartments were low in general resulting bad indoor air quality. Only in few apartments the general airflow corresponded to the requirements of II indoor climate category. Together with rising of air tightness of building envelope more attention should be paid to the performance of ventilation. It is not only question, what is the capacity of ventilation system. Increasing the ventilation airflow without proper design (noise reduction, avoiding draft, energy performance, etc.) may not guarantee the good result.

Keywords

Performance of ventilation; Airtightness of building envelope

Introduction

Energy performance of buildings and indoor air quality are becoming more important in many European countries- especially when the latest version of EPBD (European Energy Performance of Buildings Directive) calls for all new buildings to be nearly-zero energy by the end of 2020. This set higher requirements on performance of ventilation and airtightness of building envelope.

Air tightness of building envelopes affects directly indoor quality (health, thermal comfort), hygrothermal performance, noise resistance, and fire resistance of the building and also energy consumption of the building. Jokisalo et al. showed that in Finnish cold climate infiltration causes about 15–30% of the energy use of space-heating including ventilation in the two-story detached house when the building leakage rate is typical (n_{50} = 3.9ach), while the corresponding proportion is about 30–50% in the leaky house (10ach). Because the correlation between the airtightness of the building envelope and the infiltration rate is almost linear, heating energy use of the houses also increases almost linearly at the same time. Therefore, the preceding correlation reduces into a simple rule of thumb: One unit change in n_{50} corresponds to a 7 % change in the energy use of space heating including ventilation. At the same time, the change in total heat energy use is about 4%. In the studied cases, these increment percentages vary from 4 % to 12 % regarding space heating or from 2 % to 7 % regarding the total energy use. The variation of these percentages is mainly result from different wind conditions [1].

Therefore airtightness has become a single requirement in low energy buildings. In certification of new passive houses the Passive House Institute requires air leakage rate below 0.6 air changes per hour at 50 Pascal's pressure difference.

The good example about the balance between airtightness and ventilation is: « build tight — ventilate right ». To guarantee indoor air quality the performance of ventilation in airtight buildings is an important issue. If buildings become more airtight, leakage airflow is smaller and ventilation airflow should be larger. This is partly the reason, why in many countries the ventilation airflows are increased. But just increasing the ventilation airflow may not guarantee the good result. It is not only question, what is the capacity of ventilation system, but also the way how inhabitant uses the ventilation and how the ventilation is designed and built (noise reduction, avoiding draft, energy performance, etc.). Because there are many unknowns in final performance of ventilation and airtightness of building envelope, the field measurements can give the good overview about the situation in reality.

To give the overview of the final performance of ventilation and airtightness of building envelope in modern apartment buildings in Estonia, field measurements were carried out in 28 buildings built between 2000 and 2010. The study is a part of the research project about degreasing environmental impact of buildings by improving energy performance of buildings in Estonia and collecting the database of airtightness of Estonian apartment buildings.

Methods

Studied buildings

63 apartments from 28 buildings were under investigation in the cross-sectional study of the technical condition of lately built apartment buildings. The airtightness of building envelope was measured in 26 apartments in 23 buildings. Ventilation airflows were measured in 30 apartments.

Buildings were selected with different external wall structures (Figure 1, left) and with different ventilation system (Figure 1, right). The selection should represent lately built Estonian apartment buildings on average.

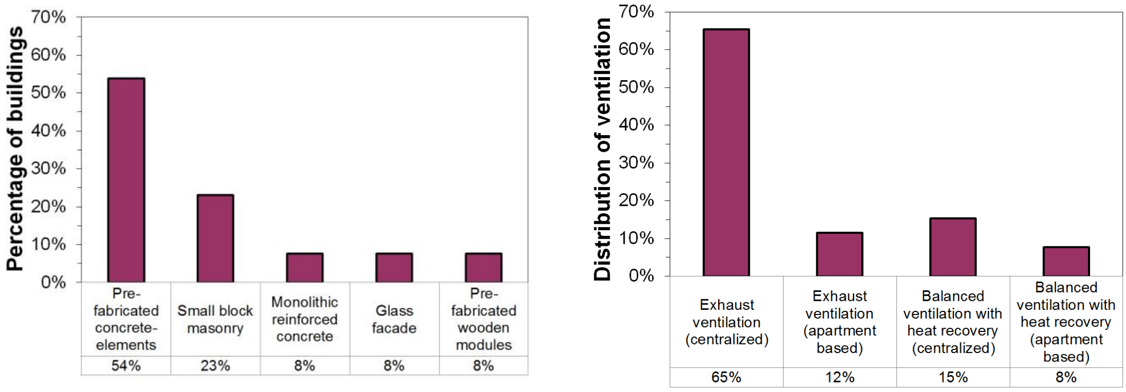

Figure 1: Distribution of studied apartments according to external wall type /left) and ventilation system (right).

Measurement methods

The air tightness of each apartment was measured with the standardized fan pressurization method [2], using “Minneapolis Blower Door Model 4” equipment (flow range at 50 Pa 25-7.800 m^3/h, accuracy ±3%). To determine the air tightness of the building envelope, depressurizing and pressurizing tests were conducted with closed exterior openings, windows and doors and sealed ventilation ducts. To compare air leakage of different apartments, the air flow at pressure difference 50 Pa was divided by the apartment’s internal envelope area (including intermediate walls) resulting air leakage rate at 50 Pa q_{50}, $m^3/(h\cdot m^2)$ or by the internal volume of the building resulting air leakage rate at 50 Pa n_{50}, h^{-1}.

To determine typical air leakage places and their distribution during the winter period, an infrared image camera was used FLIR Systems E320 (accuracy 2% or 2°C, measurement range: -20…+500°C). The temperature difference between the indoor and outdoor air was at least 20°C. Thermography investigations were conducted twice: first, to determine the normal situation, the surface temperature measurements were performed without any additional pressure difference and then to determine the main air leakage places, the 50 Pa negative pressure under the envelope was set with fan pressurization equipment. After the infiltration airflow had cooled the inner surface (~30…45 min) of the envelope, the surface temperatures were measured with the infrared image camera from the inside of the building.

Ventilation airflows were measured with anemometer (SwemaFlow 233 (accuracy ±4 % read value, minimum 1 l/s, measurement range 2 to 65 l/s). The supply air flow rates were measured with a manometer Alnor/TSI AXD610 Digital Differential Micromanometer.

Assessment criteria

A requirement on airtightness of building envelope is different country by country and in different standards [3, 4]. In Estonia the first requirement on envelope air tightness for apartment buildings was set in 1995: air leakage rate should be $q_{50} < 3{,}0$ m^3/(h·m^2) [5]. The minimum requirements on energy performance of buildings [6] suggests that the general air leakage rate could be $q_{50} < 1{,}0$ m^3/(h·m^2) and to avoid problems due to moisture convection critical joints should be made airtight.

Requirements on indoor climate are set in the standard [7]. The indoor air quality is expressed as the required level of ventilation. The general ventilation airflow in new apartment (II indoor climate category) should be at least 0.42 l/(s·m^2) or 0.6 h^{-1} and airflows in living room and bedrooms should be at least 1.0 l/(s·m^2) or 7 l/(s·person).

From measurement results, the reference value of air tightness for different types of buildings was calculated. The reference value $q_{50,delc}$ (Eq. 1) represents median value (50% fractal) with a confidence level of 90% for air tightness. The reference value of air tightness is applicable for energy calculations, when air tightness is not measured or the air tightness base value given in energy performance regulation is not suitable to use (too large or too small).

$$q_{50,decl} = \overline{q_{50}} + k * \sigma_{q,50} \qquad \mathrm{m^3/(h \cdot m^2)} \tag{1}$$

where: $\overline{q_{50}}$ is the mean value of air tightness of this building type, m^3/(h·m^2); k is the factor what takes into account the median value with a confidence level of 90% (Eq. 2), and σ_{q50} is standard deviation of air tightness measurement results of this building type.

$$k = \frac{1.645}{\sqrt{n}} \tag{2}$$

where n is the number of measurements

Results

Airtightness of building envelope

The mean air leakage rate at the pressure difference of 50 Pa in the entire database was 1.7 $m^3/(h\cdot m^2)$, the minimum being 0.8 $m^3/(h\cdot m^2)$ and the maximum 4.6 $m^3/(h\cdot m^2)$. The mean air change rate at the pressure difference of 50 Pa from all the data was 2.3 h^{-1} (minimum being 0.9 h^{-1} and the maximum 6.6 h^{-1}). The average values of air leakage rate and air change rates at 50Pa pressure difference of all measured apartments are shown in Figure 2.

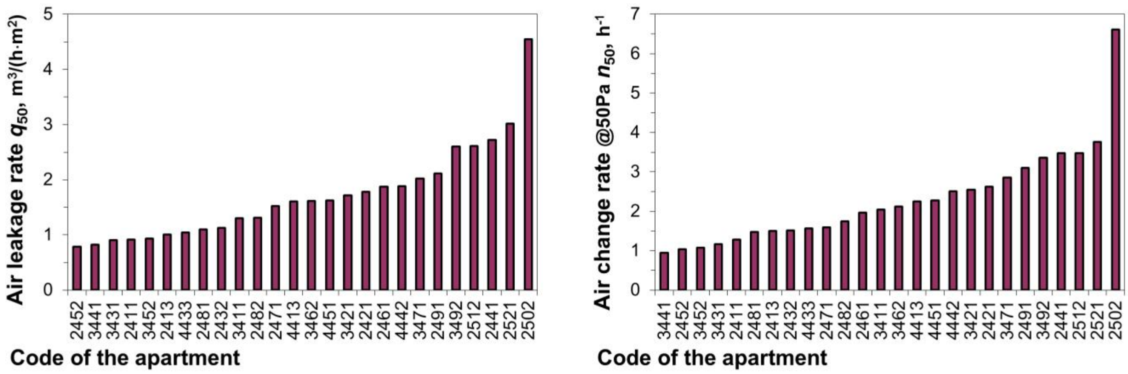

Figure 2: Air leakage rate q_{50} (left) and air change rate n_{50} (right) of all apartments.

Airtightness measurements show only small difference between different building types (q_{50}=1.5…2.2 $m^3/(h\cdot m^2)$ and n_{50}=2.2…2.7 h^{-1}), Figure 3. It shows that it is possible to build airtight building envelope with all types of structures. The larger deviation within the same building type shows that stronger influence can be the quality of constructional works.

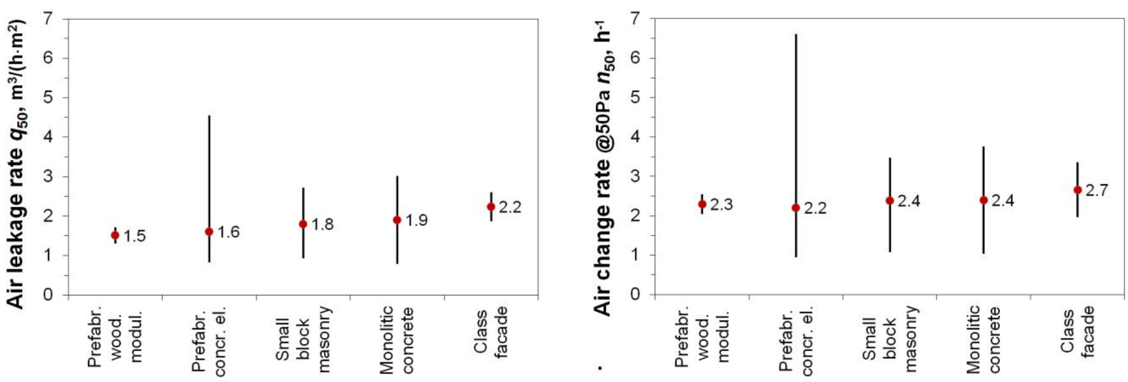

Figure 3: Air leakage rate q_{50}, $m^3/(h\cdot m^2)$ (left) and air change rate n_{50}, h^{-1} (right) of different building types.

By comparing current results with previous airtightness measurement result done in Estonia it shows that modern building envelopes are tighter, see Table 1. Older apartment buildings built with concrete and brick show similar airtightness, while old wooden apartment buildings are the leakiest.

Airtightness of building envelope influences the heating energy consumption. Energy audits of buildings are commonly dome with limited resources without airtightness measurements. Nevertheless, estimated values should be enough in the safe side, to avoid too optimistic economic estimations. Reference value of airtightness that represents median value with a confidence level of 90% can be used then, see Table 1

.

Type of the apartment building	**Air leakage rate q_{50}, m³/(h·m²)**		**Air change rate @50Pa n_{50}, h⁻¹**	
	Average	Reference value	Average	Reference value
Modern buildings built 2000-2010 [current study] 26 apartments	1.7	2.0	2.3	2.7
Prefabricated concrete elements, 1960-1990 **Error! Reference source not found.** 19 apartmnets	4,2	4,7	6,0	6,8
Brick walls, 1960-1990 **Error! Reference source not found.** 30 apartments	4,0	4,4	5,7	6,4
Wooden structures, 1900-1940 **Error! Reference source not found.** 35 apartments	10	11	13	14

Table 1: Comparison of airtightness of apartment buildings with different structures in Estonia

Typical air leakage places in modern apartment buildings were:

- Leakages around the windows (Figure 4);
- Junction of the roof/floor with the external wall;
- Junction of the ceiling with the external wall;
- Junction of the separating walls with the external wall (Figure 5);
- Penetrations of pipes trough the external wall;
- Surroundings of the fresh air valves in external wall.

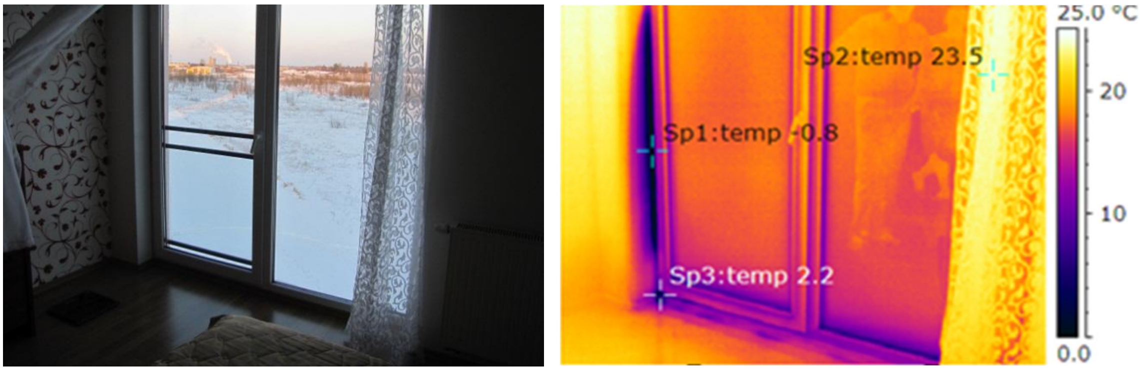

Figure 4: Leakages around the windows.

Figure 5: Air leakage between separating walls and the external wall.

Performance of ventilation

The performance of ventilation was assessed on the apartment level and on the bedroom level. Indoor climate category II (EN 15251: normal level of expectation and should be used for new buildings and renovations) was selected as reference.

Ventilation airflows in apartments were low in general (Figure 6) resulting bad indoor air quality (Figure 7). Only in few apartments the general airflow corresponded to the requirement of the II indoor climate category (>0,42 $l/(s \cdot m^2)$). Even average general airflow (0,3 $l/(s \cdot m^2)$) was below the II indoor climate category target value (>0,35 $l/(s \cdot m^2)$).

Based on measurements of indoor CO_2 levels and estimated CO_2 (as tracer gas) emission from residences during night (≈20:00…8:00) the air change in bedrooms was estimated [11], Figure 8. As measurements were done in major bedroom, the required airflow there should be at least 14 l/s. This average airflow was guaranteed only in 16 % of bedrooms during winter. Probably due to window airing during summer this airflow was in 44 % of apartments.

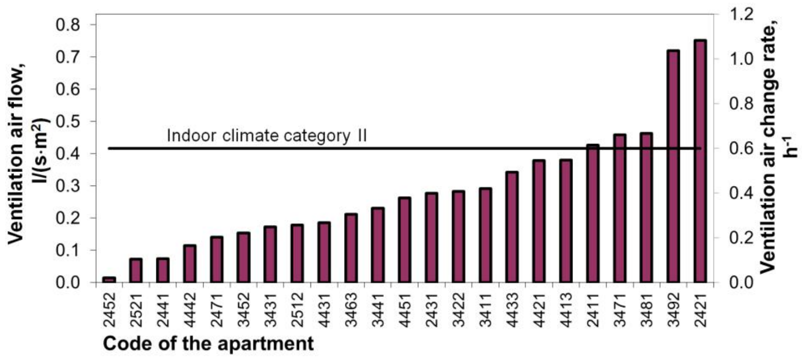

Figure 6: Ventilation airflow in apartments.

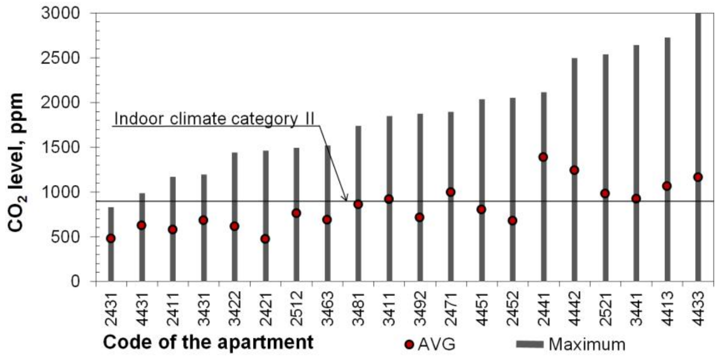

Figure 7: CO_2 levels in apartments.

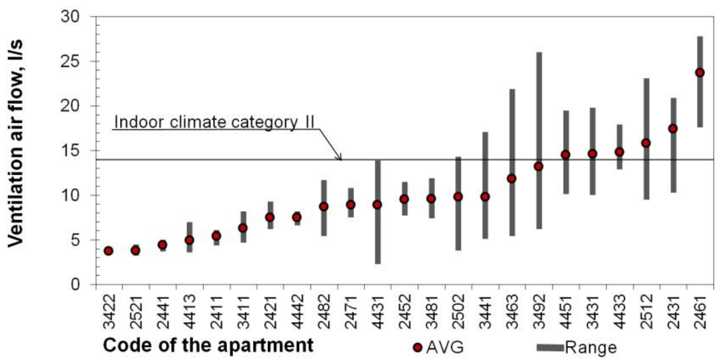

Figure 8: Ventilation airflows in bedrooms during winter.

Discussion

The results of current study show that studied buildings are substantially airtighter compared to buildings from the period 1960-1990. About 92% of studied buildings satisfied minimum requirements for airtightness in Estonia (q_{50} < 3.0 $m^3/(h \cdot m^2)$). According to international standards on ventilation [13] and heating energy consumption [14], studied apartment buildings are buildings with low air leakage rate.

However, given the fact that according to the EPBD all new buildings must meet by the end of 2020 nearly zero energy requirements, Estonian building sector have a lot of improvement to do if the airtightness requirements will be changed for example into level q_{50} < 1.0 $m^3/(h \cdot m^2)$).

Airtightness measurements showed small variation between newly built buildings with different structures and large variation within similar structural solution. For example air leakage rates of buildings made of prefabricated concrete elements where between q_{50} 0.82…4.55 $m^3/(h \cdot m^2)$, which clearly shows influence of workmanship quality. Also typical air leakage distribution indicates that reason for low airtightness performance is behind poor workmanship quality not behind low-grade building products. Airtight materials and good workmanship play important role in order to achieve high airtightness of building envelopes.

Due to larger air pressure difference over the building envelope in airtight buildings [12] and due to considerable moisture loads, special attention should be paid to the correct performance and balance of ventilation systems for ensuring good indoor environment.

The performance of ventilation was not good in studied apartments. There was very low correspondence for target values of II indoor climate category. The bad performance of ventilation is due to the extensive use of exhaust ventilation system. In cold climate taking outdoor air through the external wall without preheating does not provide thermal comfort (low temperatures, draft). If the heat recovery is not used, it results large energy bills. These are the main two reasons, why people decrease the ventilation airflows to the lover speed. If the exhaust fan located in apartment (bathroom, toilet, kitchen) then the also the noise prevents the use of ventilation in a proper way.

Conclusions

The mean air leakage rate at the pressure difference of 50 Pa in the entire database was 1.7 $m^3/(h \cdot m^2)$, the minimum being 0.8 $m^3/(h \cdot m^2)$ and the maximum 4.6 $m^3/(h \cdot m^2)$. The mean air change rate at the pressure difference of 50 Pa from all the data was 2.3 h^{-1} (minimum being 0.9 h^{-1} and the maximum 6.6 h^{-1}). Based on the results it can say that with all structural types it is possible to build airtight buildings and quality of workmanship plays important role in reaching low leakage rate level. Future airtightness requirements may need improvement of current constructional style.

Together with rising of air tightness of building envelope more attention should be paid to the performance of ventilation. It is not only question, what is the capacity of ventilation system. Increasing the ventilation airflow without proper design (noise reduction, avoiding draft, energy performance, etc.) may not guarantee the good result.

Acknowledgements

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A SURVEY OF AIRTIGHTNESS AND VENTILATION RATES IN POST 1994 NZ HOMES

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Abstract

The airtightness of 36 houses built since 1995 and across four cities in New Zealand (NZ) was measured. In a subset of 31 of these homes, the average ventilation rate was measured over several weeks in the winter using a perfluorocarbon tracer technique (PFT). These results can be added to earlier airtightness data to provide a platform for improving the air quality and energy efficiency of residential ventilation in NZ.

Earlier airtightness data from the mid 1990's showed a trend for newer houses to be more airtight than older houses, largely as a result of sheet lining materials replacing strip flooring and the development of more airtight joinery. This trend continued in this study, even though there are no airtightness requirements for houses in New Zealand. The average N_{50} result for houses built since 1995 was 6.7 air changes/hour (ACH), down from 8.5 ACH for houses built in the previous decade.

Most new houses meet NZ building code requirements for ventilation (window and door openings that exceed 5% of the floor area), but the PFT measurements showed that most houses struggled to reach recommended levels of ventilation (0.35-0.5 ACH during the winter) because the windows weren't open often enough.

In recent years it has become common for occupants to add additional supply-only ventilation to control moisture. Houses with operational supply-only ventilation systems generally had more than enough ventilation but there were several cases where the ventilation system had been turned off.

There was clear evidence of moisture problems in several of the more poorly ventilated houses.

Keywords

Airtightness, Ventilation, Residential, Tracer

Introduction

The aim of this study was to provide airtightness data for newer (post 1994) houses and to measure the achieved ventilation rate during occupancy. The measurements should provide some insight as to whether a ventilation scheme that relies on occupants to open windows can be relied on, or whether factors such as wintertime, security and noise intrusion prevent this from being so.

Earlier work at BRANZ [1, 2, 3] compiled an airtightness database of 137 homes built from the 1930's to the mid 1990's. A summary of this is shown in Figure 1.

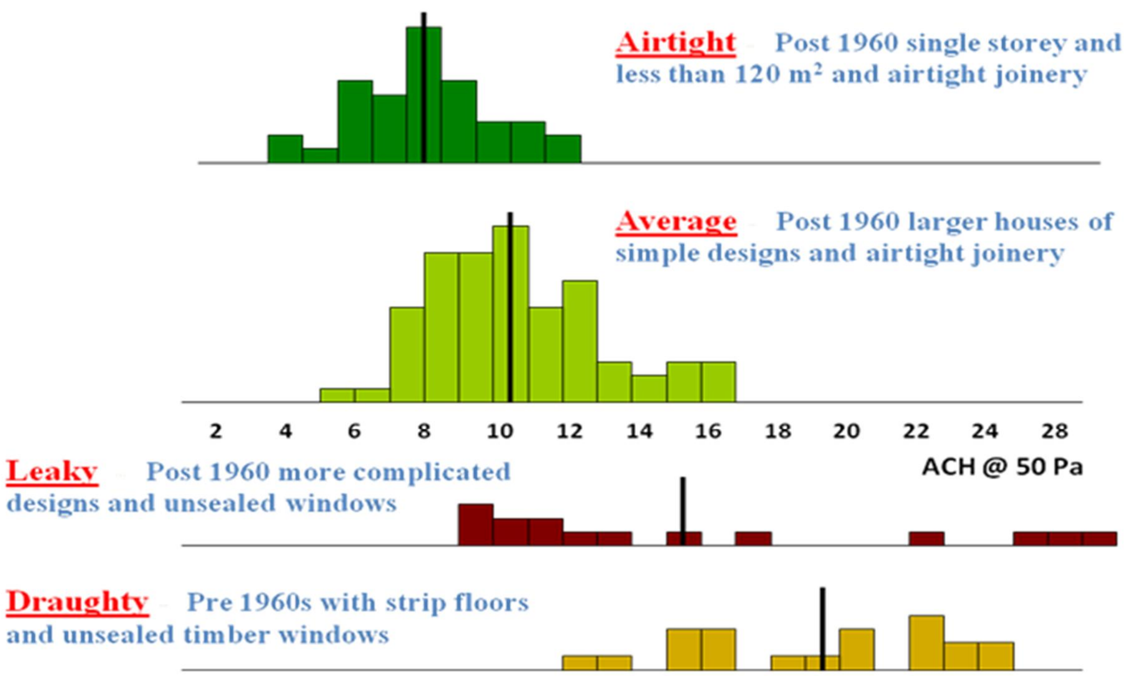

Figure 1: Summary of earlier house airtightness in New Zealand

The airtightness of New Zealand homes has increased over time, even though there is no requirement for airtightness in the NZ building code. The average N_{50} result from houses built before WWII was around 19 ACH but this reduced dramatically to 8.5 ACH for houses built between 1960 and 1980. A significant contributor to envelope air-tightening around 1960 was the shift from suspended tongue and groove flooring to sheet floor construction and slab-on-ground floors. Another change at a similar time was the shift from timber joinery to aluminium framed doors and windows, as well as a reduction of open fireplaces. This brought the opportunity to fit better air seals around opening windows and doors, at the same time improving the weather tight performance of domestic joinery. By the mid 1990's the mean airtightness result was 6.7 ACH.

In the USA, Sherman [4] reported a similar two-fold reduction in average N_{50} measurements over a similar time period. In this case the changes were largely voluntary but were also influenced by the 'weatherization programme' to improve the energy efficiency of low income homes. In contrast, Stephen [5] reports little change in the N_{50} measurements in UK houses over a similar period. Much more dramatic changes in N_{50} are reported in Canada and Sweden where mandatory airtightness targets were adopted to reduce the energy loss consequences of uncontrolled ventilation. A second driver of airtight construction in these cold climates is the need to control exfiltration to prevent interstitial condensation.

In NZ, materials and construction practices are likely to have continued to influence the airtightness of houses. Recent examples of changes are the widespread use of bonded plaster cornice or a square stopped interior plaster finish, and the adoption of air seals around window and door assemblies. In 2005, the NZ Building Code - Clause E2/AS1[6], changed to require air seals to be fitted around door and window assemblies. The aim was to improve the degree of pressure moderation across the joints between window frame and cladding and improve the weather tightness of what was seen as a weak point in window installation.

In terms of ventilation, building code requirements for residential buildings are often quite unsophisticated in countries with temperate climates. In New Zealand, occupants are expected to open windows for ventilation and the NZ Building Code offers an acceptable solution 'G4 Ventilation'[7] requiring window and door openings to be at least 5% of the floor area. It is clear from the airtightness measurements of older houses that window opening may have been unnecessary to meet ventilation needs because of the background infiltration. In newer houses, the changes in construction discussed above have closed down natural ventilation paths and it may be necessary to actually open the windows to provide adequate fresh air.

Ventilation also has a large part to play in the control of indoor moisture. Indoor moisture has always been the most pressing indoor air quality issue in New Zealand houses. A 1971 survey [8] reported moisture problems in half of the surveyed houses and later surveys [9,10] have shown that little has changed.

In the past it has been difficult to measure ventilation rates in homes because conventional tracer methods were too intrusive and expensive to use in large numbers of houses. This study used passive samplers and emitters that are more easily deployed [11,12] and to provide the first survey of ventilation achieved in NZ homes.

The study described here will help to provide a picture of the current housing stock and how New Zealander's currently ventilate their houses. This information will then be used in the wider WAVE (Weathertightness, Air Quality and Ventilation Engineering) programme at BRANZ. One of the aims of WAVE is to provide guidance on suitable ventilation options that are optimised for moisture control, energy efficiency and the airtightness of the house.

Experimental methods

Selection of houses

The airtightness and ventilation survey was split across 4 different cities in New Zealand: Wellington; Palmerston North; Dunedin; and Auckland. A database of building consents was used to obtain a random sample of consents for houses built after 1994 and these homeowners were contacted via a letter, resulting in a final total of 36 houses.

Of these 36 houses, 8 had supply-only positive pressure ventilation systems installed in the roof space. These systems distribute filtered roofspace air throughout the home depending on temperature measurements in the living space and roofspace.

Airtightness measurements

A blower door test to EN13829 [13] was completed on each of the 36 houses and then the opportunity was taken to measure the contribution of a range of different leakage paths. This was carried out by progressively sealing up openings in the envelope and repeating the blower door test.

In general, the following 3 tests were completed on each dwelling:

- A standard N_{50} test with no openings sealed
- A test with specific ventilation openings sealed. In most cases these ventilation openings consisted of extract fans in bathrooms and kitchens, some of which were simply ducted to the roof space (not outside).
- A final test with all obvious leakage openings sealed. The most obvious leakage openings to be sealed were around internal garage doors, and defective seals around attic access hatches.

The airtightness measurements were also used to give an estimate of the infiltration through the envelope using Equation 1.

$$Estimated\ Infiltration\ Rate = \frac{N_{50}\ result}{20} \tag{1}$$

Ventilation measurements

Ventilation measurements were performed in 31 of the 36 houses during winter. Winter was chosen because it was perceived that ventilation would be at its lowest i.e. windows are open less often.

A Perfluorocarbon Tracer (PFT) technique[12] was used and the equipment and analysis was supplied by the UK's Building Research Establishment (BRE). The technique involves deploying passive tracer gas sources and activated carbon sampling tubes in a building for a period of time. The resultant concentration of tracer in the sampling tubes can then be used to calculate an average ventilation rate.

Plans for each house were obtained to allow the room volumes to be pre-calculated. Key dimensions were measured upon arrival to ensure the plans matched the building and any differences were marked on the plans and the locations of sources and samplers modified accordingly.

The tracer sources were distributed around the home in a volume weighted manner, with the bathroom being chosen as a reference volume in all cases. Figure 2 shows a typical floor plan with tracer sources marked in red, and sampling tubes in blue.

Sampling tubes were placed in 4 rooms in each house, typically the lounge, bathroom, kitchen, and master bedroom. These were left in place for at least three weeks, but sometimes this was as long as 4 weeks because of occupants' unavailability. There were several important considerations when it came to the location of the source and sampling tubes:

- Source and sampling tubes need a good degree of separation to ensure the sampler collects tracer that has been well mixed in the zone.
- Both sources and sampling tubes needed to be located as far as practicable from windows/doors to allow incoming air to mix within the zone.
- Temperature has a direct influence on the emission rate; the sources should not be in direct sunlight or within 1.5 metres of heat sources. The temperature was also measured at each source location using Dallas DS1923 iButtons.

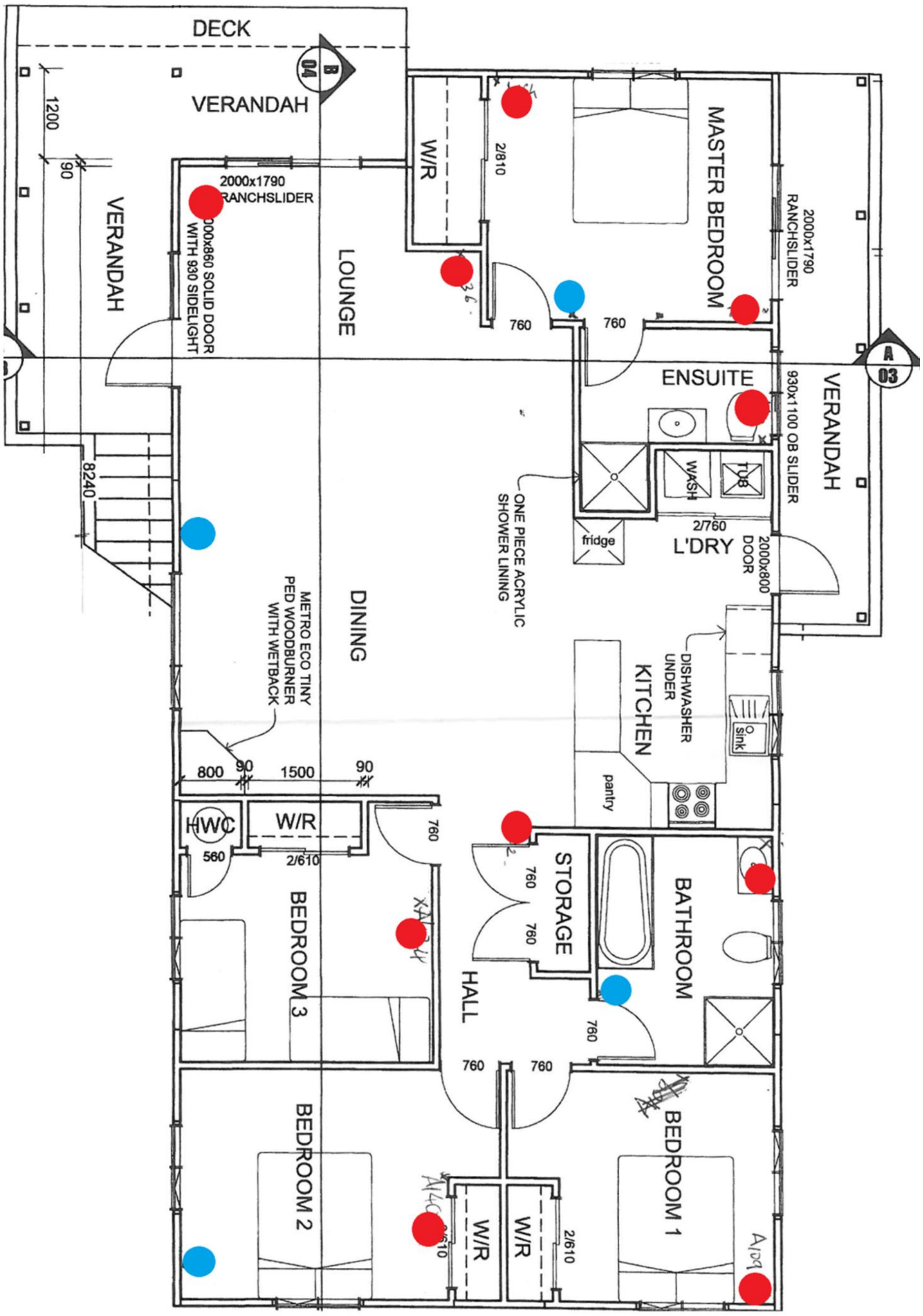

Figure 2: Typical distribution of tracer sources and sampling tubes

Results

Airtightness

The N_{50} results for the 36 houses are shown in Figure 3. Figure 4 shows the effect from sealing ventilation and obvious leakage openings (final test).

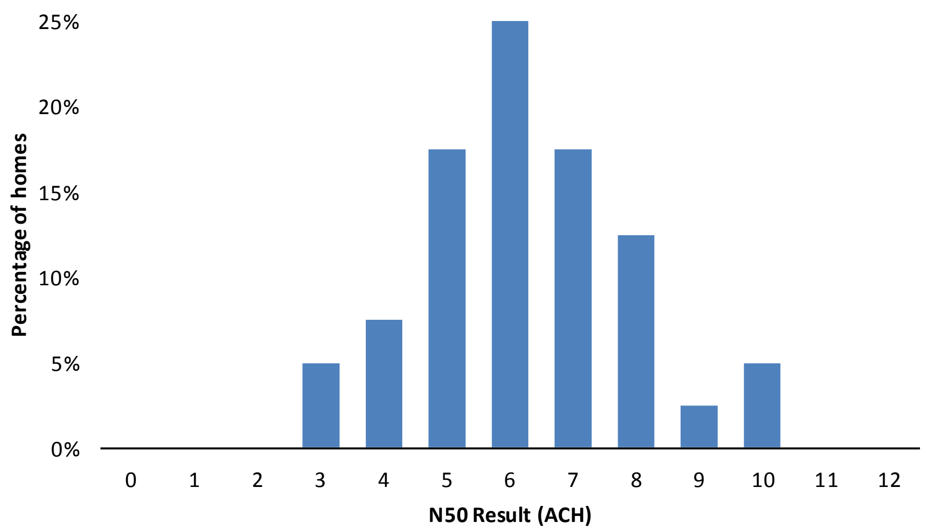

Figure 3: Distribution of airtightness measurements for post 1994 homes

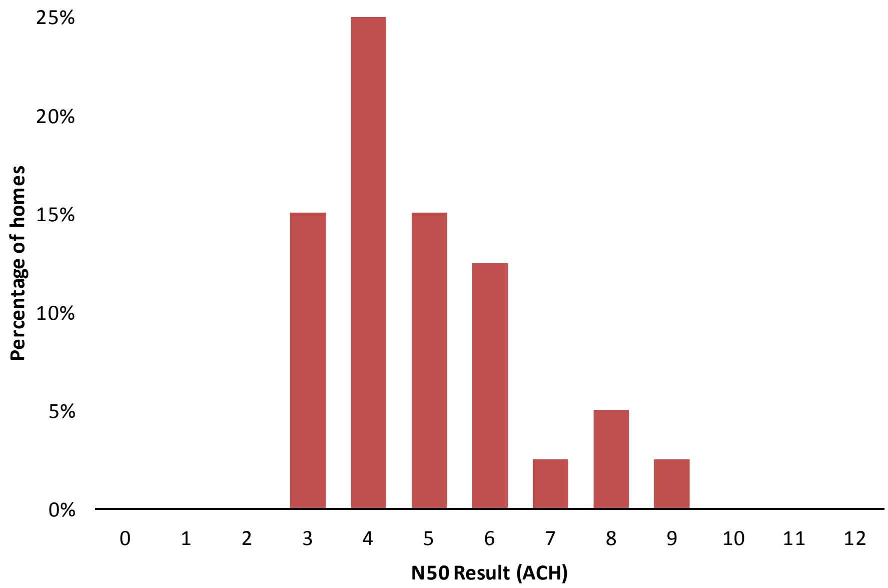

Figure 4: Distribution of airtightness results, with specific ventilation and obvious leakage openings sealed

Ventilation survey

The results of the ventilation survey are plotted in Figure 5, against the estimated rate from the airtightness measurements (using Equation 1). Circled on the right are several outliers, three of which had a supply only roofspace sourced ventilation system. A line of slope 1 is also plotted.

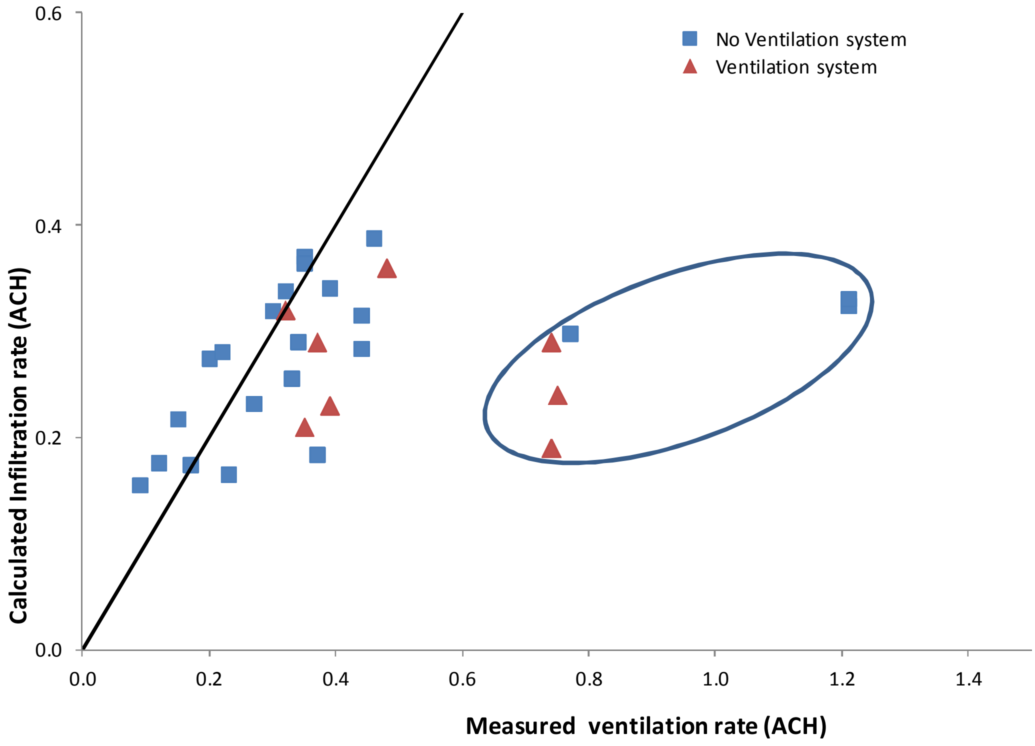

Figure 5: Infiltration vs. measured ventilation (ACH), with outliers circled

Discussion

Airtightness

The most important change from the earlier surveys was the significant reduction in the mean N_{50} result from 8.5 ACH to 6.7 ACH. The floor area of the newer houses was also bigger than those in the last survey, increasing from 115m^2 to 155m^2 (and not including internal access garages). The recent N_{50} results also fell in a much tighter range (7.8 to 3.1 ACH), suggesting more consistency in construction.

Much of the difference between Figures 3 and 4 was due to the leakage under internal access garage doors. On average, a drop in the N_{50} result of 1.4 ACH was noted when the internal access for the garage spaces was sealed from the rest of the house.

Internal garage doors therefore present an opportunity for increasing airtightness, and reducing infiltration from an unheated (and potentially polluting) part of the building.

Ventilation survey

There are clearly two groups of houses in Figure 5: those where the estimated infiltration rate and the measured ventilation rate are similar (25 cases) and those (6 cases) where additional ventilation (either from opening windows or supply-only ventilation systems) has been provided.

In the larger group, the small difference between the estimated infiltration rate (0.28 ACH) and the measured ventilation rate (0.32 ACH) indicates limited window opening by the occupants over the period. The measured ventilation rate of 0.32 ACH sits at the lower end of guidelines for acceptable indoor air quality [14]. In addition, observations of the presence of mould and mildew were made at several of the homes studied, evidence of excess indoor moisture.

The PFT technique is a longer-term, time-averaged measurement method and thus does not lend itself well to resolving small, short-term changes in ventilation performance. However, it is clear that window opening and the operation of extract systems in bathrooms and kitchens has added less than 0.2 ACH on top of the background air infiltration in most of these houses.

Overall, there is limited evidence of window opening providing the ventilation needed to control moisture and provide good indoor air quality in the more airtight homes constructed in the last 15 years.

Eight homes in Figure 5 were fitted with supply only ventilation systems. Three of these systems were shown to substantially increase ventilation above background infiltration to around 0.7 ACH. In the other 5 cases, little additional ventilation was provided by systems, several of which were apparently turned off to save energy during the period of PFT measurements.

Conclusions

This paper reports the results of a survey of house airtightness in New Zealand along with average ventilation rates measured using the PFT method. The conclusions of this study are as follows:

- **The airtightness of New Zealand homes continues to increase**. The average airtightness of houses built between 1994 and 2011 in this survey was an N_{50} of 6.7 ACH. Between 1960 and 1994 the average N_{50} was 9.7 ACH, dropping to 8.5 ACH for houses built in the early 90's. For even earlier houses it was 19 ACH at 50 Pa. This change has occurred without any intervention by the New Zealand Building Code.

- **Internal access garages have a large impact on airtightness**. The door into the garage was found to be a weak point in the envelope, contributing an average 1.4 ACH to the N_{50} result. A more effective door in this location would reduce the infiltration of potentially contaminated air from this unheated zone in the building.

- **Measured ventilation rates are similar to estimated infiltration in many houses**. Comparing the average infiltration (approximated as the N_{50} result divided by 20) and measured ventilation rates, resolves the ventilation added by small kitchen and bathroom ventilators and by opening windows. In 24 of the 30 cases the average infiltration rate of houses without mechanical ventilators is 0.28 ACH and the measured ventilation rate 0.32 ACH and in several of these houses indoor dampness was evident. In the six cases where infiltration had clearly been supplemented with additional ventilation, three of these were fitted with a supply ventilation system and in the other three this was achieved by opening windows.

- **Reliance on open windows for ventilation may not be adequate** This passive ventilation solution appears to have worked adequately at times when New Zealand homes were not particularly airtight. Since 1960, a wider choice of large sheet lining materials and changes in the standard of interior finish have increased the airtightness to the point where window opening is now questioned as a ventilation source for moisture control and indoor air quality. Particularly with modern lifestyles, and when there are security concerns.

- **The control algorithms for supply only ventilation systems may have scope for improvement**. Eight homes were fitted with roof-space sourced supply only ventilation systems that distribute filtered roof-space air under a simple temperature controlled regime. Three of these boosted the average ventilation well above the background infiltration but in five cases there was little evident change. The data indicates significant differences in the operation and control of these supply only systems.

This work has provided a platform on which to discuss ventilation options for New Zealand housing. The survey has shown that the trend to more airtight houses has continued in the last decade and that that occupant controlled ventilation by opening windows is limited and too unreliable for indoor moisture control. The next steps in the WAVE programme will investigate alternative ventilation solutions that adapt to window opening in a temperate climate and are optimised for indoor moisture control [15].

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NUMERICAL EVALUATION OF AIRTIGHTNESS MEASUREMENT PROTOCOLS

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ABSTRACT

In France, starting January 1st, 2013, the energy performance regulation will impose an airtightness treatment for every new residential building. This translates into several tens if not hundreds of thousands of envelope airtightness measurements a year that will have to be performed. They will have to be performed by a certified operator and according to the NF EN 13829 standard. This ISO standard is being revised under the Vienna agreement to become an EN ISO standard. This revision should include changes in the measurement protocol to reduce the uncertainty for two indicators commonly used: the air change rate at 50 Pa and the air permeability at 4 Pa.

As far as it is quite impossible to determine the real airtightness of a building, the measurement error cannot be estimated only by a numeric protocol. Our approach relies on the simulation of the measurement protocol with the software CONTAM, varying wind conditions and airtightness levels.

This article addresses three issues that impact the uncertainty on these derived quantities: the wind speed, the distribution of the leaks, and the pressure correction with the zero-flow pressure difference. This implicitly entails the investigation of influencing factors such as airtightness level

of the building. Based on the analyses of those simulations results, this paper proposes protocols for extracting the air permeability at 4 Pa with better accuracy.

KEYWORDS

Airtightness, Simulations, measurement protocols, uncertainty

INTRODUCTION

In France, the new energy performance regulation will start applying for every new residential building starting January 1st, 2013. It will impose an airtightness treatment and each building will have to justify a level for Q_{4Pa_Surf} (the air permeability at 4 Pa divided by the loss surfaces area excluding basement floor), which will have to be lower than 0.6 $m^3\ h^{-1}\ m^{-2}$ for houses. In most cases, this justification will involve an envelope airtightness measurement. It will have to be performed by a certified operator and according to the NF EN 13829 [1] standard and its implementation guide GA P50-784 [2]. The ISO 9972 [3] is the international standard associated to this European standard.

This ISO sets out the airtightness measurement protocol. Since the procedure for the review of this ISO is under way, various publications (e. g. [4] and [5]) look at the uncertainty of this protocol. The uncertainty is a crucial issue as soon as the measured value becomes a requirement. Various research works have shown that the uncertainty could be really important depending on the measurement conditions.

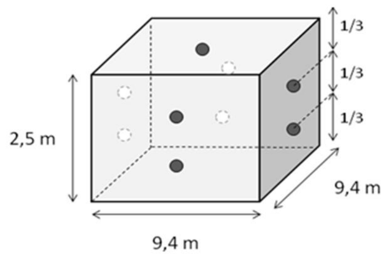
The objectives of this study are to determine the wind impact on the uncertainty of the measurement, and to find out a way to reduce it. So our approach relies on simulations of airtightness tests done with CONTAM[13].

This paper presents the impact of a constant wind during an airtightness measurement, depending on the airtightness level and the leaks distribution. Then, it explains how it is possible to drastically reduce the uncertainty due to the wind. The issue of the pressure correction with zero-flow pressure difference is also discussed.

METHOD

A numerical study has been carried out using CONTAM as multizone airflow calculation. In order to simulate airtightness measurement, a 1-zone model building has been designed. The simulated building envelope has 9 leaks: 2 leaks on the up-wind facade, 2 leaks on each of the 3 others facades and 1 leak on the roof. The following diagram describes the geometrical properties of the model.

[13] Multizone Airflow and Contaminant Transport Analysis Software



Local wind pressure coefficients:

C_p=-0.6 for the roof

C_p=0.5 for upwind façade

Figure 1: Geometrical properties of the model

CONTAM calculates the flow through each leak using the principle of the mass conservation in each zone. For this model, each leak flow's derives from the following equation:

$$q_{mi} = \rho_{air} * c_i * \Delta P^{0.67} \quad (2)$$

With q_{mi} = flow through a leak *[m³ h⁻¹]*, ρ_{air} = air density *[kg m⁻³]*

and c_i = air leakage coefficient *[m³.s⁻¹.Pa⁻⁰·⁶⁷]*

The pressure difference depends on the imposed pressure between the outdoor and the indoor, and the pressure due to the wind:

$$\Delta P = P_{out} - P_{int} - P_{wind} \quad (2)$$

The wind pressure depends on:

$$P_{wind} = \frac{1}{2} * \rho_{out} * c_p * {V_{wall}}^2 \quad (3)$$

With c_p = local wind pressure coefficient [-], and V_{wall} = Wind speed at the height of the wall [m s^{-1}]

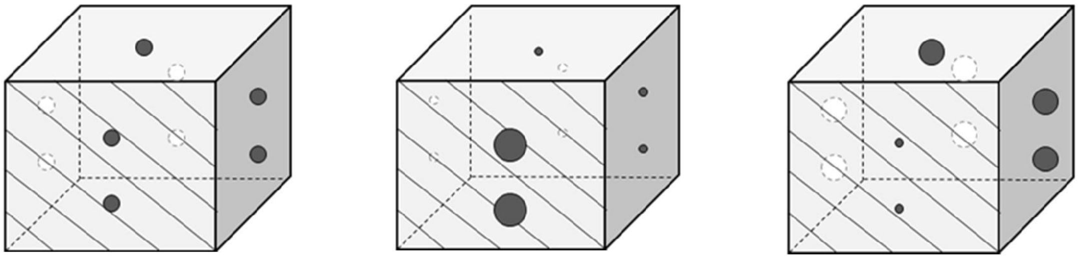
The wind speed at the height of the wall depends on the wind speed at 10 m:

${V_{wall}}^2 = {A_0}^2 * (\frac{H_{house}}{10})^{2a} * {V_{wind}}^2$	(4)

(4)

With $A_0 = 0.6$ and $a = 0.28$ (coefficients for houses in a suburban area, [6]).

Three different geometric models have been tested. The nine leaks of the first model are all the same, i.e. the size of the "hole" is the same for all of them. For the second model, the size of the two leaks on the upwind side represents 75% of the leakage area. And for the third model, the size of the 2 leaks on the upwind side represents 5% of the leakage area.



Model 1: equal leaks — Model 2: 75% on the up-wind side — Model 3: 5% on the upwind side

Figure 3: Three different distributions of leaks

Each simulated airtightness measurement consists of 7 measurement points from 10 to 70 Pa for a pressurization test (or from -70 to -10 Pa for a depressurization test). With these 7 points, we made a linear regression according to the ISO9972. The impact of the stack effect is not studied, al the simulated tests are applied under isothermal conditions.

The major objective was to estimate the wind impact depending on the airtightness level. For three airtight levels (0.1 then 0.6 and 3 $m^3\ h^{-1}\ m^{-2}$), the wind speed varies from 0 $m\ s^{-1}$ to 8 $m\ s^{-1}$ or 9 $m\ s^{-1}$ (depending on the leaks' distribution).

RESULTS

Wind impact

For each leaks' distribution, the simulated measurement of Q_{4Pa_Surf} evolution depending on the wind speed is represented. For some wind speeds, the relative error between the simulated measurement Q_{4Pa_Surf} and the Q_{4Pa_Surf} assumed to represent the real leak, is estimated. The two following graphs show results for the Model 1: "equal leaks". The figure 3 represents the depressurization tests results, and the figure 4 represents the pressurization tests results.

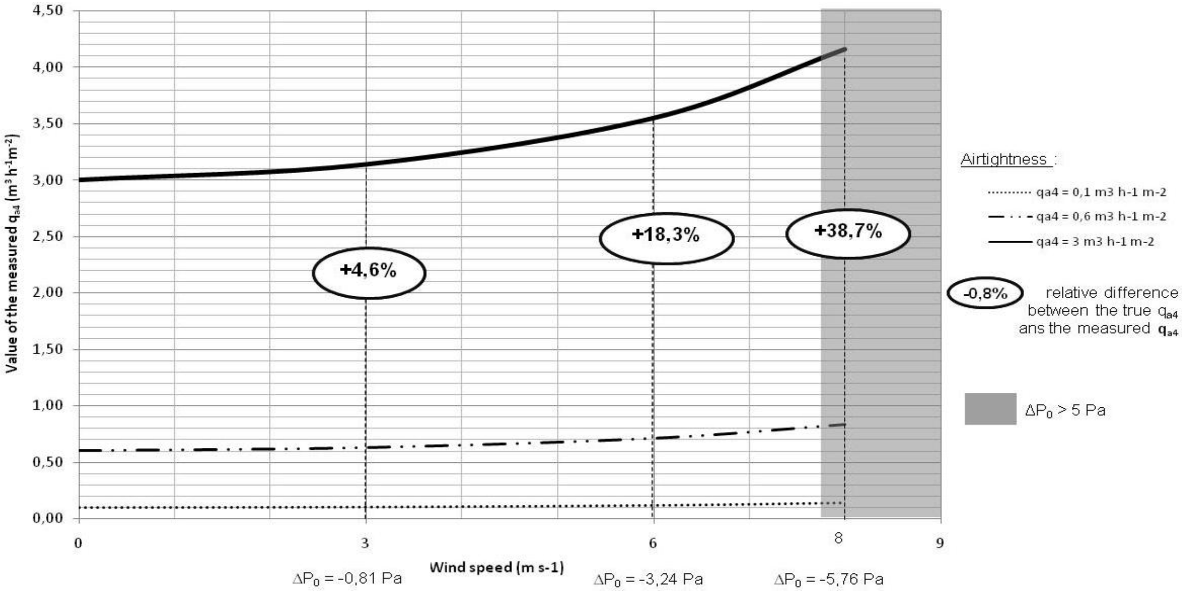


Figure 2: Wind impact on the value of the measured Q_{4Pa_Surf} for depressurization tests, with 9 identical leaks

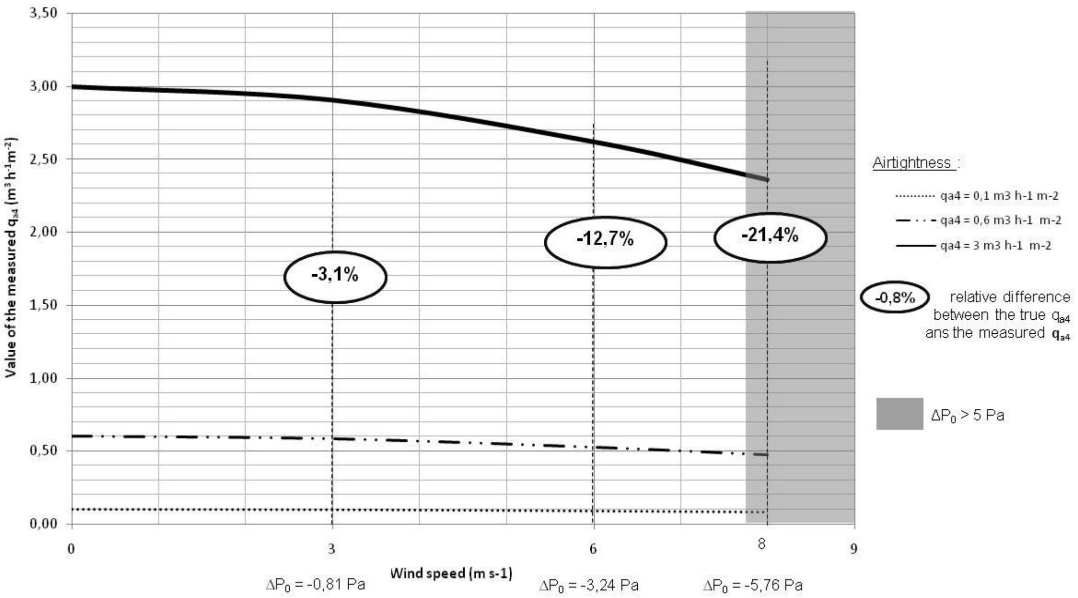


Figure 3: Wind impact on the value of the measured Q_{4Pa_Surf} for pressurization tests, with 9 identical

According to the ISO 9972, if the zero-flow pressure difference is greater than 5 Pa, the test is not conform. For the distribution of the model 1, the zero-flow pressure difference exceeds 5 Pa when the wind speed is between 7 and 8 m s^{-1}. Thus, for a wind speed lower than 8 m s^{-1}, the test is conform (it has been checked that n is in range 0.5 to 1 and that r^2 is not less than 0.98 for each linear regression).

For the model 1, the relative error for a test declared valid could be more than 20% in pressurization and more than 35% in depressurization. For the three models, the relative error due to the wind is independent of the airtightness level. The following table gives the same key figures for the models 2 and 3.

	Model 2		**Model 3**	
Wind speed [m s^{-1}]	**Relative error in pressurization**	**Relative error in depressurization**	**Relative error in pressurization**	**Relative error in pressurization**
3	+1,3%	-0,2%	-0,2%	+1,4%
6	+3,5%	-1,3%	-1,8%	+3,5%
9	+6,1%	-3,5%	-4,5%	+8,9%

Table 1: Relative error due to the wind for models 2 and 3

The zero-flow pressure difference exceeds 5 Pa for wind speed higher than 12 m s^{-1} for the model 2, and for wind speed in range 8 and 9 m s^{-1} for the model 3. For all linear regressions, n and r^2 respect the ISO 9972 requirements.

Table 1 shows that the impact of the wind depends greatly on the leakage distribution on the envelope. It highlights that the error drastically decreases when there is as much leakage on upwind façade ($C_p>0$) as in all others not upwind ($C_p<0$).

For one test, the ISO9972 recommends to make two sets of measurements: for pressurization and depressurization. With those figures, the average of a depressurization set result and a pressurization set results was estimated. The following table gives the relative error in this case for the three models.

Wind speed [m s^{-1}]	**Relative error for Model 1**	**Relative error for Model 2**	**Relative error for Model 3**
3	+0,8%	+0,6%	+0,6%
6	+2,8%	+0,3%	+0,8%
8	+8,7%	--	--
9	--	-0,9%	+2,2%

Table 2: Relative error due to the wind for two sets of measurements: for pressurization and depressurization

The simulated measurement of pressure differences correction with the zero-flow pressure difference

According to the ISO 9972, in order to obtain the induced pressure differences, the average zero-flow pressure difference is subtracted from each of the measured pressure differences. The measured Q_{4Pa_Surf} calculated without this correction and the measured Q_{4Pa_Surf} calculated with this correction have been compared. These figures are valid for each tested airtightness level.

	Wind speed: 3 m s^{-1}		Wind speed: 6 m s^{-1}		Wind speed: 9 m s^{-1}	
	Without correction	**With correction**	**Without correction**	**With correction**	**Without correction**	**With correction**
Depressurization	-2,6%	4,6%	-12,9%	18,3%	-24,1%	+38,7%
Pressurization	3,8%	-3,1%	13,1%	-12,7%	22,0%	-21,4%

Table 3: Impact of the pressure correction on the relative error due to the wind for the Model 1

According to these figures, the pressure correction with the average zero-flow pressure difference has a big influence on the result. Nevertheless, in these geometric models this correction does not decrease the error between the simulated measurement Q_{4Pa_Surf} and the Q_{4Pa_Surf} assumed to represent the real leak.

DISCUSSION

The ISO9972 explains that if the meteorological wind speed exceeds 6 m s^{-1}, it is unlikely that the zero-flow pressure difference can be lower than 5 Pa. Nevertheless, there is no wind speed limit. Considering a wind speed of 6 m s^{-1}, with the leaks distribution of the model1, the uncertainty of the measured Q_{4Pa_Surf} could be more than 18%. Moreover, the relative error on Q_{4Pa_Surf} could be more than 35% if a wind speed for which the zero-flow pressure difference is just under 5 Pa is considered. And none of the validation criteria of the ISO9972 could reject those tests.

These simulated tests have shown that making two sets of measurements in pressurization and depressurization is definitely a way to avoid the wind impact. For each leak distribution, if depressurization tests overestimate the Q_{4Pa_Surf}, then pressurization tests underestimate it (and vice versa), in the same order of magnitude. So, the average of the two results is far closer to the true Q_{4Pa_Surf}. This solution reduces significantly the uncertainty, which is not more than 9% in the worst scenario.

Another significant point of those results is that the uncertainty and the zero-flow pressure difference are independent of the airtightness level. This is true here because the n is the same for each leak. However, they depend on the leaks distributions. But, because the n of each leak and their distribution are unknown during a test, it is not possible to estimate for each measurement the mistake done because of the wind.

The final important issue raised by this article is the impact of the pressure differences correction. In this model, the impact is important, but does not reduce the relative error. Ideally, the correction should be done with the pressure difference at each leak, but it is not feasible. However, the difference between a result without and with correction shows that a better way to correct the measured pressure differences has to be found.

Those results have been obtained with a numerical study that does not exactly reflect what could happen during a true test. Firstly, the stack effect is not taken into account in those models. Secondly, the model is based on three hypothetical leaks and pressure coefficient distributions, and a flow exponent n constant for each leak. And thirdly, the wind speed is supposed constant during a test. Nevertheless, this simple model reveals some interesting results regarding the order of magnitude of the uncertainty due to the wind.

CONCLUSION

The objectives of this study were to determine the wind impact on the uncertainty of the measurement, and to find out a way to reduce it. Even if the model used to simulate a measurement of the airtightness of a building has some limits, it showed the wind could be responsible of significant errors (in some cases, more than 35%). Doing two sets of measurement in pressurization and depressurization could reduce this deviation in a very important way. This study also showed that the pressure differences correction imposed by the protocol might not be the better one to reduce the measurement error.

Finally, imposing the two sets of measurement and determining another way to correct the pressure differences should lead to reduce the errors during an airtightness measurement.

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AIRTIGHTNESS OF OFFICE AND EDUCATIONAL BUILDINGS IN SWEDEN – MEASUREMENTS AND ANALYSES

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Abstract

The airtightness of office and educational buildings influences energy use and thermal comfort. A leaky building is likely to have a high use of energy and thermal discomfort. The knowledge of real airtightness levels of entire buildings and their impact on the energy use is very low, except for a study carried out in the USA. Therefore two different methods of airtightness testing were applied to six entire Swedish office and educational buildings built since 2000. The first method involves using the ventilation system of the building and the second one to use a number of blower doors. Information on 30 other airtight tests was collected. During the airtightness testing the air leakage paths were detected using infrared scanning and smoke sticks.

The two methods are useful for testing entire office buildings, apartment buildings, industrial buildings and other premises.

The thirty-six tested buildings show a very good airtightness level, close to the Swedish passivehouse requirements. All previously tested office buildings in the USA, Canada and the UK are much leakier. The tested buildings showed some leakage paths, which could easily have been taken care of during construction, but are rather difficult to stop now.

The paper describes and evaluates the airtightness tests of thirty-six Swedish office and educational buildings and their implication for energy use.

Keywords

Airtightness, blower door, energy, measurement, office building, pressurisation, school.

Introduction

It is well-known that the building sector plays an important role in the work towards sustainable development. The sector represents extensive economic, social and cultural values, at the same time as it causes extensive environmental impact due to its high use of energy and materials. An important part of the energy use within the building sector is related to office and educational buildings. The total energy use of an average Swedish office building is 220 kWh/(m²year) (heated usable floor area) of which electricity stands for 108 kWh/(m²year). Of this 108 kWh/(m²year), 57 kWh/(m²year) is due to office equipment, of which 23 kWh/(m²year) is lighting. This was shown in a study of 123 office and administrative buildings of different ages [1]. Of the floor area in all office buildings, 69 % is heated by district heating and the average use of district heating energy is 110 kWh/(m²year) [2]. Both new and old office buildings have a substantial potential for energy savings and improvement of indoor climate. While many new office buildings may have a low energy use for heating compared with older office buildings, they may have a higher electricity use. This is due to a high use of electricity for ventilation, cooling, lighting and office equipment. An important parameter affecting the energy use for space heating and cooling, and thus the indoor climate, is the airtightness of the building envelope. In a leaky building the energy use increases due to uncontrolled infiltration/exfiltration. The air leaking in and out through the building envelope increases the energy use as it, for example, does not pass through a heat recovery unit. The uncontrolled air leakage can contribute to discomfort such as draught, which can result in the indoor temperature being raised to improve the comfort, causing an increased energy use from the user's behaviour.

Unfortunately, there is no simple and accurate method of relating the airtightness of a building to the air leakage for an office or educational building in operation. This is due to difficulties in determining the location and characteristics of all leakage paths and determining the wind pressure coefficients [3].

The aim of this project [4] was:

- to use different measuring methods for determining the airtightness of educational and office buildings,
- to determine the airtightness for modern educational and office buildings,
- to determine the influence of airtightness on the energy use for space heating.

Method

The hypothesis is that, in many cases, the airtightness can be measured using the ventilation system of the building. Two different methods were used:

- Airtightness testing using a number of blower doors (portable fans), www.energyconservatory.com. European standard 13829, Method B was applied [5].

- Airtightness testing using the ventilation system of the building. Canadian standards were applied [6, 7].

The measurements involve pressurizing or depressurizing the entire building and measuring the corresponding air flow to maintain the different pressure differences between inside and outside. Ventilation openings and lead-throughs are sealed before the measurements. Thus the airtightness of the building envelope is determined. The location of leakage paths are determined using thermography and smoke.

When using the ventilation system of the building the following has to be investigated before:

- Exploring the building automation system to ensure that the ventilation air flows can be controlled and that it is likely to arrive at the necessary air flows. It is usually easier if the building has a demand controlled ventilation system.

- Ensuring that the air flows can be measured and that it can be done with adequate accuracy.

Within this project three schools and three office buildings were tested. An additional 31 tests had been carried out before by other Swedish organizations.

To determine the air infiltration/exfiltration rate from the results of pressurization tests there are different ventilation models. The ventilation models can be divided into: “air change” methods, reduction of pressurization test data, regression techniques, theoretical network methods, simplified theoretical methods [8]. The first three models are empirical techniques, which tend to be loosely based on the physical principles of air flow. The other models are theoretical models, which are based on a much more fundamental approach involving the solution of the equations of flow for air movement through openings in the building envelope. Empirical methods are usually straightforward to use, but tend to be unreliable and have a limited field of application. On the other hand, theoretical models have a potentially unrestricted applicability but are often demanding in terms of data and computer execution time. Theoretical calculation techniques can divided into: single zone network models, multi zone network models and simplified theoretical techniques. These models require a lot of information e.g. wind pressure coefficients, air leakage distribution for the building envelope, local wind speed, geometry of the building. Due to the limited amount of information on the tested buildings the method using reduction of pressurization test data was chosen in order to determine an order of magnitude for the average infiltration/exfiltration rate.

The reduction of pressurization test data method does nevertheless provide valuable information concerning the average infiltration performance of the building. The artificial pressurisation/depressurisation of a building to determine air leakage performance is now fairly common practice. The test only provides data regarding the “leakiness” of the building. The result provides no information on the distribution of openings or on how infiltration will be affected by wind, temperature, terrain, or shielding. However, several experimental results have shown that the approximate air infiltration rate will be of the order of one twentieth of the measured air change rate at 50 Pa [9], i.e.:

$$Q_{inf} = Q_{50}/20 \qquad (1)$$

where Q_{inf} = infiltration rate (h^{-1})

Q_{50} = air change rate at 50 Pa.

Calculations have shown that the ratio can vary between 6 and 40 depending upon the house, the climate and the shielding [3].

To determine the energy use caused by air infiltration/exfiltration the infiltration/exfiltration rate was first calculated from the pressurization tests and then the energy use was calculated using degree days for Stockholm. For most of the buildings the only available information was the floor area, the volume, type of ventilation system and type of building technology, the results of a pressurization test.

Tested building

The aim was to test educational and office buildings built after the year 2000 with a floor area preferably larger than 1000 m². It should be a mix of buildings with specific airtightness requirements and without.

Outside this project

31 buildings had been tested by different organisations e.g. the Technical Research Institute of Sweden, Akademiska Hus, Skanska, WSP. All the buildings were built between 2007 and 2012. The buildings are mainly schools and offices, but also homes for the elderly, shops, and sports centres (see Table 1). The smallest building has a floor area of 800 m² and the biggest 17 000 m². All buildings have balanced mechanical ventilation with heat recovery. The building envelopes vary, ranging from prefabricated concrete to stud walls.

Type of building	Year	Number of storeys above ground	Floor area, m²	Volume, m³	Building envelope
Shop	2011	1-2	8,221	61,090	Prefabricated concrete/stud wall
Sport Centre	2011	1-2			Prefabricated concrete/stud wall
Office	2008		1,950	5,250	Sheet metal/expanded plastics elements
Office	2010		3,905		Prefabricated concrete
Office	2010	6	4,094	15,171	Some kind of facade system, TRP
Office	2010	5	17,000		
Office	2007	5	8,574	25,722	Prefabricated glass façade/stud wall
Office/industry	2009		379/1,269		Plannjaelement/stud wall
Storage/workshop /office	2011	1-2			Stud wall, TRP
Food store	2011		1,540	8,000	Concrete PPM, plaster expanded clay, TRP plastic foil
School	2009				
School	2011	1-2			Stud wall
School	2008	1-2			Stud wall
School	2008	1	1,840		Stud wall
School	2009	1-2	1,134		Stud wall, TRP
School	2008	1-2			
School	2010	1-2	973		Stud wall
School	2010	1-2	973		Stud wall
School	2010	2-3			Concrete/stud wall
School	2010	1-2	761		Stud wall
School	2010	2	3,425	13,500	Infill wall, loft ceiling beams of HDF
School	2011	1-2	959		Stud wall
School	2011	1-2	2,250	8,995	Stud wall, TRP
School	2007	2			
School	2011		880	3,300	PPM, stud wall, plasict foil,

School	2010		800	3,190	Prefabricated concrete/infill wall
School	2011		2,950	11,500	PPM, stud wall, TRP tak, plastic foil
School	2010		3,340	14,000	PPM, stud wall /TRP, plastic foil
Home for the elderly	2012	7	4,762	14,800	Prefabricated concrete
Home for the elderly	2011		4,200	11,000	Infill walls, concrete roof

Table 1: Description of tested buildings. Year refers to year of construction.

Within this project

Five buildings were tested for the purpose of this project, three office and three educational buildings. All the buildings were built between 200x and 2011 (see Table 2). The smallest building has a floor area of 800 m² and the biggest 20 000 m². All buildings have balanced mechanical ventilation with heat recovery. The building envelopes vary, ranging from prefabricated concrete to stud walls.

Type of building	**Year**	**Number of storeys above ground**	**Floor area, m²**	**Volume, m³**	**Building envelope**
Exhibition/office	2011	1-2	20,000	204,000	Prefabricated concrete sandwich elements, HDF-floor structure
Office	2009	6	12,000	48,000	Façade bricks and glass
Office	2009	10			Prefabricated glass facade
School	2007	2	2,628	8,600	Light-weight concrete block wall
School	2011	1	1,030	2,967	Wood-framed wall
School	2009	2	2,098	7,148	Wood-framed wall

Table 2: Description of tested buildings. Year refers to year of construction.

Results

All the buildings tested outside the project are very airtight (see table 3). The average airtightness was 0.3 l/sm² @ 50 Pa which is equivalent to the voluntary Swedish requirement for passive houses [10]. The best building had a value of 0.1. For most of the buildings airtightness requirements were made ranging from 0.2 to 0.8 l/sm² @ 50 Pa, which can be compared with the requirement of the previous Swedish building code (before year 2006), 1.6 l/sm² @ 50 Pa. Only two buildings did not meet their requirement. The current building code does not have any specific requirement. All previously tested office buildings in the USA, Canada and the UK are much leakier [11]. Common leakage paths were exterior doors and connections between façade elements and floors/roofs, most of which would be difficult to tighten afterwards. Most buildings were tested with blowerdoors covering most of the buildings. Some were tested with the ventilation system.

Type of building	**Year of construction**	**Test method**	**Envelope area, m²**	**Airtightness require-ment, l/sm² @ 50 Pa**	**Measured air tightness, l/sm² @ 50 Pa**	**Main leakage paths**
Shop	2011	Blowerdoors, three fans, the whole building	18,721		0.18	Concrete element joints, exterior doors
Sport Centre	2011	Blowerdoors, two fans, the whole building	6,616	0.4	0.44	Exterior doors etc.
Office	2008	Ventilation system	2,580		0.34	Entrance parts/windows /exterior doors
Office	2010	Ventilation system		0.4	0.27	
Office	2010	Blowerdoors, one fan, the whole building	4,237	0.5	0.43	Connections between floor and wall
Office	2010	Blowerdoors, three storeys, one at a time	14,610	0.6	0.55	
Office	2007	Ventilation system/two blowerdoors		0.8	0.7	Connection between facade elements, facade and roof elements
Office/in dustry	2009	Ventilation system	4,560	0.25	0.26	Connection between ceiling and wall/workshop – exterior doors

Storage/ workshop /office	2011	Blowerdoors, two fans, the whole building	10,034	0.3	0.29	Exterior doors
Food store	2011	Blowerdoors, two fans, the whole building	3,995	0.8	0.62	TRP/expanded clay, windows, Entrance parts
School	2009	Ventilation system, the whole building excl. basement	4,912	0.5	0.36	
School	2011	Blowerdoors, one fan, the whole building	2,607	0.2	0.13	
School	2008	Blowerdoors, one fan, the whole building	3,335	0.45	0.41	
School	2008	Blowerdoors, one fan, the whole building	5,180	0.4	0.21	
School	2009	Blowerdoors, one fan, the whole building	2,832	0.6	0.27	Exterior doors
School	2008	Blowerdoors, one fan, the whole building	2,414	0.3	0.26	
School	2010	Blowerdoors, one fan, the whole building	2,460	0.6	0.23	Exterior doors and windows
School	2010	Blowerdoors, one fan, the whole building	2,460	0.6	0.19	Exterior doors and windows
School	2010	Blowerdoors, one fan, the whole building	2,182	0.6	0.57	
School	2010	Blowerdoors, one fan, the whole building	2,054	0.5	0.38	Exterior doors
School	2010	Blowerdoors, one fan, the whole building	5,513	0.2	0.09	No major leakage paths
School	2011	Blowerdoors, one fan, the whole building	2,520	0.40	0.28	Exterior doors

School	2011	Blowerdoors, one fan, the whole building	4,973	0.25	0.17	Exterior doors
School	2007	Blowerdoors, one fan, the whole building	3,941	0.4	0.45	Exterior doors etc.
School	2011	Blowerdoors, one fan, the whole building	2,261	0.6	0.48	Roof, windows and doors
School	2010	Blowerdoors, one fan, the whole building	2,295	0.3	0.4	Connection wall-ceiling, exterior door
School	2011	Blowerdoors, one fan, the whole building	4,822	0.2	0.16	
School	2010	Blowerdoors, three fans, the whole building	5,641	0.8	0.88	
Home for the elderly	2012	Blowerdoors, one fan, the whole building	4,081	0.3	0.20	Exterior doors
Home for the elderly	2011	Blowerdoors, x fans, the whole building	3,900	0.2	0.14	
Average				0.44	0.30	

Table 3: Measured air leakage and leakage paths.

For twelve of the buildings information on the volume was available and the airtightness could be recalculated to ach @ 50 Pa (see table 4). A comparison of the buildings is now different due to different ratios between volume and envelope area. Using a simple method of calculating the infiltration (see Method) an average infiltration rate was estimated. The result was an average air infiltration rate during the heating season of 0.03 ach (air changes per hour), varying between 0.01 and 0.06. This is equivalent to an energy use for space heating of 4 kWh/m^{2}year. If the buildings would have only met the requirements of the previous building code the energy use might have been five times higher i.e. 20 kWh/m^{2}year.

Type of building	Year	Measured airtightness l/sm² @ 50 Pa	Measured airtightness ach @ 50 Pa	Infiltration/ex filtration, ach	Energy use for heating infiltration, kWh/m²year
Shop	2011	0.18	0.20	0.01	2
Office	2008	0.34	0.60	0.03	3
Office	2010	0.43	0.43	0.02	3
Food store	2011	0.62	1.11	0.06	10
School	2010	0.09	0.13	0.01	1
School	2011	0.17	0.34	0.02	2
School	2011	0.48	1.18	0.06	7
School	2010	0.4	1.04	0.05	7
School	2011	0.16	0.24	0.01	2
School	2010	0.88	1.28	0.06	9
Home for the elderly	2012	0.20	0.20	0.01	1
Home for the elderly	2011	0.14	0.18	0.01	1
Average		0.34	0.58	0.03	4

Table 4: Measured air leakage and calculated energy use for heating infiltrating air.

Also the recently tested five buildings were fairly airtight, but not as airtight as the previously tested buildings (see Table 5). For the sixth building the result was not available at the time of writing this report. One contributing factor might be that there were only two buildings which had a specified airtightness requirement.

Type of building	Year of construction	Test method	Envelope area, m²	Airtightness require-ment, l/sm² @ 50 Pa	Measured air tightness, l/sm² @ 50 Pa	Main leakage paths
Exhibition/ office	2011	Ventilation system, the whole building	40 400	0,4	0,39	Connection between façade elements and columns, between facade and roof, exterior doors.

Office	2009	Ventilation system, storey 3, back pressure storey 2, 4, atrium and staircase	5 600		0,85	Connection between infill walls and steel columns, windows
School	2007	Blower Door	3 923	-	0,87	Lead-throughs, windows
School	2011	Blower Door	2 775	-	0,45	Doors, windows
School	2009	Blower Door	4 307	-	0,62	Lead-throughs, windows, doors.
Average					0,64	

Table 5: Measured air leakage and leakage paths.

For the recently tested buildings, information on the volume was available and the airtightness could be recalculated to ach @ 50 Pa (see table 6). The comparison of the buildings is now different due to different ratios between volume and envelope area. Using a simple method of calculating the infiltration (see Method) an average infiltration rate was estimated. The result was an average air infiltration rate during the heating season of 0.05 ach (air changes per hour), varying between 0.01 and 0.08. This is equivalent to an energy use for space heating of 6 kWh/m²year. If the buildings would have only met the requirements of the previous building code, the energy use might have been three times higher 20 kWh/ m²year.

Type of building	Year	Measured airtightness l/sm² @ 50 Pa	Measured airtightness ach @ 50 Pa	Infiltration/exfiltration, ach	Energy use for heating infiltration, kWh/m²year
Exhibition/office	2011	0,39	0,28	0,01	5
Office	2009	0,85	0,36	0,02	2
Office	2009				
Education	2007	0,87	1,44	0,07	8
Education	2011	0,45	1,51	0,08	7
Education	2009	0,62	1,34	0,07	8
		0,64	0,99	0,04	6

Table 6: Measured air leakage and calculated energy use for heating infiltrating air.

Conclusion

This study clearly shows that it is possible to build very airtight educational and office buildings. Most likely, the energy use for infiltration in these buildings are almost negligible i.e. in the order of magnitude of a couple of kWh/m²year. This number can be compared with the total energy use for space heating for a typical average Swedish office building of 110 kWh/ m²year, where infiltration might account for 10-20 kWh/m²year if only the airtightness requirement of the previous building code is fulfilled, which is likely.

Two different methods of measuring the airtightness of entire buildings have been used, using the building's ventilation systems and using a number of blower doors. Both methods can be used and combined. The choice of method depends on the prerequisites of the test object. For big buildings using the ventilation system can be preferable. Tests during construction, which are recommended to ensure good airtightness, can often only be carried out using blower doors. The two methods can be applied to office buildings, apartment buildings, industrial buildings and other premises. For apartment buildings the blower door technique is often the only method as the ventilation system often has insufficient capacity, unless the building is very airtight. Complete testing includes determination of the location of leakage paths.

Acknowledgements

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A NUMERICAL STUDY ON THE ROLE OF LEAKAGE DISTRIBUTION AND INTERNAL LEAKAGES UNDER UNSTEADY WIND CONDITIONS

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Abstract

The existence of air leakages in a building has been very clearly stated as an important reason for energy loss. The decrease in the efficiency of the mechanical ventilation has also been clarified. The global demand for achieving nearly zero-energy buildings makes the uncontrolled leakage paths even more undesired. Despite the fact that steady state measurements of in- and exfiltration rates offer a simple and easy way of estimating the airtightness level of an eclosure, a supplement to those methods might be imposed.

While a significant amount of studies points out the key role of the 'artificial' unsteady conditions to the actual leakage rates of a building, there are only few that discuss the influence of natural unsteady phenomena. In this context, the correlation between the dynamic characteristics of the wind and the leakage numbers of a building, should be more studied. Computational Fluid Dynamics (CFD) could be employed in order to investigate the role of the air flow mechanisms.

In the current numerical study, unsteady wind conditions are performed around a one-storey building-model of size 5m x 10m x 3m. Variable leakage areas A_{leak} around windows are simulated and solved in a transient mode aiming to investigate the role of the distribution of the leakages under natural conditions. A ratio ($0 \leq \alpha \leq 1$) that represents the portion of leakages (distribution) per surface is employed and the infiltration rates respect to this ratio are shown. Different situations of the enclosure volume (from the perspective of internal wall airtightness) are assumed in order to investigate the influence of the latter to the infiltration rate of the building's envelope. The impact of the internal leakages is proven and the importance of controlling them is discussed.

Keywords

Leakage rate, air flow, air infiltration, leakage distribution, internal leakages, unsteady wind conditions, wind gust, computational fluid dynamics, shear-stress-transport

Introduction

Air infiltration has been recognized as one of the major reasons for energy loss [1]. The decrease in the efficiency of the mechanical ventilation has also been clarified [2]. Uncontrolled leakage paths have very clearly stated as pervasive, resulting in severe consequences [3]. The nature and extent of uncontrolled air flow have also been studied through testing, measurement and monitoring. Many researchers have also stated the uncertain phenomena that are connected to the airflow through leakages located on a building envelope. The dynamic characteristics of air infiltration have been pointed [4] and therefore challenges arise upon that field. The role of the climate parameters and location characteristics on average infiltration rates has also been studied [5]. Turbulence causing wind gustiness is recognized as one major factor that affects infiltration [6]. In addition, building aerodynamics contributes to air infiltration too. In that context, modelling approaches have been presented [7], [8]. Although, the air leakage of a building envelope can be determined from fan pressurization measurements with a blower door, estimating in a simple and easy way an enclosure's airtightness level [9], further research that takes the latter phenomena into account should be done.

Furthermore, leakage distribution has been mentioned as important factor towards the annual infiltration rate calculation [10]. Models have been developed towards the estimation of leakage distribution [11]. In addition, the later affects even the air pressure conditions in building and the wind-induced internal pressure fluctuations [12], [13]. In the same manner, the role of internal volume has been mentioned [14] as well as the influence of internal air leakages [15].

Computational fluid dynamics (CFD) could be employed to investigate the role of the air flow mechanisms from the perspective of the phenomena presented above, especially under unsteady conditions. Numerical studies could contribute to an estimation of the impact of potential leakages areas in the building envelope as well as in internal elements. Facing the global demand for achieving nearly zero-energy buildings, a more holistic and detailed approach of the phenomena linked to air infiltration should be given through both measurements and numerical simulations.

Case Study

The current numerical study deals with the influence of unsteady wind to the instantaneous infiltration (exfiltration) rates of a one-storey building-model (of size 5m x 10m x 3m) on which variable leakage areas around windows are simulated. Two 'windows' are used on each side. The size of each 'window' is 0,8m x 0,8m. The leakages are supposed to be 'cracks' along their frame. The total leakage area (whole building-model) is assumed to be 64cm^2.

The leakages are located on the windward and on the leeward side of the model. Seven different cases of distribution (windward vs leeward) are solved. For the representation of the latter, a ratio α is defined as follows:

$$a = \frac{A_{leak,front}}{A_{leak,total}} * 100\ [\%] \tag{1}$$

where

$A_{leak,front}$: the leakages located on the windward side (front side) for the building-model, expressed in cm^2 and

$A_{leak,total}$: the total leakage area of the model in cm^2 (both on windward and leeward sides), which as mentioned above equals 64cm^2.

In fact, the ratio α expresses the leakages located on the windward side as fraction to the total leakage areas of the building. The α takes the values: $\alpha = 5$, $\alpha = 15$, $\alpha = 30$, $\alpha = 50$, $\alpha = 70$, $\alpha = 85$ and $\alpha = 95$ [%]. To give a magnitude of order of the amount of the leakages:

$$\frac{A_{leak,total}}{total\ model\ surface} = 4{,}57 * 10^{-5} \tag{2}$$

Furthermore, since the influence of wind gust frequency ω has been discussed (especially for single-side airflow) [14], studying of its connection to the leakage distribution would be useful. Thus, two different gust frequencies are assumed, ω_{high} and ωl_{ow} and they are implemented in the wind profile formula as a sinusoidal factor (explained in the 'methodology').

Finally, three different 'situations' (S_1, S_2, S_3) regarding the internal volume are simulated in order to research the influence of the internal leakages and their connection the external ones. The first case S_1 refers to an internal volume without internal walls ('uniform', single space) (Figure 1). The second and the third cases (S_2 and S_3 respectively) both assume the existence of internal wall that divide the whole space in two 'rooms'. The difference is that in S_2 a leakage area of 4cm^2 is assumed to be located on the low level of the wall, allowing the inter-flow between the two rooms (Figure 3a and 3b), while in S_3 there are not internal leakages at all (assumption of completely tight internal wall) (Figure 2).

Summarizing, 42 cases are studied in total:

Σ = 7(leakage distribution cases) * 2(wind gust frequency cases) * 3(internal space cases).

A notation described by the following rule is employed and used hereinafter:

(Internal volume case S_i) - (leakage distribution α_j) - (frequency of the wind gust ω_k),

where:

i = 1, 2 or 3,

j = 5, 15, 30, 50, 70, 85 or 95 and

k = 'high' or 'low'.

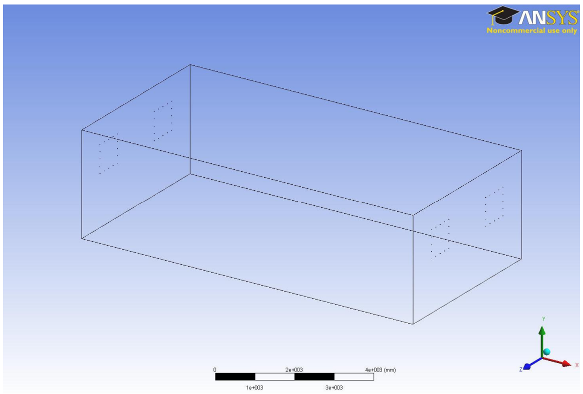


Figure 1. The case S_1: 'uniform' single space (no internal wall)

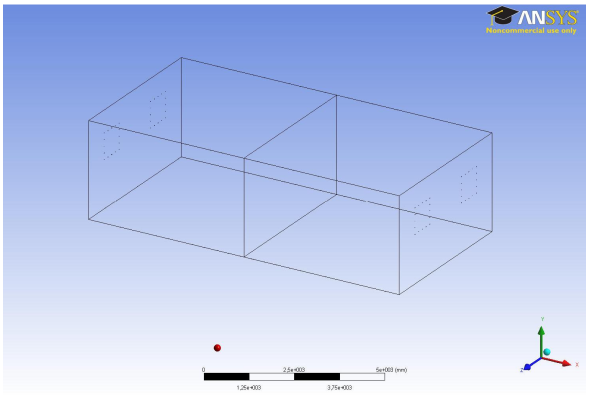
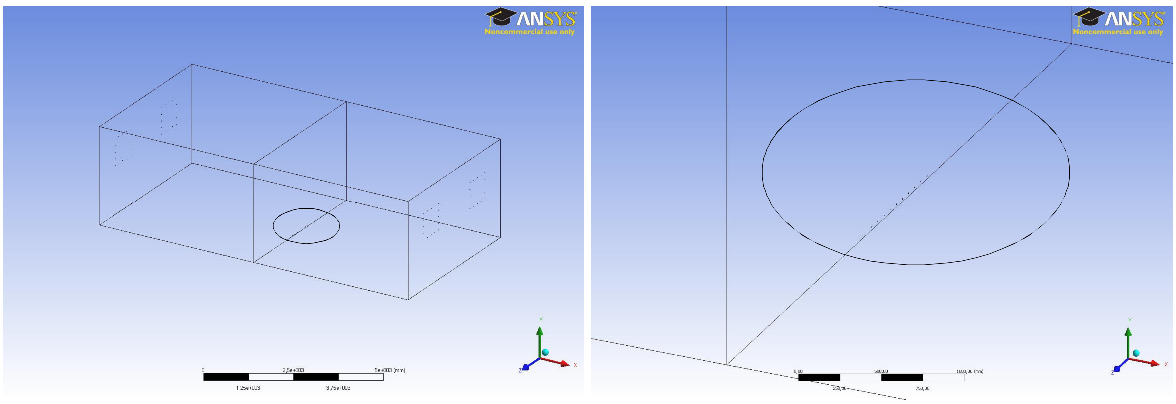


Figure 2: The case S_3: two spaces separated by an internal wall. No internal leakages



(a) (b)

Figure 3. The case S_2: two spaces separated by an internal wall. Internal leakages are located on the low level of the wall (circle area).

Table 1 shows, as example, the notation for leakage distribution of α = 5% and α = 70% for all the subcases of the internal volumes (and in the high gust frequency).

Case	Internal volume	Leakage distribution	Wind gust frequency
S_1-α_5-ω_{high}	'uniform' space	α = 5%	high
S_2-α_5-ω_{high}	two spaces – with internal leakages	α = 5%	high
S_3-α_5-ω_{high}	two spaces – no internal leakages	α = 5%	high
S_1-α_{70}-ω_{high}	'uniform' space	α = 70%	high
S_2-α_{70}-ω_{high}	two spaces – with internal leakages	α = 70%	high
S_3-α_{70}-ω_{high}	two spaces – no internal leakages	α = 70%	high

Table 1: Example of the notation followed. Here, the notations for the leakage distribution α = 5% and α = 70% in the high gust frequency ω_{high}.

Methodology

The CAD model was developed in ANSYS Design Modeler™ 12.1. The CFX-mesh method of the ANSYS Mesh program (involved in ANSYS Workbench) was employed for committing the meshes. The fluid dynamic package ANSYS CFX 14.0 was used as solver for the numerical simulations. Pressure distribution around a building is in general important to get correct prediction of the pressure gradients and consequently of the air infiltration through the envelope. Among the available turbulence models, the Shear-Stress-Transport (SST) model, a two equation k-ω based model [16], was imposed. The reason for that is the inclusion of transport effects into the formulation of the eddy-viscosity. This results in a major improvement in terms of flow separation predictions [17]. In addition, other relevant studies have shown a good agreement between SST model and full scale data, better rather than compared with standard k-ε and RNG k-ε models [18].

A period of 30*sec* was assumed to be the total time per run, while a fine timestep of 0,25*sec* was selected. At the inlet of the domain, a logarithmic wind profile was assumed based on the equation (Figure 4):

$$\frac{u}{u_*} = \frac{1}{\kappa}\ln[\frac{z}{z_0} - \Psi_m(\frac{z}{L})] + 2\sin(2\pi\omega t) \quad (3)$$

where u is the wind velocity at height z, u_* is the shear velocity, κ von Karman's constant, z_0 the roughness length and Ψ_m a stability function. The stability function can be evaluated directly from the Monin and Obukhov length L, knowing the flux of sensible heat, or indirectly through simultaneous measurements of air temperature profiles [19]. Under neutral stability conditions Ψ_m and $\frac{z}{L}$ vanish.The second term in the right side of the wind profile represents the wind gustiness frequency ω.

As mentioned above, two different gust frequencies ω have been employed, $\omega_{high} = 0{,}5Hz$ corresponds to the high frequency and $\omega_{low} = 0{,}1\ Hz$ to the low one (Figure 5). Thus, the period of the wind velocity on a certain height is $T_{high} = 2sec$ and $T_{low} = 10sec$ respectively.

The leakage area along each window side represents a 'crack' of 0,8*m* long, simulated by a row of 5 circular 'holes'. The latter are equally distributed along the window side and their total 'opening area' equals the leakage area of the relevant crack.

The instantaneous mass flow rate Q_m is solved numerically and extracted. Thus, the instantaneous volumetric flow rates Q_v across the leakage areas are calculated (based on the transient, local density field) for the interval run time (30*sec*) for every case. Assuming that the dynamic mathematical and physical behaviour of the model does not change within an hour, the equivalent air change rate ΣACH_i extrapolated over time $t_{tot} = 1h$ is calculated:

$$\Sigma ACH_i = \frac{3600}{t_{run}} * \frac{\left(\int_0^{t_{run}} Q_v\, dt\right)}{V} \quad (4)$$

where

t_{run} is the total run time per case, means $t_{run} = 30sec$ and

V the volume of the enclosure.

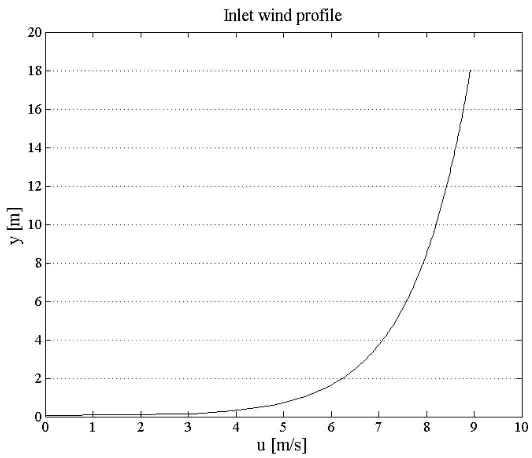


Figure 4: The selected inlet wind profile.

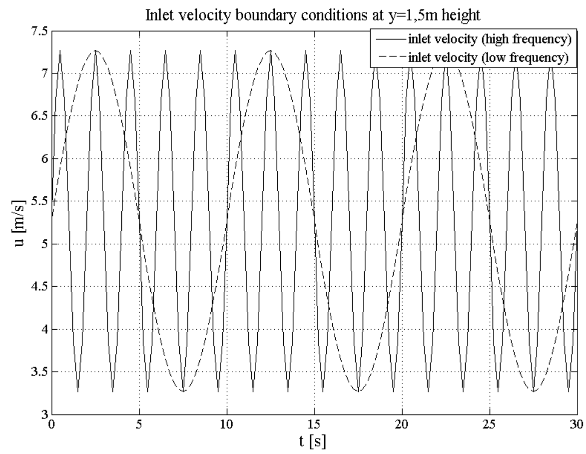


Figure 5: Inlet velocity boundary conditions at the height of $y = 1{,}5m$ as they have been defined for the high frequency ω_{high} and the low ω_{low}.

Results

The equivalent air change rates ΣACH_i for all the cases S_1, S_2 and S_3 are plotted against the leakage ratio α and shown in figures 6, 8 and 11 respectively. In each graph, two lines appear representing the rates under high and low wind gust frequency.

In Figure 6, it is clear that the strong 'cross ventilation' that takes place in the case of the single space results to relatively very high infiltration rates. Especially under the conditions of the high frequency gustiness the air exchange becomes even more severe. Having employed the assumption of 'one room' with no internal wall, there are no serious resistance against the flow. The ΣACH_i increases respect to the ratio α, and appears the maximum value when the leakages are equally distributed on the windward and leeward façade of the model ($\alpha = 50\%$). The air change rates seem to get lower again when α increases more. The role of the inertia forces of the enclosure appear to be in general weak in the case S_1. However, it would be reasonable to claim that when the leakages are mostly located either on the windward or on the leeward side (the ΣACH_i seems to have fairly symmetric picture), the compressibility of the volume tends to reduce the actual leakage rates, as the model behaviour is getting more similar to single-side infiltration (Figure 7).

In the case of S_2 the existence of a relatively tight internal wall (the internal leakages are only 6,25% of the leakages of the envelope) seems to have a dramatic impact (drop) to the air change rates (Figure 8). The ΣACH_i appear (for both the gust frequencies ω_{high} and ω_{low}) to be much lower. Although a 'cross ventilation' takes place even in this case, the quite high level of tightness of the interior element 'activates' the inertia forces of the enclosure, resulting to lower infiltration rates. Especially for the high wind gustiness, it seems that the most unbalanced the leakage distribution, the lowest the infiltration (exfiltration) rates that are caused. When the gustiness of wind is getting more mild (ω_{low}), the influence of the relatively tight wall is becoming even more significant, resulting in air change rates within the acceptable range, as described in building regulations [20].

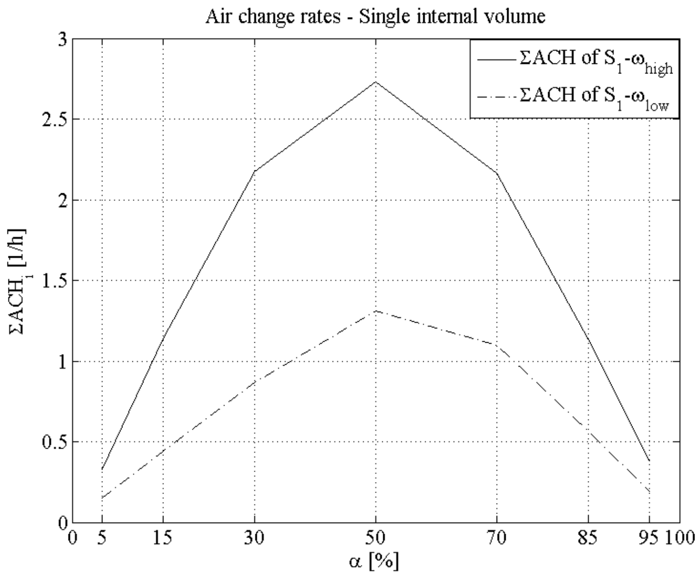
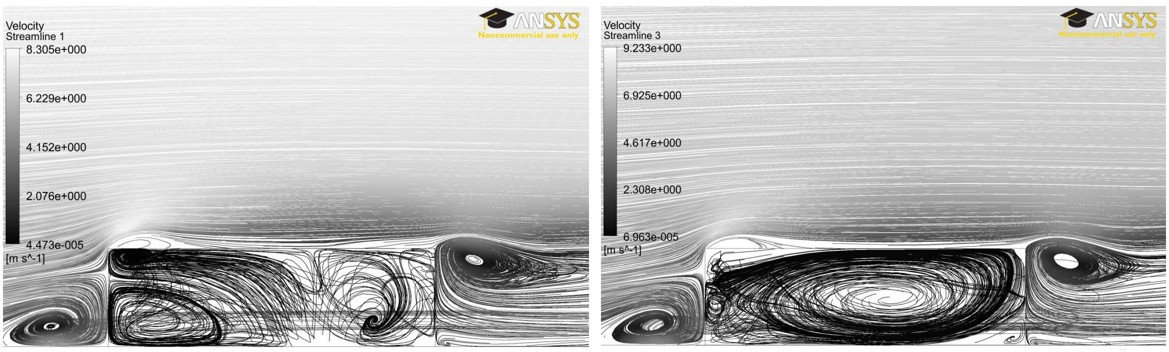


Figure 6: The air change rate for the case of the 'single space'.



(a) (b)

Figure 7: The velocity steamlines using a symmetry plane (timestep : $t = 2s$). (a) case of S_1-α_{95}-ω_{high}, (b) case of S_1-α_{30}-ω_{high}.

However, a difference can be pointed out when comparing the cases of high and low frequency. Under ω_{high}, the infiltration rate of S_2-α_5-ω_{high} is higher than the 'inverse' case of S_2-α_{95}-ω_{high}, as well as S_2-α_{15}-ω_{high} > S_2-α_{85}-ω_{high}, as well as S_2-α_{30}-ω_{high} > S_2-α_{70}-ω_{high}. In contrast, in the low wind frequency ω_{low}, higher air change rates appear as result of leakage concentration mostly on the windward side. The flow patterns in figure 9 (a) show a mild air circulation during ω_{high} even when the size of the leakages on windward is relatively big. The reason could be the size of the internal leakages compared to the external ones on the leeward façade; when they have the same magnitude of order, the inertia forces of the 'second room' seem to increase, preventing the air to flow from the 'first room', even though there is a significant amount of air that enters from the environment to the latter. But when the leeward leakage areas are getting larger, the pressure field in the 'second room' changes, forcing the air to flow out through them.

In case the unsteady wind is more mild (low frequency), the size of the 'inlet' on windward dominates the airflow (Figure 10). The reason could be that the wind gusts are not anymore so strong enough in this case that they would force great amount of air to flow to the 'second room', which remains more 'neutral' compared to the 'first room'.

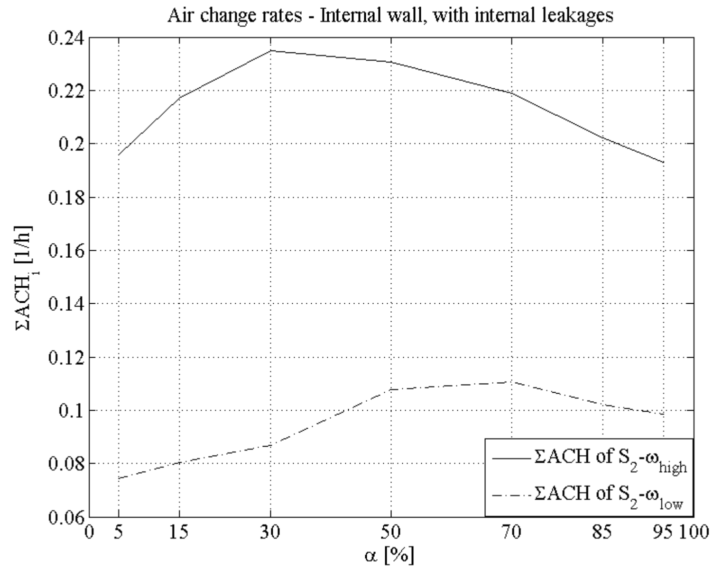
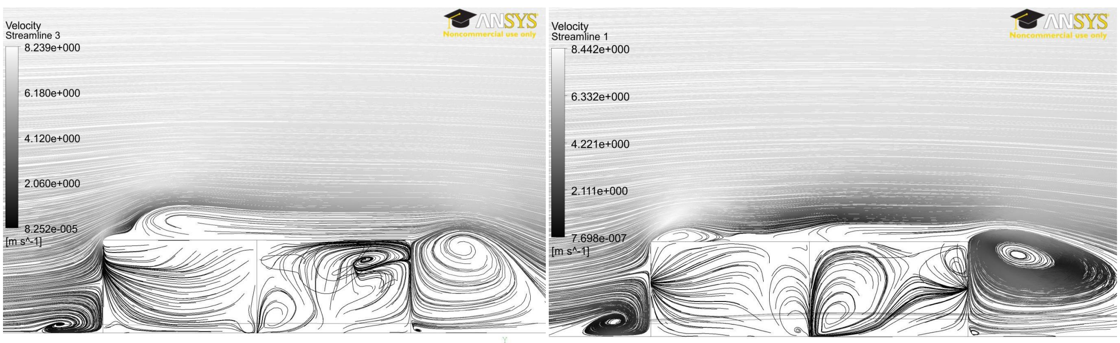
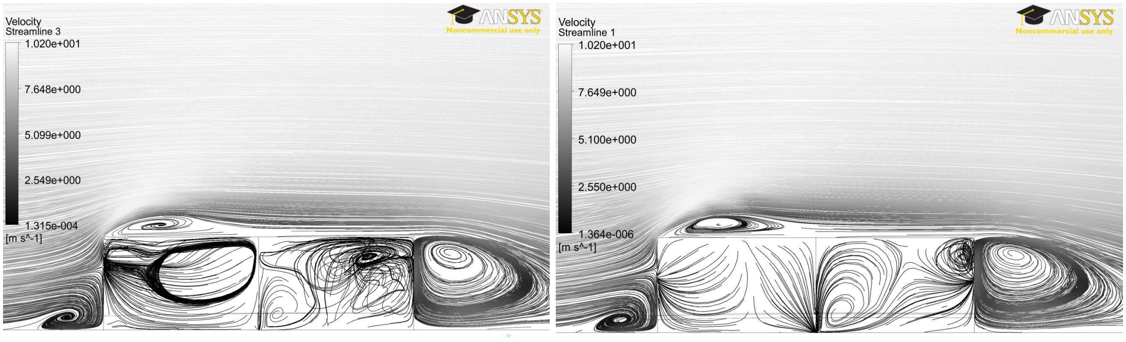


Figure 8: The air change rate for the case of the two rooms, separated by an internal wall where leakages are located on.



(a) (b)

Figure 9: The velocity steamlines using a symmetry plane (timestep : $t = 2s$). (a) case of S_2-α_{95}-ω_{high}, (b) case of S_2-α_{30}-ω_{high}.



(a) (b)

Figure 10: The velocity steamlines using a symmetry plane (timestep : $t = 3s$). (a) case of S_2-α_{95}-ω_{low}, (b) case of S_2-α_{05}-ω_{low}.

The role of the internal leakages is even more clearly shown in the figure 11 that represents the situation S_3. Assuming that the internal wall is completely tight, the air change rates seem to become even lower compared to S_2 highlighting the importance of controlling the internal leakage paths. Furthermore, reading the infiltration rates from the perspective of the blower door 'rule-of-thumb' ($ACH_{50} = \Sigma ACH_i * 20$), they fullfil requirements of a 'passive house airtighness level' [21]. The inertia forces of the first 'room' are in this case higher because of the single-side infiltration and the compressibility of the volume decreases. The second 'room' has gotten 'isolated' in this case, so there is not significant air exchange through the leeward leakages. Thus, the most favourable case seems to be when the leakages are mostly concentrated on this façade (α_{05} - leeward).

The ΣACH_i increases with the ratio α in both the wind frequencies studied. The maximum value appears when the leakage area on windward is getting big enough (α_{95}).

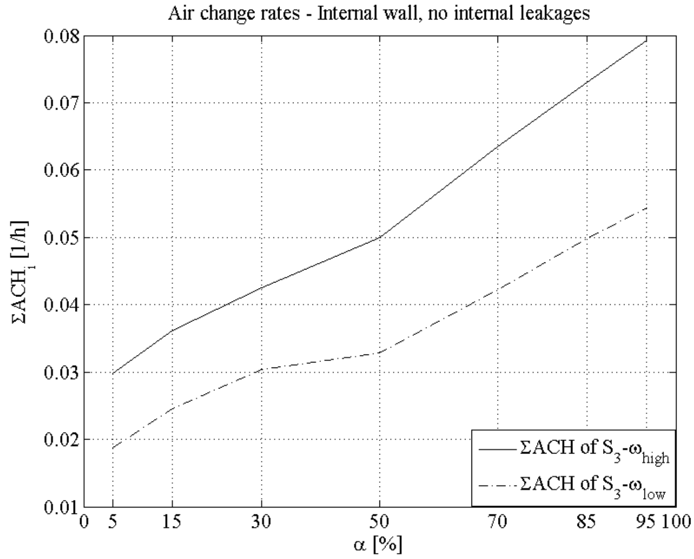
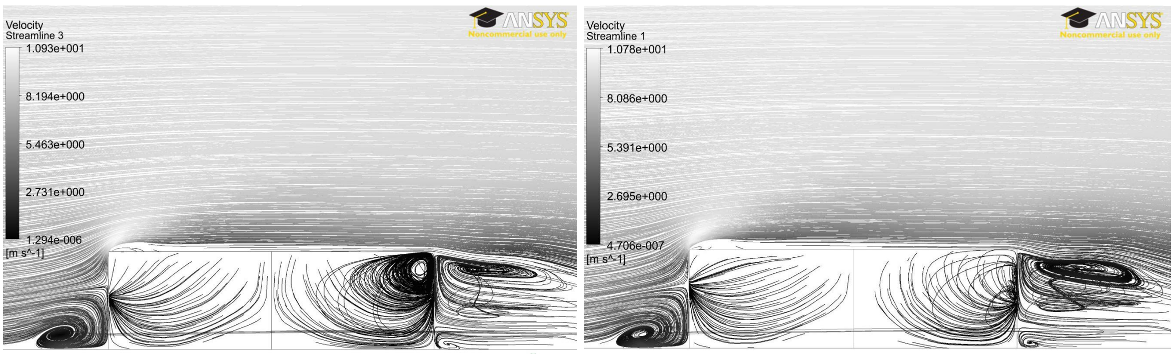


Figure 11: The air change rate for the case of the two rooms, separated by a totally tight internal wall.



(a) (b)

Figure 12: The velocity steamlines using a symmetry plane (timestep : $t = 3s$). (a) case of S_3-α_{05}-ω_{high}, (b) case of S_3-α_{95}-ω_{high}.

In all the cases (S_1, S_2 and S_3), the impact of the gust frequency ω_i seems to be very important resulting to increased infiltration rates. The normalized difference δ between the air exchanges during the high frequency ω_{high} and those during the low one ω_{low} is drawn against the ratio α (Figure 13).

$$\delta = \frac{\Delta(\Sigma ACH_{high} - \Sigma ACH_{low})}{\Sigma ACH_{low}} \tag{5}$$

In figure 13, it is clear that the influence of wind gustiness, in both the cases S_1 (single space) and S_2 (internal wall with leakages), is more significant compared to the case S_3 (completely tight internal wall). Again, increasing the tightness of the internal elements, the impact of the wind unsteadiness becomes less important. In addition, in the first cases the normalized difference δ has similar behaviour, showing that higher wind gustiness results to even higher infiltration rates when most leakages are concentrated on the windward façade. In contrast, in case S_3 (internal wall with no leakages), the increase of wind frequency has similar results to the ΣACH_i in the whole range of the leakage distribution that is studied. The dynamic characteristics of the wind and the inertia of the enclosure mass seem to influence in an analogue manner the actual air change rates.

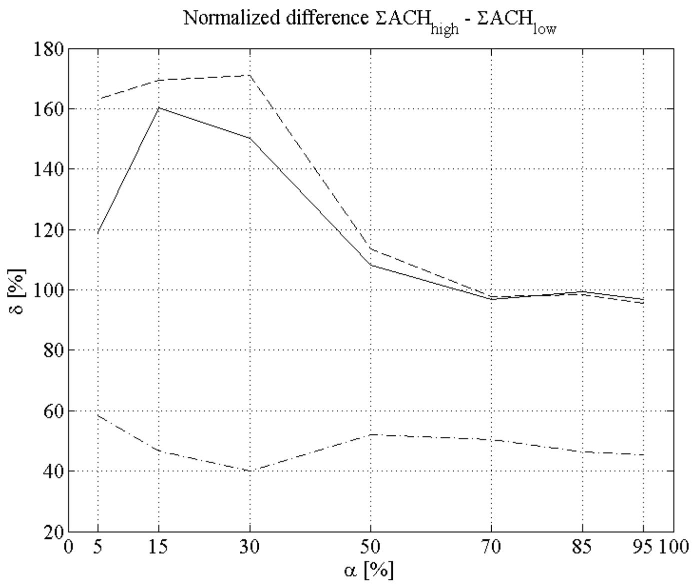


Figure 13: The normalized difference δ between the air exchanges under the high frequency ω_{high} and those under the low frequency ω_{low} is drawn against the ratio α.

Conclusion

A one-storey building-model with variable leakage areas on the windward and the leeward side was simulated and studied numerically under unsteady wind conditions. Two wind gust frequencies ($\omega_{high} = 0{,}5Hz$ and $\omega_{low} = 0{,}1Hz$) were used to describe the inlet boundary conditions. A ratio α [%] ($5\% < \alpha < 95\%$) was employed to describe the leakages located on the windward side as fraction to the total leakage areas of the building. Three different situations of the internal volume were assumed; a single space (S_1), an enclosure with an internal wall with leakages (S_2) and an enclosure similar to the latter but without internal leakages (S_3).

In total 42 cases were solved using the shear-stress turbulent model (SST). The equivalent air change rate ΣACH_i, extrapolated over time $t_{tot} = 1h$, was calculated and was shown against the leakage distribution α. The leakage distribution seems to govern the infiltration rates in case of a strong cross 'ventilation' (S_1). The most severe situation appears to be when the leakages areas on the windward and the leeward façade are of the same magnitude of order. Again, the most 'unbalanced' the way that the leakages are distributed the least air exchanges that take place.

Existence of relatively tight internal walls (S_2) decrease dramatically the leakage numbers. Even though a 'cross ventilation' takes place even in this case, the quite high level of tightness of the interior element 'activates' the inertia forces of the enclosure (of the 'front' room). Fulfilling high tightness of the internal elements (S_3), the air change rates decrease even more, reaching almost passive house airtightness standards (even under more severe wind gustiness). In addition, in the latter case, it seems to be of relatively high importance to eliminate as possible the leakages on the windward façade (according to the main wind direction of a location).

It would be reasonable to claim that internal leakages seems to be a major parameter towards the demand of decreasing the infiltration rates. Gustiness of wind is also a critical factor that results to higher leakage numbers. However, increasing the tightness of the internal elements, the impact of the wind unsteadiness becomes less severe. To determine even further the influence of wind frequency, a graph that represents the normalized difference between ΣACH_{high} and ΣACH_{high} is defined and is shown against the ratio α.

The study sets up issues regarding the uncontrolled leakages on the building envelope. The detection of leakages and their distribution should might be considered as critical factor. Furthermore, internal leakages seem to play an important role towards the nearly-energy-zero building target. Further research needs to be done, in order to investigate the connection between internal and external leakages in a detail way.

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Partners

Diamond Partners

Eurima is the European Insulation Manufacturers Association. Eurima members manufacture mineral wool insulation products. We actively support TightVent to develop knowledge and application of efficient airtightness solution for a successful implementation of the recast of the EPBD. This requires a good coordination between strong insulation and well-functioning ventilation in order to guarantee both energy efficiency and good indoor air quality.

Lindab is an international group that develops, manufactures, markets and distributes products and system solutions primarily in steel for buildings and indoor climate. With TightVent Europe, we learn more about the process of building airtight and energy efficient buildings; we fine-tune our product range by networking with suppliers confronted with the same issues. Our ambition is to transfer this knowledge all the way to building owners, architects/consultants, construction companies and workers.

Soudal NV is Europe’s leading independent manufacturer of sealants, PU-Foams and adhesives. The company, established in 1966, proudly remains family owned. Soudal serves professionals in construction, retail channels and industrial assembly and has 45 years of experience with end-users in over 100 countries worldwide. Since sealing, bonding and insulating is our business, we actively support the Tightvent platform. And with 7 manufacturing sites on 4 continents and 35 subsidiaries worldwide, we hope to contribute to a wide-scale implementation of nearly-zero energy buildings

Tremco illbruck has a leadership position in the sealants and building protection market throughout Europe, Africa and the Middle East. Our efforts are focused on Window, Façade, Coatings, Fire Protection, Insulating Glass and non-construction industries. Through TightVent Europe, we share our experience and expertise in the airtight connection of building components to reach ambitious goals and to improve knowledge of building professionals by implementing training programs in the EU.

Wienerberger is the world's largest producer of bricks and No. 1 on the clay roof tiles market in Europe with 245 plants in 27 countries. TightVent Europe enables us to further develop and optimize the sustainable building solutions we offer to our customers. Moreover, we want to transfer knowledge to our customers (both builders, renovators and building professionals such as architects, engineering agencies, contractors, etc.) by means of theory- and practice-oriented training courses, seminars, workbooks etc

Platinum Partners

Since 1989, BlowerDoor GmbH has been a pioneer in the fields of airtightness, especially airtightness measurements, and BlowerDoor product design in Europe. Synergies in engineering, product development and training have made the Minneapolis BlowerDoor a high quality device for air tightness measurements all over the world. BlowerDoor GmbH actively supports TightVent to achieve a good and durable quality in building air tightness as one important criterion to reach the ambitious goals of the Energy Performance of Buildings Directive (EPBD) recast.

Since 1980, Retrotec has pioneered the manufacture of advanced air permeability measurement equipment and analysis software. Retrotec has for many years been actively involved in the development of new standards for ISO and NFPA fire suppressant containment standards and large building testing standards for the US Army Corps of Engineers. With its renown experience and high-quality systems used in over 60 countries around the world, Retrotec looks forward to contributing its expertise to help reach TightVent's ambitious goals.

Gold Partners

Aeroseal offers an effective solution for testing and sealing ductwork leakage from the inside using a water-based sealant. The Aeroseal application is capable of sealing new and existing ductwork in commercial and residential buildings. Aeroseal's aerosol ductwork sealing technology was invented and developed at Lawrence Berkeley National Laboratory in 1994. Aeroseal is looking forward to creating a long lasting relationship with TightVent Europe, and maintaining high efficiency within buildings

Associate Partners

The Buildings Performance Institute Europe (BPIE) is an independent, non-profit organisation based in Brussels. BPIE supports the development of ambitious but pragmatic building-related policies and programs at both EU and Member State levels. We timely drive the implementation of these policies by teaming up with relevant stakeholders from the building industry, consumer bodies, policy and research communities. With the TightVent Europe Platform, our ambition is to play a key role in implementing policies on building and ductwork airtightness, bearing in mind ventilation needs.

CDPEA has been created in 2007 as a resource centre for building professionals in the field of sustainability, indoor air quality and energy performance in the Aquitaine region. CDPEA reaches directly a growing network of 5000 professionals with its tailored services in training, research and dissemination. CDPEA actively contributes to TightVent activities and thereby brings expertise and field feedback from professionals on airtightness. We look forward to strengthen our collaboration with TightVent to further increase the impact of both our organizations towards nearly zero-energy targets.

Platform facilitator

INIVE is a registered European Economic Interest Grouping (EEIG) that brings together the best available knowledge from its member organisations in the area of energy efficiency, indoor climate and ventilation. INIVE strongly supports and acts as facilitator of TightVent Europe because it clearly fits within the objectives of our grouping, namely, fostering and structuring RTD and field implementation of energy-efficient solutions and good indoor climate in new and existing buildings.