Effects of Air Leakage of Residential Buildings in Mixed and Cold Climates

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ABSTRACT

This paper deals with the effects of air leakage in residential buildings and provides an overview of the influence of air leakage on the measured performance of the interior temperature and relative humidity in two very different US climate zones (IECC zone 4, Knoxville) and (IECC zone 6, Madison).

The air leakage of residential buildings depends on a number of factors like building age, volume or the climate zone, as it is a common assumption that in colder climate zones more importance is attached to airtight buildings than in warmer climates. To quantify these differences and to show the dependence of air leakage on various influences an investigation in occupied buildings has been carried out. The air tightness of a number of homes in the mixed climate of eastern Tennessee and in the cold climate of south-central Wisconsin was measured on a seasonal basis. The interior conditions were monitored for each of the homes to investigate the link to the respective air leakage of the buildings. The results show that an estimation of the air leakage of residential buildings can be made with knowledge of some simple boundary conditions. Seasonal changes do not have a significant influence on the air leakgage. This information is critical for developing reasonable boundary conditions for hygrothermal models.

INTRODUCTION

Heat, air and moisture transport is a complex phenomenon in buildings. A number of unknowns still remain with respect to the hygrothermal performance of residential buildings. The thermal performance is influenced by the heat fluxes through the building envelope. The heat fluxes through the walls depend on the surface short wave and long wave radiation exchange, internal heat sources/sinks, forced or natural air leakage and the boundary interior and exterior temperatures, as well as thermal resistance of the wall, and the possible presence of moisture. Air leakage in many cases can be many times more important than conduction transport. Moreover, in buildings with designed ventilation systems, especially those with heat recovery, air tightness may be a determining factor in the performance of that system (Sherman and Chan 2004).

The moisture transport occurs due the vapor, liquid and air transport. The moisture flow through the envelopes is influenced by moisture production from sources, moisture addition or removal by the HVAC systems and the moisture flux caused by operation of the ventilation equipment. Air leakage that allows damp air to come in contact with cool surfaces may lead to biological growth.

A good understanding of hygrothermal fluxes through building envelopes was gained in the last decade. Fortunately, a special class of tools have been developed to predict the interior response as a function of various designs, or to conduct forensic analysis. Hygrothermal tools like WUFI-ORNL, Künzel et al (2001) or WUFI+, Holm et al (2004), include some enhanced analysis, that depend on the boundary conditions.

Most heat and humidity sources in buildings are not well researched, in particular those with integrated HVAC systems. The couplings that are associated with the intentional and unintentional air exchange still remain unknown in many applications. Infiltration is mainly influenced by air tightness. That is why almost all infiltration models require a measure of air tightness.

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With an HVAC system the fresh air exchange can be controlled. But even then, the fresh air exchange as a result of leaks in the building is not known, for example when unbalanced ventilation systems require that make-up air come through building leaks. The above is also true for buildings without any mechanical ventilation. These air exchange rates influence the hygrothermal performance of residential buildings in a substantial manner. Often the effects are described qualitatively, such as “a residential building is more airtight in colder climates than it is in warmer climates” or “older buildings are less airtight than newer”. To quantify these assumptions, this paper attempts to further study air leakage in residential buildings. This should lead to the development of better predictive capabilities for hygrothermal models by studying the resulting interior climate as a function of the measured airtightness in residential buildings.

An multi-year field investigation was carried out. The dependence of air leakage on various influences will be shown. The airtightness of 18 buildings in the mixed climate (IECC zone 4, Knoxville) of eastern Tennessee and 16 buildings in the cold climate of south-central Wisconsin (IECC zone 6, Madison) was measured on a seasonal basis. Information on each of the participating building, interior temperature and relative humidity, and occupant information was collected along with the measured air leakage of the building. The indoor climate conditions were collected with stand-alone data loggers. It is expected that with the insight provided by this study, reasonable loads (interior boundary conditions) can be developed for hygrothermal models.

The air tightness is affected by a number of different factors. Sherman and Chan (2004) reviewed what is known about air tightness. They refer to a report by Orme at al. (1994), who found that age of the construction, building type, severe climate and construction material affect air tightness among other factors. Chan et al. (2003) also found year of construction and size of the tested dwellings to be the most influential factors influencing air leakage. In 1985 Bassett (1985) studied the influence of building geometry on air tightness from measurements in 80 single family houses in New Zealand. He showed that as the geometry of the envelope gets more complex – which means a longer joint length between the building components divided by the envelope area – the envelope normalized air leakage rate at 50 Pa increases.

In a recent study by McWilliams and Jung (2006), the authors developed a mathematical air leakage model of single-family homes based on measured leakage data. The database contained approximately 100,000 blower door measurements. Income of the occupants was found to be the most significant characteristic determining Normalized Leakage. Additional significant building characteristics as a function of the energy efficiency were building age and floor area. In the regression analysis assumptions made are that variables were random and the predicted variables normally distributed.

DESCRIPTION AND IMPLEMENTATION OF THE EXPERIMENTAL APPROACH

Air Tightness Measurements

Air tightness measurements are usually performed via fan pressurization with blower door technology. Standard test methods such as ISO Standard 9972 (ISO, 1996), ASTM Standard E779-99 (ASTM, 2000) and E1827-96 (2002) or CAN/CGSB Standard 149 (CAN/CGSB, 1986) describe how to perform the fan pressurization measurements. These kinds of tests were first used around 1977 in Sweden (as reported by Kronvall, 1980), investigating the effect of window installation methods on air tightness. In 1979 the first blower door tests in the US were implemented (Harrje, Dutt, Beya 1979). From then, the diagnostic potentials of blower doors to uncover hidden bypasses have been used extensively.

A large amount of blower door data with a variety of additional information has been collected. Researchers at Lawrence Berkeley Laboratory have developed models to convert a series of fan pressurization measurements into a number of quantifiable values such for example the "equivalent leakage area” (ELA). The equivalent leakage has been defined as the area that corresponds to the combined area of all the house's leaks. Sherman (1992) also showed that sets of fan flow and house pressure pairs can be expressed empirically as a power law:

$$Q = C(\Delta P)^n \tag{1}$$

where C [m/s·Pa^n] is the flow coefficient and n is the pressure exponent. A measure of the relative tightness is the normalized leakage (NL), defined in ASHRAE Standard 119 (ASHRAE 1988) or in the ASHRAE Handbook of Fundamentals (ASHRAE 2005). Normalized leakage is air leakage normalized by some factor to account for building size. NL can be calculated with knowledge of the ELA, the building floor area and the height of the building. Having measurement of the normalized leakage, one can estimate the real-time air flows under natural conditions.

ASHRAE Standard 119 defines leakage classes for the NL as requirements for different climate zones. A rule-of-thumb by Sherman and Wilson (1988) helps to convert between the air leakage rate measured at 50 Pa air pressure dfference (ACH50) and the NL. The ACH50 value devided by 20 as approximate NL allows to quickly and easily generate estimates. The leakage classes A-C for tighter houses between 0.1 and 0.2 NL approximate 2.0 to 4.0 ACH50. The R2000 Standard in Canada requires that the air change rate at 50 Pascals is no greater than 1.5 air changes per hour. Similar requirements can be found in most European Countries, for example in Germany with 1.5 ACH50 with mechanical ventilation or 3.0 ACH50 without mechanical ventilation (EnEV 2002).

To quantify air tightness, the air flow through the building envelope at a specific reference pressure difference is used. In this study the air flow at 50 Pa was used. It is the most common pressure to measure the air flow. On one hand it is low enough to be generated by standard blower door equipment in most residential buildings. On the other hand it is high enough that the dependency on weather influences is little.

This metric refers to the total amount of flow at 50 Pa. To compare different houses, normalization is necessary. The most common normalized air tightness metric is the ACH50 value. It normalizes the air flow by building volume and gives a measure of the air changes per hour with a pressure difference of 50 Pa between the inside and the outside. A normalization by volume was choosen so that in further studies some of these dependencies of house air leakage can be investigated as a function of interior moisture loadings, which are often given normalized by volume. In some countries, for example Germany, the ACH50 value is the only value given for most buildings. This was another reason, why the effect of floor area and shape factor was neglected or rather included in the volume dependency.

Equipment Description

The blower door tests were performed with Minneapolis Blower Door Type 3. The testing wasa done using an Automated Performance Testing System (APT), which enables the operator to fully automate the blower door test from an laptop computer with the TECTITE software. Test pressures were chosen according to CGSB standard 149.10-M86 as an 8 point blower door test with building pressures varying from 50 to 15 Pascals. At each target pressure, 200 consecutive measurements were recorded and the average value was used to deduce the mass air flow at the corresponding target pressure. Only depressurization tests were performed. All buildings were tested in an as-is state. The testing protocol was consistent during all measurements and all openings to the outside of the tested volume were closed. A two-channel logger with internal temperature and relative humidity (RH) sensors from the HOBO pro series was used for long-term interior monitoring of temperature and relative humidity. Each building tested was instrumented with 3 to 5 HOBO loggers. The loggers were installed in the sleeping room, bathroom, living room, kitchen and basement or crawlspace where applicable. This allowed us to gather differences in spatial moisture source loading. Installation height was sought to be approximately 5 ft with the exeption of the crawlspace location. The loggers took a pair of readings for Temp/RH every 15 minutes. They were installed somewhere in the middle of the room, at least one ft away from external walls. Each logger prior to installation was calibrated at the ORNL Advanced Hygrothermal Laboratory. Three set point relative humidities (50, 70 and 90 % RH) at one set point temperature (21 °C) were used during the calibration.

Selection of Buildings for the Measurement

Buildings in two different climate zones were selected for this study. Eighteen buildings are in IECC zone 4, Knoxville and 16 buildings are in IECC zone 6, Madison. The Knoxville homes are located within 30 miles of the Oak Ridge National Laboratory (ORNL), and similarily the Madison homes are located within 30 miles from the USDA, Forest Products Laboratory (FPL). The exterior weather data was also collected for each of these two locations. Monthly average values for temperature and relative humidity are shown in Figure 1.

All homes chosen for this study are detached single family homes. The homes encompass a broad variety of home types, and these very diverse buildings allowed us to collect a wide variation of bundary conditions. Even though the actual number of buildings is low, the samples represent a broad cross-section for all one-family-houses in the respective area.

The first set of homes were tested and instrumented in Knoxville around the end of September 2004. At the end of January 2005 the data loggers were collected from the homes, the data were downloaded and the loggers were reinstalled in their original location. All Madison location loggers were installed, and the first values for airtightness measurements were obtained, in February 2005 for the 11 homes. In September 2005 the next airtightness measurements were performed for Madison homes, the data was gathered and data loggers relaunched. All Knoxville home loggers were removed from their old locations and installed in 8 new locations, where blower door measurements were also performed. The next time the data was gathered was May 2006. No blower door measurements for the new locations in Knoxville were performed in May. In Madison 5 new houses were instrumented and tested for air tightness. Table 1 shows a combination of all dates for the measurements on the different sets.

RESULTS

In Table 2, the results from the blower door measurements are shown. In addition, information is also provided for the home age, climate zone, experimental uncertainty and home volume.

Table 2 tabulates the information for all 34 tested buildings, with the building area and volume characteristics. The building age was classified into three groups: old, mid and new. The new houses were not older than 5 years when the first test was performed. In the mid age category homes had an age between 5 and 25 years. Buildings older than 25 years were categorized as old. The exact construction date was used for the age assessment if known; if not, the age was estimated based on the construction design, and home owners association data. The climate zone classification as per the IECC was used. In the next column the mean ACH50 are given, as calculated by the blower door software. The last column in Table 2 gives the total number of blower door tests performed on each building.

Figure 2 shows the blower door histogram distribution for all ACH50 values for Knoxville and Madison locations. The first observation is that for Knoxville, the bloor door values follow a normal distribution in spite of the low number of

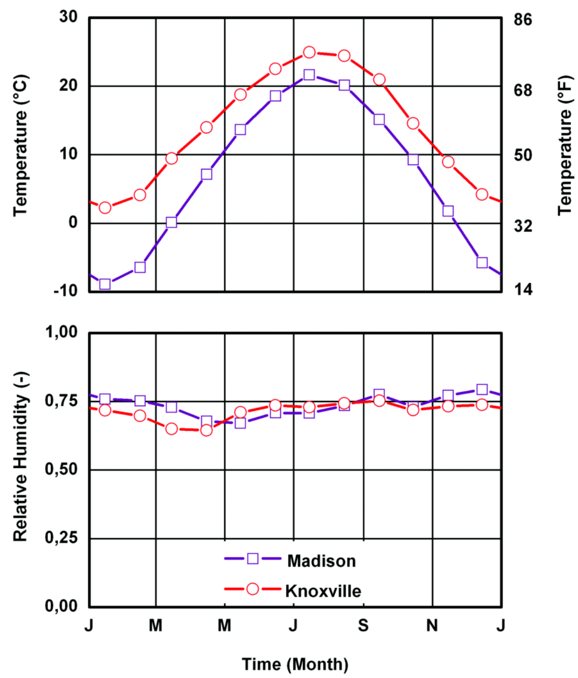

Figure 1 *Monthly average temperature and RH in Knoxville and Madison.*

Table 1. Dates for Blower Door Measurements

	Sep 04	Jan 05	Feb 05	Sep 05	May 06
Knoxville Set 1	×	×			
Knoxville Set 2				×	×
Madison Set 1			×	×	×
Madison Set 2					×

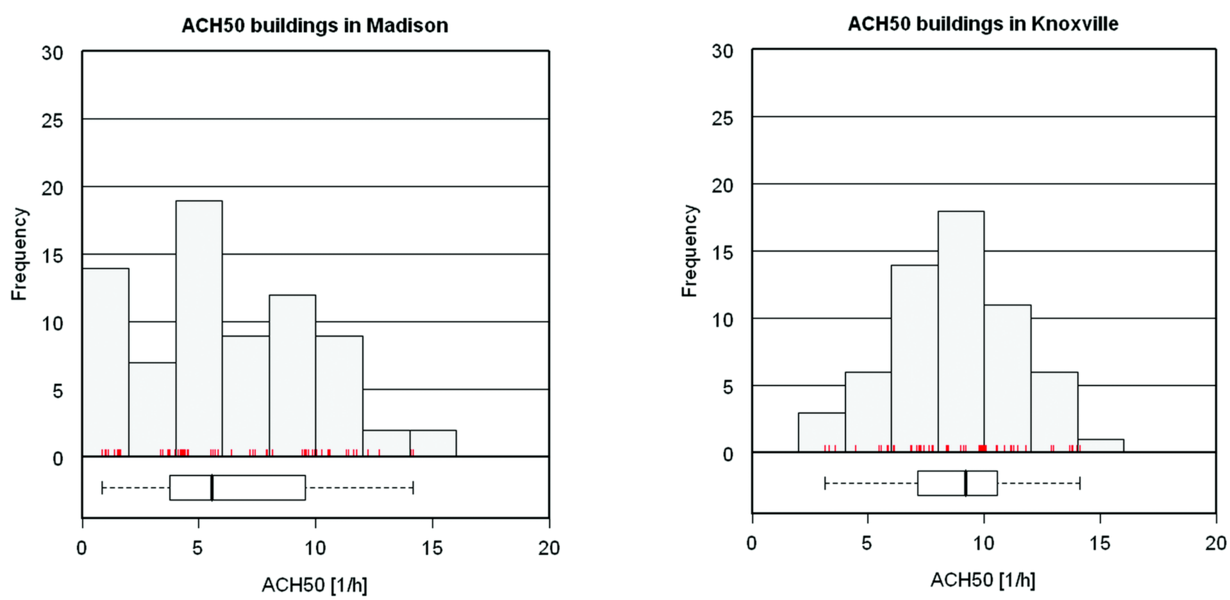

Figure 2 *Frequency distribution of all ach50 values for Madison and Knoxville.*

Table 2. Building Information and Average Blower Door Measurements

Name	Volume,		FloorArea,		Age	Climate Zone (IECC)	ach50 Mean	Number of Measurements
	m	ft	m	ft				
Building 1	561	19800	214	2300	new	4	9.8	2
Building 2	544	19200	223	2400	old	6	10.9	6
Building 3	370	13050	145	1560	mid	6	7.6	4
Building 4	1572	55522	322	3470	mid	4	3.3	3
Building 5	680	24000	279	3000	mid	4	8.8	4
Building 6	322	11370	130	1395	new	6	4.5	2
Building 7	850	30000	139	1500	old	4	10.5	3
Building 8	530	18700	204	2200	old	6	12.2	6
Building 9	227	8000	94	1009	old	6	9.9	2
Building 10	1421	50180	492	5300	new	6	1.5	6
Building 11	355	12528	145	1566	old	6	9.6	7
Building 12	483	17070	177	1900	mid	4	12.9	2
Building 13	1249	44100	455	4900	new	4	6.9	4
Building 14	702	24800	288	3100	mid	4	9.9	6
Building 15	421	14850	157	1690	mid	4	10.4	3
Building 16	463	16340	183	1975	mid	6	4.0	2
Building 17	913	32256	375	4032	new	4	4.4	2
Building 18	1324	46750	502	5400	mid	4	7.2	4
Building 19	314	11104	129	1388	mid	4	13.8	2
Building 20	408	14400	167	1800	old	4	11.3	6
Building 21	539	19020	221	2380	mid	6	5.9	6
Building 22	496	17520	174	1870	mid	4	9.8	2
Building 23	239	8430	98	1054	mid	4	14.0	2
Building 24	380	13410	165	1780	old	6	8.1	2
Building 25	612	21600	255	2744	old	4	7.1	3
Building 26	809	28560	316	3400	new	6	4.4	6
Building 27	604	21320	247	2660	mid	4	9.1	2
Building 28	1117	39456	404	4348	old	4	5.7	4
Building 29	272	9600	111	1200	old	6	8.8	4
Building 30	668	23600	223	2400	new	4	7.5	4
Building 31	648	22880	260	2800	new	6	3.8	7
Building 32	1066	37650	409	4400	new	6	1.1	6
Building 33	848	29936	284	3052	new	6	0.9	2
Building 34	525	18530	299	3220	new	6	4.8	6

tests. The median for value for the air change at 50 Pa (ACH50) is 6 for Madison and 9 for Knoxville.

DISCUSSION

Effect of Volume10

Figure 3 shows the ACH50 as a function of Volume for all measurements performed. The linear regressions for all buildings and separated regressions for Knoxville and Madison are also plotted. It was also found, that as the volume of the home is larger, the air change rate becomes smaller. However, we realize that this is at least in part due to the fact that the surface to volume ratio of a building declines as buildings get bigger. To obtain the ACH50 the measured air leakage rate (ft^3/h or m^3/h) is devided by the building volume, and total envelope air leakage is more likely to vary with envelope surface area. Thus it should not be a surprise that ACH50 dimishes with building volume.

In Knoxville the buildings were found to be leakier than in Madison. A higher slope was found for the linear regression for Madison. This means, that the air change rate reduces faster at higher volumes.

Effect of Age

As mentioned in the introduction, the building age is said to be one of the most influencing parameters on air tightness. Figure 4 shows the dependence of ACH50 on the three age categories as documented previously. This is a standard box plot where the box represents the range between the 25% and 75% quantile, the horizontal line the median value (50% quantile), and the vertical lines the range of values not considerd outliers. Individual outliers are shown as dots. It can be seen from Figure 4, that the 75 % quantile is very close to the median, which means a strong concentration of values in this region. The medians and distributions for middle-old and old houses are almost the same.

The dependence found as a function of age is as expected. For new houses the lowest ACH50 values are found. However, the difference between mid-old and old buildings was not very large. To confirm these differences in a statistical manner, an analysis of variance (ANOVA) was performed. The distribution of the attributes of ACH50 for the different age groups was analyzed. The null hypothesis H0 : mo = mm = mn was initially tested against H1: mi mj, wich means that the test determines if the expected values for all three groups are the same or not.

The result of the ANOVA is shown in Table 3. The first line shows the scattering between the groups, the second the scattering within each group. The null hypothesis will be rejected, if the F-value is bigger than the value of an F distribution with a 1-a-quantile and the given degrees of freedom. The Pr(>F) in the table gives a transgression probability for F. As it is close to zero, the null hypothesis is rejected, which means H1 is accepted. The influence of the age on the air change rate is probably large because the expected values for the groups are significantly different.

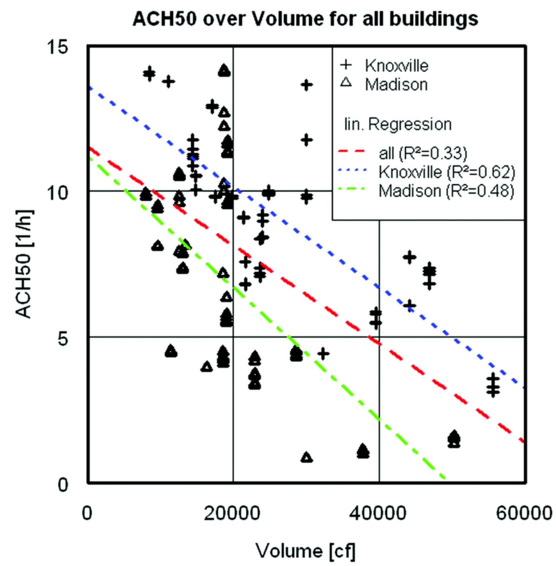

Figure 3 *ACH50 over volume for Madison and Knoxville with linear regression.*

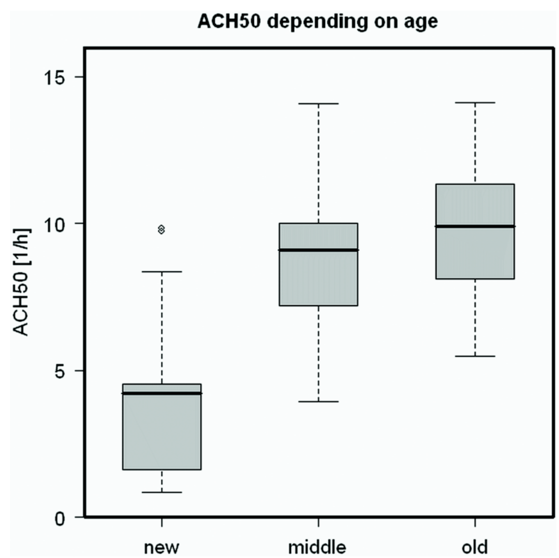

Figure 4 *Box plot for all ACH50 values in different age groups.*

While the effect of age is expected, it should be pointed out that a confounding factor is the difference in home size with age: older homes tend to be smaller homes, especially when compared with recently built homes. This may be another reason why newer homes seem more air tight, especially homes built very recently. Additional analysis is needed to separate size effects from the effect of home age.

Table 3. Result of ANOVA for ACH50_All Modeled with Age

	Degree of Freedom	Sum Square	Mean Square	F-Value	Pr (>F)
Age	2	28.264	14.132	47.471	3.54E-016
Residuals	129	38.403	0.298		

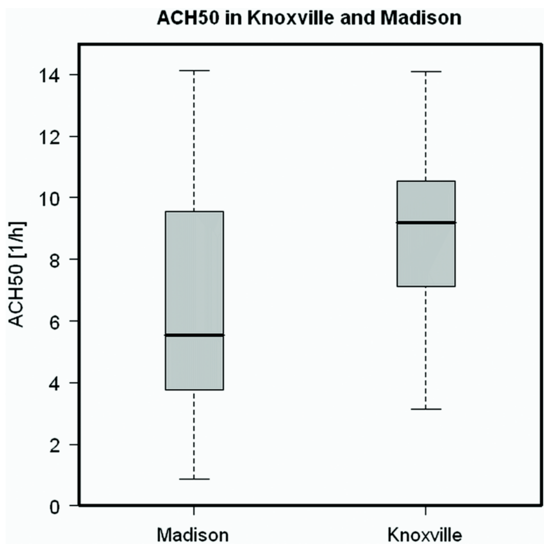

Figure 5 *Boxplot for all ach50 values in Madison and Knoxville.*

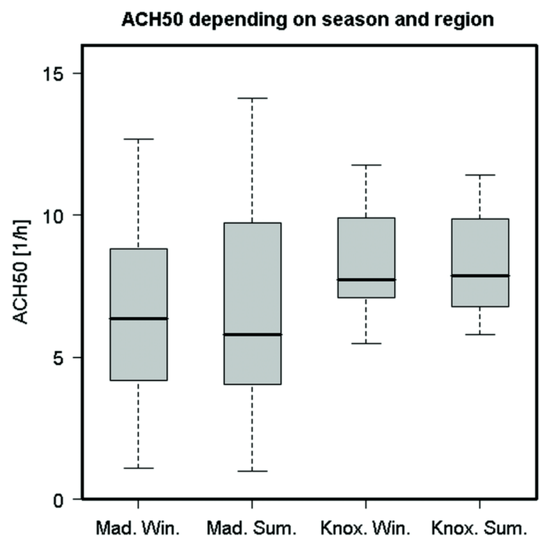

Figure 6 *Boxplot for selected ach50 values for summer and winter separated per region.*

Effect of Climate Zone

Another parameter with particular influence on the airtightness is the climate zone. The effect of climate is demonstrated in Figure 5. In Madison a median of 5.8 was found, while for Knoxville the median is 9.3. The maximum values for both locations are similar, but the minimum values were much lower for Madison. No tested house in Knoxville had an ACH50 value below 3.3.

An ANOVA for the dependence of the air change rate at 50 Pa on the climate zone was performed. A similarly low Pr (>F) value like for the age dependency was found. This means there is a strong variation of the ACH50 with climate zone.

Effect of Season

One could expect the air tightness to change over the year. Wood shrinking and changes in other building materials as a result of differences in the external climate may cause the whole building to become tighter or leakier. This effect was tested separately for both climate zones. Also the number of blower door tests used for this examination was reduced. Only buildings where both, summer and winter tests were performed, were used in the analysis. Figure 6 shows the different ranges of measurement results for each location during the summer and winter period. The median values were found close to each other for each location. The distributions between the winter and summer differ more for Madison than for Knoxville.

To prove that the expectancy values for each location do not differ in winter from summer, another ANOVA was performed. The results in Table 5 show a Pr(>F) value of 0,668 for all measurements, which means, that it is 67 % likely that the null hypothesis is rejected and therefore the expectancy values for summer and winter are the same. This means, that there is no significant difference in the ACH50 values between summer and winter and the season has little effect. A look at the locations alone shows, that the probability for expectancy values to be the same is not as high for Madison as it is for Knoxville.

Effect of Air Tightness on Interior Climate

As mentioned above, knowledge of the airtightness of the building is critical for developing interior loads for building simulation. Therefore a first insight in the effect of air tightness on interior climate is shown. Figure 7 gives an impression on how airtightness might change interior temperature. Temperature conditions in January and in July are compared for Building 2 and Building 10. These Madison buildings represent two extremes with an ACH50 value of 10.9 for Building 2 and 1.5 for Building 10. Building 2 is an old detached house with four inhabitants. The standard of insula-

Table 4. Result of ANOVA for ACH50_All Modeled with Climate Zone

	Degree of Freedom	Sum Square	Mean Square	F-Value	Pr (>F)
Climate Zone	1	7.802	7.802	17.230	5.95E-005
Residuals	130	58.865	0.453		

Table 5. Results of ANOVA for ACH50_Selected Modeled with Season for All Measurements and Separated for Each Location

All	**Degree of Freedom**	**Sum Square**	**Mean Square**	**F-Value**	**Pr(>F)**
Season	1	1.930	1.930	0.185	6.68E-001
Residuals	78	812.470	10.420		
Knoxville	Degree of Freedom	Sum Square	Mean Square	F-Value	Pr (>F)
Season	1	0.413	0.413	0.117	7.35E-001
Residuals	32	113.149	3.536		
Madison	Degree of Freedom	Sum Square	Mean Square	F-Value	Pr (>F)
Season	1	4.380	4.380	0.301	5.86E-001
Residuals	44	639.360	14.530		

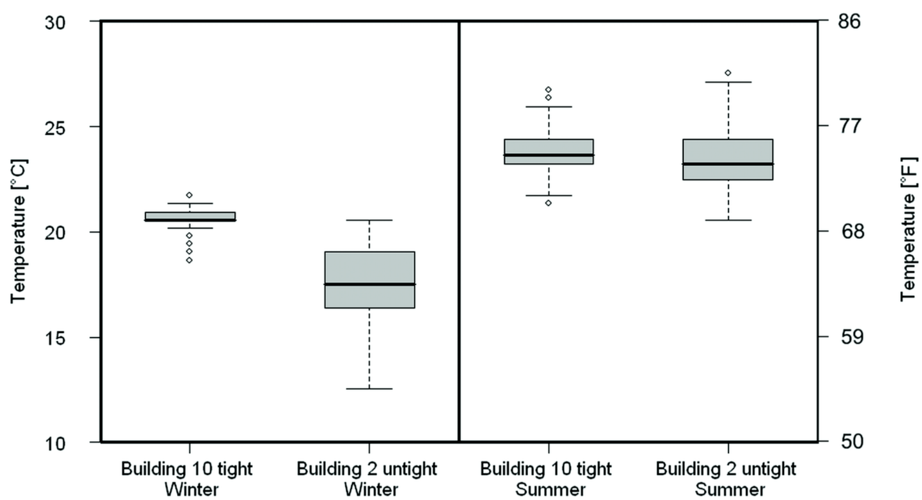

Figure 7 *Temperature boxplots for Buildings 2 and 10 in winter and summer.*

tion is average for old buildings. Also four inhabitants live in Building 10. This is a detached SIPs house with correspondingly good insulation. Both buildings are heated in winter and cooled in summer.

To develop internal loads, the relative humidity is also important. Figure 8 graphs the same boxplots like Figure 7 for relative humidity.

In winter a big difference between the tight Building 10 and the leaky Building 2 is found. Very small fluctuations in temperature and relative humidity on the tight building may be the result of good insulation and an airtight building. The low temperatures found in Building 2 may arise from high air change rates, which allows large amounts of cold air into the building. In summer the HVAC is partially turned off in Building 10 and the windows and doors are open. This results in almost equal humidity fluctuations.

However, we do not have enough information to unequivocally state that these temperature and humidity differences

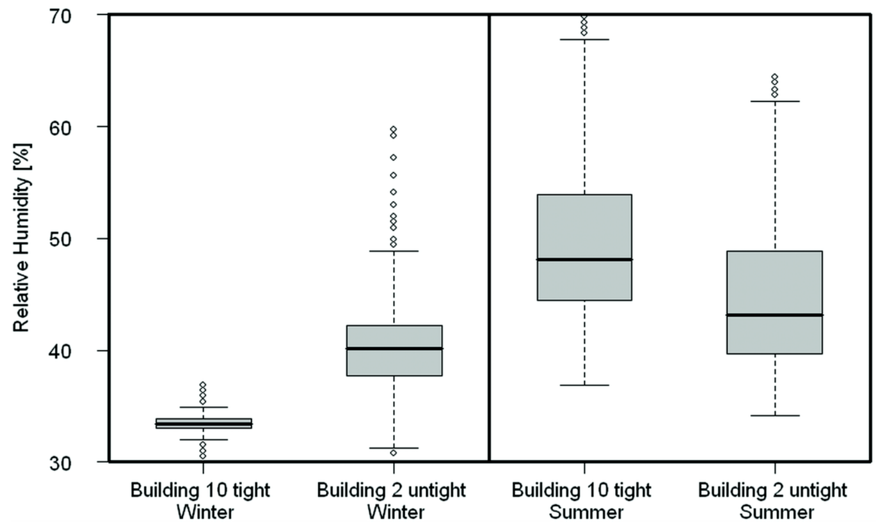

Figure 8 *RH boxplots for Buildings 2 and 10 in winter and summer.*

are due to differences in air tightness. Many other variables, such as occupant behavior, thermostat settings, furnace and air-conditioning equipment capacity and performance also play an important role.

CONCLUDING REMARKS

This study investigated a limited number of buildings, and any conclusion are preliminary as the home sample may be skewed. From this limited measurement analysis, the building volume was found to have a strong influence on the air change rate of the building. The ratio of external surface to building volume is likely to decrease for increasing volumes. Therefore less external surface, where leaks can occur is available and the surface area to volume ratio is more favorable. The same conclusion is made in Sherman and Chan (2004). The envelope complexity was not considered in this study. The higher position of the linear regression for the Knoxville results from different building standards in the different climate zones. The same is true for the steeper decline of air change rate with building volume for Madison.

The measured air change rates in dependence of the building age show the expected behavior. As reported in Chan et al. (2003) new homes tend to be tighter than old homes because of improved materials, better building and design techniques and lack of age-induced deterioration. Also building codes with specifiations on air tightness lead to a constant improvement. A paper by Sherman (2002) concludes that the air tightness of buildings improved from around 1980 and leveled off around 1997. The present paper shows that the buildings built in the last five years are the tightest. The ones that meet the "build after 1980" requirement are not much different from the ones which are older. This can be a result of the limited number of observations or the choice of our particular age classification. However, older homes tend to be smaller homes, especially when compared with recently built homes, and may be another reason why newer homes seem more air tight, especially homes built very recently. Additional analysis is needed to separate size effects from the effect of home age.

Another objective of these air tightness measurements were to determine the effect of different climate zones. The climate zones themselves are not the influencing parameter, but different requirements on building standards with changing external boundary conditions make the climate zones an appropriate classification. Sherman and Chan (2004) quote the need to conserve energy and the maintainance of thermal comfort as main reasons for tighter construction in severe climates. The measured air change rates differed significantly between the two selected climate zones. This was expected and is also implemented in existing air tightness models. In the past reported literature and Sherman (2006) found that buildings in the humid zone (which includes Knoxville in his partitioning) are as tight as the ones in Alaska. In the present paper the buildings in IECC zone 4, Knoxville, are less tight than the ones in IECC zone 6, Madison.

Seasonal changes were found to show no significant influence on building tightness. We found no similar analysis in the literature. The analysis of variance for the seasons showed, that it is very unlikely that the mean expectanded values for summer and winter differ. It makes no big difference if all buildings are considered, or if the measurements are separated by climate zone. Influences like wood shrinking and changes in other building materials, which were thought to result in leakier buildings in the winter, seem to be canceled out by other measures undertaken to keep the buildings tight, such as installation or closure of storm windows.

The results for effects on air tightness presented in this paper will be next introduced into our hygrothermal interior load model and compared to the results from the ASHRAE SPC 160P standard. We hope that with better knowledge of the air exchange rate we can make better estimates of the expected indoor conditions for use in building simulation tools.

REFERENCES

ASHRAE Handbook of Fundamentals. 2005. American Society for Heating, Refrigerating and Air-conditioning Engineers, Atlanta, GA..

ASHRAE Standard 119. 1988. Air Leakage Performance for Detached Single_family Residential Buildings. American Society of Heating, Refrigerating and Air-conditioning Engineers, Atlanta, GA.

ASTM, Standard E779-99. 2000. Test Method for Determining Air Leakage by Fan Pressurization. ASTM Bood of Standards, Vol 4 (11).

ASTM, Standard E1827-96. 2002. Standard Test Methods for Determining Airtightness of Buildings Using an Orifice Blower Door. ASTM Bood of Standards, Vol 4 (11).

Basset M. 1985. The Infiltration Component of Ventilation in New Zealand Houses. In proceedings: Ventilation Strategies and Measurement Techniques, 6th Air Infiltration and Ventialtion Centre Conference, the Netherlands.

CGSB Standard 149. 1986. Determination of the Airtightness of Building Envelopes by Fan Depressurization Method. Canadian General Standards Board.

Chan W.R., Price P.N., Sohn M.D., Gadgil A.J. 2003. Analysis of U.S. Residential Houses Air Leakage Database. LBNL report 53367.

EnEV (Energieeinsparverordnung). 2002. Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden. Verordnung Bundesrepublik Deutschland.

Harrje D.T., Dutt G.S., Beya J.E. 1979. Locating and Eliminating Obscure, but Major Energy Losses in Residential Housing. ASHRAE Trans. V85(II), pp521-534.

Holm. A., Künzel H.M., Radon J. 2002. WUFI+ 1.0. Rechenprogramm zur instationären Berechnung des Wärme- und Feuchteverhaltens von Räumen.

ISO, Standard 9972. 1996. Thermal Insulation - Determination of Building Air Tightness – Fan Pressurization Method. International Standards Organization.

Kronvall J. 1980. Air Tightness Measurements and Measurement Methods. Swedish Council for Building Research, Stockholm..

Künzel. H.M., Karagiozis A.N, Holm A.. 2001. WUFI/ORNL/IBP. A hygrothermal design tool for architects and engineers.

McWilliams J., Jung M. 2006, Development of a Mathematical Air-Leakage Model from Measured Data. LBNL report 59041.

Orme M., Liddament M. and Wilson A. 1994. An Analysis and Data Summary of the AIVC's Numerical Database, Technical Note 44, Air Infiltration and Ventilation Centre, Coventry.

Sherman M.H. 1992. A Power Law Formulation of Laminar Flow in Short Pipes. J Fluids Eng, Vol 114 No 4 pp601-605.

Sherman M.H. 2002. Air Tightness of New U.S. Houses: A Preliminary Report. LBNL 48671.

Sherman M.H. 2006. Air Tightness of US Homes: Model Development. LBNL report 59202.

Sherman M.H. and Chan W.R. 2004. Building Airtightness: Research and Practice. LBNL report 53356.

Sherman M.H., Wilson D.J.. 1986. Relating Actual and Effective Ventilation in Determining Indoor Air Quality. Energy and Buildings. Vol 21, No. 3/4.