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Analysis of air leakage measurements of US houses

Wanyu R. Chan*, Jeffrey Joh, Max H. Sherman

Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, One Cyclotron Road, Mailstop 90R3058, Berkeley, CA 94720, USA

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ABSTRACT

Building envelope airtightness is important for residential energy use, occupant health and comfort. We analyzed the air leakage measurements of 134,000 single-family detached homes in US, using normalized leakage (NL) as the metric. Weatherization assistance programs (WAPs) and residential energy efficiency programs contributed most of the data. We performed regression analyses to examine the relationship between NL and various house characteristics. Explanatory variables that are correlated with NL include year built, climate zone, floor area, house height, and whether homes participated in WAPs or if they are energy efficiency rated homes. Foundation type and whether ducts are located outside or inside the conditioned space are also found to be useful parameters for predicting NL. We developed a regression model that explains approximately 68% of the observed variability across US homes. Of these variables considered, year built and climate zone are the two that have the largest influence on NL. The regression model can be used to predict air leakage values for individual homes, and distributions for groups of homes, based on their characteristics. Using RECS 2009 data, the regression model predicts 90% of US houses have NL between 0.22 and 1.95, with a median of 0.67.

1. Introduction

Residential energy efficiency and weatherization assistance programs (WAPs) have led to many measurements of air leakage being made in the US in recent years. We gathered these data to characterize the air leakage distribution of homes in the US. Uncontrolled airflow through the building envelope has important implications to energy consumption in residences. Most US homes depend on air infiltration as the dominant mean of ventilation, so air leakage also impacts the indoor environmental quality of homes. It is the goal of this regression analysis to identify housing characteristics that can explain the observed variability in air leakage of single-family detached homes. Using the regression results and US housing data, we estimated an air leakage distribution that is representative for the current housing stock.

In 2011, we gathered a large number of air leakage measurements from more than 100,000 US homes. These measurements were added to data that were previously analyzed [1,2] to form the Lawrence Berkeley National Laboratory Residential Diagnostics Database (ResDB). Previous versions of ResDB were dominated by a few data sources. As such, the data were not representative of the US. The vast majority of the data were provided by an income-qualified WAP in Ohio. At that time, the dataset was also dominated by energy-efficient homes that were built for the extreme weather in Alaska. Furthermore, all of the ResDB data previously analyzed were collected in 2001 and earlier. Therefore, there is a need to update the database to include homes that are built more recently, especially because many residential analyses by other researchers [3–5] has since relied on that dataset dated 2001 as one of the model inputs.

In response to changes in building codes, recent studies have evaluated the energy use and other performance aspects of new US homes [6–8]. These studies suggest a general trend that new homes are being built tighter in some parts of the US. But many factors influence the air leakage of homes. In the presence of considerable house-to-house variability that is inherent in a housing stock, a large dataset is necessary for the regression analysis to evaluate the associations of air leakage with a number of housing characteristics. The approach used in this work largely follows previous regression analyses [1,2]. Recent studies in other countries have also found meaningful associations of air leakage with various housing characteristics: e.g., differences by construction and structural types [9–11], dwelling age and size [12]. In Canada, a study of 100 newly constructed homes that are representative of the new home market of 2008 found attached houses to have higher air leakage than detached houses, using average ACH_{50} as the metric of comparison [9]. Houses with a garage or are multi-story, for example, also tend to higher ACH_{50} on average. However, a similar comparison among 230 new Finnish single-family houses and apartments built in mid-2000 found the

* Corresponding author. Tel.: +1 510 4866570; fax: +1 510 4866658.
E-mail address: wrchan@lbl.gov (W.R. Chan).

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reverse [10], where the airtightness of apartments was better than that of the single-family houses. The study identified the joint between the exterior wall and the ceiling as being the most common source of air leakage, and houses with a concrete ceiling are more airtight than with a timber-frame ceiling. Both of these studies only compared the average air leakage values of homes with different characteristics, and did not evaluate the relationship of house characteristics and air leakage using statistical method.

Multivariate linear regression and other statistical techniques were used to analyze the relationship between house characteristics and air leakage among 287 dwellings in UK [11] and 483 single-family dwellings in France [12]. The regression models resulted from these fairly small datasets explained roughly half of the variability in air leakage, where the R^2 equals 0.5 and 0.4 for the homes studied in the two countries, respectively. The UK dwellings [11] include detached, semi-detached, and apartments that were built by three companies in different regions after 2006. Similar to the Finnish study, apartments showed better airtightness than houses. In addition, there are notable differences between the three builders, and the construction types (e.g., precast concrete panel the most airtight, followed by timber frame). The French database [12] contains houses that are more diverse in year built, which allows the relationship with air leakage be captured also in the regression model.

The objective of this work is to characterize the air leakage distribution of homes in the US. A large air leakage dataset was analyzed by regression to identify housing characteristics that are correlated with the air leakage measurements. The housing characteristics considered are descriptive parameters that are available from various US housing surveys. This enables the estimate of air leakage distribution representative of the US housing stock, as well as subgroups of homes based on their characteristics, as presented in this paper. This approach is similar in concept to other predictive methods recently reviewed [13], but different in that the parameters considered are not component based (i.e., summing of the total air leakage area of window and door frames, electrical outlets, etc.), but rather it is largely based on more general descriptions of the whole house (e.g., climate zone, year built, floor foundation type, etc.). Results of this regression can be used to expand the scope of energy use and occupant health and comfort analysis from small-scale studies of a few homes [14] to a housing stock-scale evaluation [15].

1.1. Air leakage measurements

Air leakage is quantified by measuring the airflow through the building envelope, Q (m^3/s), as a function of the pressure across the building envelope, ΔP (Pa). This relationship fits a power law [16], as described in Eq. (1).

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

where C (m^3/s Pa^n) is the flow exponent, and n is the pressure exponent. E779-10 is the measurement standard most commonly used in the US [17]. Typically, airflow is measured using a blower door at ΔP = 50 Pa. This pressure difference is low enough for standard blower door devices to achieve in most houses. At the same time, it is high enough to be reasonably independent of weather influences. For a more detail discussion of the blower door measurement technique that is commonly used to collect air leakage data, see [18].

Air leakage measurements are converted to normalized leakage (NL) for this analysis, as follows:

$$\begin{aligned} \text{NL} &= 1000\left(\frac{\text{ELA}_4}{Area}\right)\left(\frac{H}{2.5\ \text{m}}\right)^{0.3} \\ \text{ELA}_4 &= \sqrt{\frac{\rho}{2(4\ \text{Pa})}}Q_{50}\left(\frac{4\ \text{Pa}}{50\ \text{Pa}}\right)^{0.65} \end{aligned} \tag{2}$$

where ELA_4 (m^2) is the effective leakage area at 4 Pa, Q_{50} (m^3/s) is the airflow at 50 Pa, *Area* (m^2) is the floor area, H (m) is the house height, and ρ = 1.2 kg/m^3. ELA_4 is a measure of air leakage, which represents the area of an orifice that would result in the same airflow through the building envelope at a pressure difference of 4 Pa. Other commonly used metrics of air leakage include air changes per hour at 50 Pa (ACH_{50}), which equals Q_{50} divided by the house volume. The conversion of NL to ACH_{50} can be easily performed using Eq. (2) by first estimating Q_{50}, and then divide Q_{50} by the house volume. Roughly speaking, NL = 0.55 corresponds to ACH_{50} = 10. NL is a useful and convenient metric to describe the air leakage of buildings of different sizes because *Area* and *H* often are known parameters or they can be measured quite easily. NL is used in this analysis also for the sake of consistency with earlier work on the air leakage of US homes [1,2,19,20].

2. Data description

ResDB contains air leakage data from 147,000 US homes (Fig. 1), of which 92% are from single-family detached homes that will be analyzed here. The remaining data are mostly from manufactured homes (5% of the data) that participated in WAPs, and also from single-family attached homes and multi-family housing units but in fewer numbers. Because there are potential differences in the air leakage characteristics of these other housing types, this analysis will focus on single-family detached homes only. Approximately two-fifth of the air leakage data were added to ResDB in 2011. Data sources contributed voluntarily to ResDB. Therefore, even though the sample size is large, these self-selected data do not form a representative sample of US homes. In addition, there are also many missing data in ResDB. The handling of these missing data, such as year built, foundation type, and duct location, will be described below. Other detail characteristics, such as frame, wall, and roof materials and construction types, are available in too few of the homes to be considered in the regression analysis. In the US, stick frame structures are the most common, so it is likely that they are also the most represented in ResDB.

Income-qualified WAPs contribute half of the data in ResDB. In addition to the Ohio data that dominated the previous analyses, states with WAP data include Arkansas, California, Iowa, Idaho,

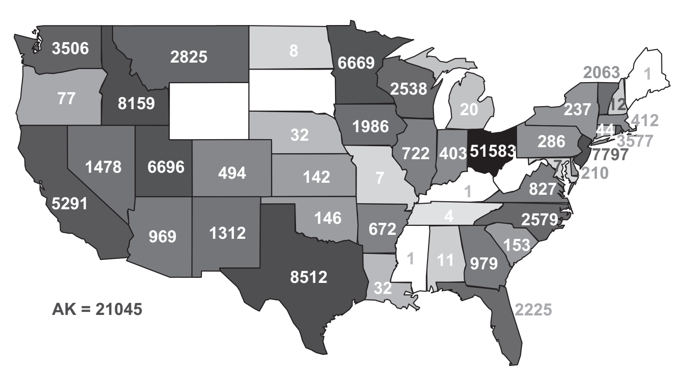

Fig. 1. Number of homes represented in ResDB. Counts include all single-family detached and attached homes, multi-family housing units, and manufactured homes.