Techniques to Estimate Commercial Building Infiltration Rates

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ABSTRACT

The estimation of low-rise, residential building infiltration rates using envelope airtightness values from whole building fan pressurization tests has been the subject of much interest and research for several decades, constituting a major topic of discussion during the early years of the AIVC. A number of empirical and model-based methods were developed, with their predictive accuracy evaluated in field studies around the world. Infiltration estimation methods for residences are now commonly available in guidance documents and employed in whole building energy and indoor air quality modeling. However, the greater complexity of many commercial buildings, including their size, multizone airflow dynamics and the influence of mechanical ventilation systems, makes the estimation of infiltration rates from fan pressurization test results more challenging. As a result, progress on infiltration estimation methods for commercial buildings has been slower than in low-rise residential. This paper reviews methods for estimating commercial building infiltration rates going back to the 1970s. More recent approaches using correlations based on a large number of multizone airflow model simulations are presented as a more feasible approach. Particular attention is given to how energy models have dealt with infiltration estimation in commercial buildings, with a detailed discussion of how the energy analysis program EnergyPlus has considered infiltration. More complex and presumably more accurate methods of accounting for the energy impacts of infiltration in commercial buildings, based on coupled airflow and energy analysis models, are also discussed as they have become more accessible in recent years given the increasing power of personal computing.

KEYWORDS

airflow; commercial buildings; infiltration; modeling

1 INTRODUCTION

Building infiltration rates have important impacts on energy use, indoor air quality (IAQ), and moisture management, and these rates have been studied for more than 80 years (Coleman and Heald, 1940). The importance of infiltration was demonstrated by the creation of the Air Infiltration Centre (AIC), which held its first conference in 1980 focusing on infiltration measurement (Air Infiltration Centre, 1980), and subsequently evolved into the Air Infiltration and Ventilation Centre (AIVC). The term infiltration is used in this paper to describe the airflow into and out of buildings through unintentional leakage in the exterior building envelope due to pressure differences induced by wind, indoor-outdoor temperature differences and the operation of ventilation and other building systems. It is interesting to compare this with the definition promulgated by the AIVC in 1992, i.e., “The uncontrolled inward leakage of outdoor air through cracks, interstices, and other unintentional openings of a building, caused by the pressure effects of the wind and/or the stack effect” (Limb, 1992). This earlier definition mentions only inward flow, although many discussions of infiltration implicitly include outward flow or exfiltration. It doesn’t mention pressure differences induced by building systems, such as exhaust fans, atmospherically-vented combustion appliances and unbalanced ventilation systems. In addition to these pressures, infiltration rates also depend on building envelope airtightness, airtightness of interior partitions and air temperatures within individual building zones. The physics of infiltration are well-understood and have been documented in a variety of places, including Dols and Polidoro (2015) and Etheridge and Sandberg (1996).

Much of the early work on infiltration focused on low-rise residential buildings based in part on their relative simplicity compared with commercial and institutional buildings, which are often larger and more complex, and have more zones and more elaborate ventilation systems. For the purposes of this paper, the term commercial building is used to describe commercial and institutional buildings that are used for a variety of purposes (e.g. work, education, healthcare, retail, public assembly) but not as residential living spaces. Multi-family residential buildings are also not included in this discussion. This description of commercial buildings is admittedly quite broad, and it includes buildings of the same size as single-family residences; the key point is that these commercial buildings include many large, complex, and mechanically ventilated buildings. In general, infiltration rates are more challenging to measure in commercial buildings than low-rise residential, again given their multizone layout, larger size and variations in ventilation system layout and operation. These factors often make it difficult to apply single-zone tracer gas measurement techniques as they complicate achieving uniform tracer gas concentration, which is required in using these techniques (ASTM, 2011). Multi-zone tracer methods exist, which can overcome these challenges, but they are much more difficult to apply (Etheridge and Sandberg, 1996) .

Given that infiltration rates in commercial buildings vary with weather and system operation, they need to be measured many times to characterize infiltration in a given building. Such long-term infiltration measurements have only been done in a small number of large commercial buildings (Grot and Persily, 1986). Therefore, in lieu of extensive measurement efforts, methods to estimate commercial building infiltration are needed to support design, energy calculation, IAQ analysis, retrofit planning and other applications. There is a long history of infiltration estimation methods in low-rise residential buildings, going back to the first AIC conference (Kronvall, 1980; Warren and Webb, 1980; Sherman and Grimsrud, 1980). This earlier work focused on methods to estimate infiltration rates from blower door measurements of envelope airtightness and weather conditions. These techniques evolved over time and are widely used and described in practical guidance (ASHRAE, 2017).

In contrast to low-rise residential buildings, the development of infiltration estimation methods for commercial buildings has progressed more slowly. Due to the often greater complexity of commercial buildings, there have been fewer measurements of envelope airtightness and infiltration rates in commercial buildings to support the testing of estimation methods, also contributing to slower advancement. Nevertheless, infiltration estimation methods in commercial buildings have progressed, and this paper outlines their development and summarizes tools currently available to designers, building scientists and other practitioners.

2 EARLY ESTIMATION METHODS

The earliest description of a large building infiltration estimation method known to the present authors was published before the first AIC conference (Shaw and Tamura, 1977). In that work, separate equations developed specifically for tall buildings are presented for infiltration flow rates due to wind and stack effect. The inputs to the wind infiltration component include building height and width, an envelope air leakage coefficient (that could come from a building pressurization test), wind speed and a wind direction adjustment factor. In addition to the leakage coefficient, the stack infiltration equation requires the length of the building perimeter, the indoor and outdoor air temperatures, the height of the neutral pressure level, and a thermal draft coefficient. The authors do not provide guidance on the neutral pressure level, but it can be measured in conjunction with a fan pressurization test. The thermal draft coefficient depends on the airtightness of the exterior walls relative to the interior partitions and captures how the static pressure decreases with height within the building interior, i.e., whether it is linear with height, which would reflect a relatively open interior, or whether there are pressure drops across floors and other interior partitions. The authors note that the value of this coefficient is around 0.8 in office buildings based on the small number they had studied but note the lack of measured values for apartment buildings. The reference also includes an equation to combine the wind and stack infiltration components to estimate the total infiltration rate. In the 42 years since its publishing, Shaw and Tamura (1977) is only cited 34 times in Google Scholar, most of which are publications on infiltration modeling. None of these references appear to have employed the model to predict infiltration rates and compare them with measured values.

The other means of calculating infiltration rates in commercial buildings is multizone airflow modeling, i.e., CONTAM or other software (Dols and Polidoro, 2015; Walton, 1989b; ESRU, 2002; IES, 2019). These models involve a multizone representation of a building and use mass balance analysis to solve for the airflows between all building zones including the outdoors, from which building infiltration rates can be calculated. These models account for all relevant building airflow physics, though their neglect of the conservation of momentum and energy limits their applicability in buildings that are naturally ventilated and with interior air that is not quiescent. Given the need to for many inputs to describe multizone building airflow systems, such models are generally not considered to be readily accessible to practitioners, though they are widely used in the design of smoke control systems (Klote et al., 2012).

3 INFILTRATION ESTIMATION IN ENERGY ANALYSIS

While commercial buildings have always experienced air infiltration through envelope leaks, and early studies showed that the rates were significant (Grot and Persily, 1986), infiltration was often neglected in energy analysis in part due to its perceived complexity. Rather than take this important phenomenon seriously, many simply assumed infiltration was equal to zero. In some cases, at least in the U.S., this assumption was justified by claiming that mechanically ventilated buildings are pressurized, thus eliminating infiltration. This justification was based on the common practice of providing more supply air than return air. In reality, the complexity of multizone building airflow systems results in indoor-outdoor pressure differences being localized phenomena that depend on outdoor wind patterns, building height, and differences between the rate at which ventilation air is delivered to and removed from individual building zones. As a result, infiltration will occur even when more ventilation air is supplied to a building than removed by exhaust unless detailed analyses and control strategies are implemented to control pressure differences across the entire envelope.

Another approach, embodied in the EnergyPlus energy analysis software and other tools, is to use empirical equations for estimating infiltration. These empirical equations were developed from analysis and testing of low-rise residential buildings as noted below, and do not capture the airflow physics of large, multizone or mechanically ventilated buildings. In the case of EnergyPlus, the following equation is available for calculating infiltration rates:

$$\text{Infiltration} = I_{\text{design}} \cdot F_{\text{schedule}} \left[A + B|\Delta T| + C \cdot W_s + D \cdot W_s^2\right] \tag{1}$$

where I_{design} is defined by EnergyPlus as the "design infiltration rate", which is the airflow through the building envelope under design conditions. Its units are selected by the user and can be h^{-1}, $m^3/s \cdot m^2$ or m^3/s. To apply this infiltration approach in EnergyPlus, a value of I_{design} is assigned to each zone. F_{schedule} is a factor between 0.0 and 1.0 that can be scheduled, typically to account for the impacts of fan operation on infiltration. $|\Delta T|$ is the indoor-outdoor temperature difference in °C, and W_s is the wind speed in m/s. *A, B, C* and *D* are constants, for which values are suggested in the EnergyPlus Engineering Reference (DOE, 2019). As noted in that reference, this equation is based on measurements in 10 one- and two-story houses, for which

30 infiltration rates were fit to the equation (Coblentz and Achenbach, 1963). The default strategy in EnergyPlus is to assume a constant infiltration rate, i.e., A=1 and B=C=D=0. However, this approach does not reflect known dependencies of infiltration on outdoor weather and HVAC system operation. The EnergyPlus Engineering Reference provides values of A, B, C and D based on two energy analysis programs that preceded EnergyPlus, BLAST and DOE-2. No references are provided for these values, but they are presumably based on studies in low-rise, residential building as there were no studies of infiltration in commercial buildings available when these two predecessor programs were developed. The EnergyPlus Engineering Reference also includes two other empirical infiltration models developed for low-rise residential buildings, i.e., the Sherman-Grimsrud and the AIM-2 models described in Chapter 16 of the ASHRAE Fundamentals Handbook (ASHRAE, 2017). While these approaches account for weather effects, they are also based on low-rise residential buildings and do not account for the airflow physics in larger buildings and in buildings with the more complex mechanical ventilation systems typical of commercial buildings.

Gowri et al. (2009) proposed a method to account for infiltration in commercial buildings that was developed using a square medium-size office building and a building envelope airtightness value, such as can be obtained through pressurization testing. Assuming a constant indoor-outdoor pressure difference of 4 Pa, Gowri calculated an infiltration rate using an approach that accounts for wind but not temperature effects, despite their known importance in taller buildings and colder climates. Gowri recommends that this infiltration rate be multiplied by a wind speed adjustment and by a factor of 0.25 when the HVAC system is on and 1.0 when the system is off. Overall, the method greatly oversimplifies the dependence of infiltration on building envelope airtightness, weather, and HVAC system operation.

EnergyPlus also has the ability to perform multizone airflow analysis, as embodied in the CONTAM model discussed above, using the EnergyPlus Airflow Network model (DOE, 2019). This model is based on a predecessor to CONTAM referred to as AIRNET (Walton, 1989a) and an earlier version of CONTAM (Walton and Dols, 2003). It is worth noting that while CONTAM has evolved considerably in the intervening years, the EnergyPlus Airflow Network model does not incorporate all of those improvements.

Han et al. (2015) compared the use of various infiltration estimation methods in improving the accuracy of building energy simulations. One method used the EnergyPlus Airflow Network model with three infiltration levels (leaky, medium and tight) as defined via DesignBuilder, which is a graphical front-end to EnergyPlus. The other methods utilized various means to establish monthly and annually averaged wind pressures including the use of an AIVC database of wind tunnel measurements and the use of computational fluid dynamics (CFD) to model the building exterior. For this case study, the CFD-based methods resulted in energy predictions that more closely matched utility bills.

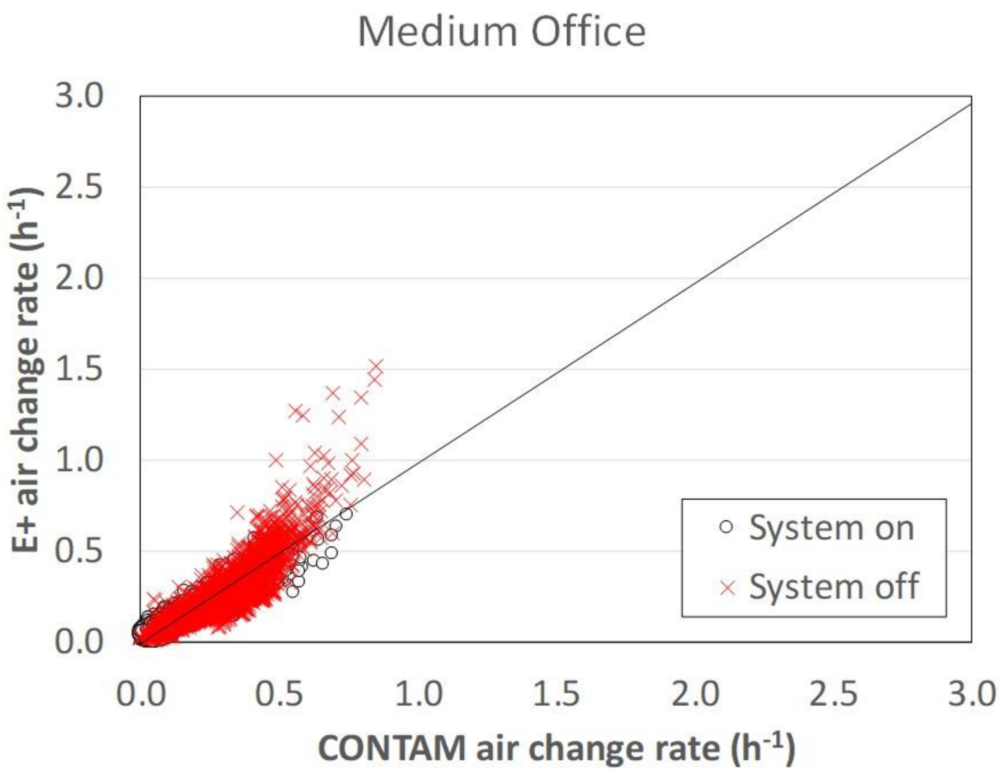
4 MORE RECENT ADVANCES

As building energy use has become of increasing interest over the years and as envelope insulation levels have increased, there has been more recognition of the importance of infiltration, including the need to control air leakage and to reliably estimate infiltration rates. These changes were reflected in the inclusion of requirements for continuous air barriers and envelope airtightness testing in energy efficiency standards such as ANSI/ASHRAE/IES Standard 90.1 (ASHRAE, 2016). As a result, new approaches to estimating infiltration were developed and are becoming more widely applied. This section describes one such approach, which uses values of the coefficients in Equation (1) developed specifically for commercial buildings, as well as a second approach using coupled energy and airflow analysis methods.

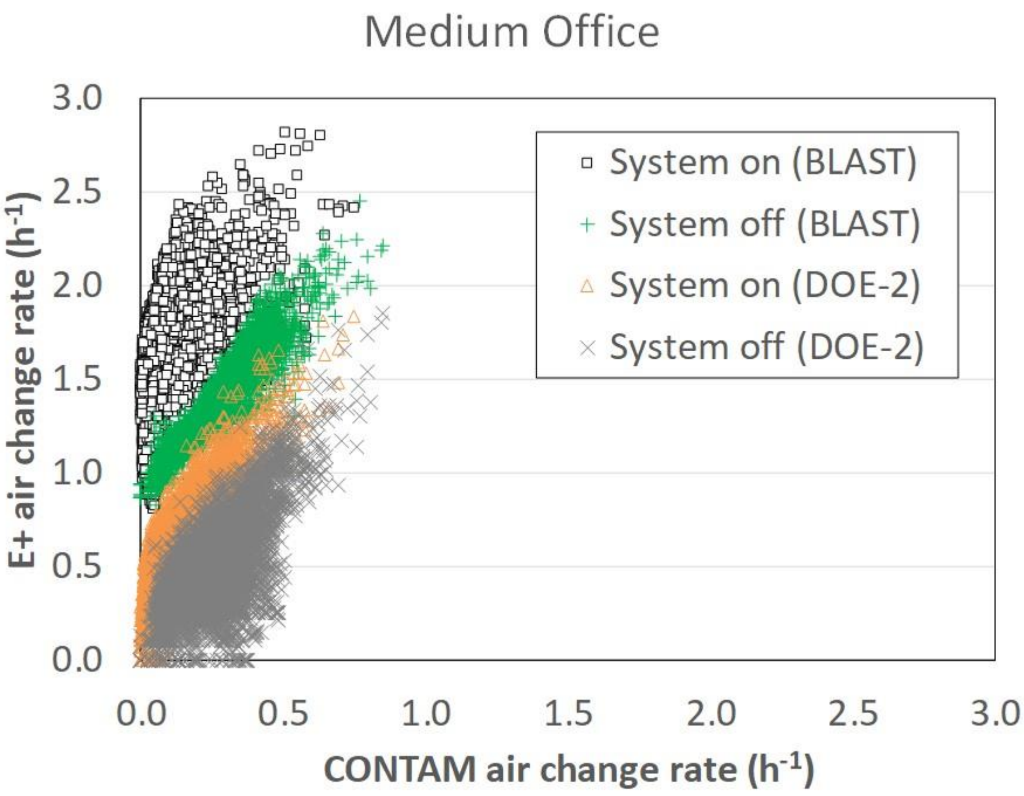
4.1 Large Building Infiltration Correlations

Values of the coefficients in Equation (1) for commercial buildings were recently developed by NIST. These coefficients were identified from investigations of the relationships between infiltration rates calculated using multizone airflow models, weather conditions, and building characteristics, including envelope airtightness and HVAC system operation. These relationships were developed using CONTAM models of the EnergyPlus models of 16 DOE commercial reference buildings (DOE, 2011; Goel et al., 2014). For each of these 16 buildings, different versions of the EnergyPlus models exist that correspond to different versions of ASHRAE Standard 90.1. In the ASHRAE 90.1-2004 versions, infiltration was modeled as 100 % of the design value when the HVAC system was off and 25 % (or 50 %) of that value when the HVAC system was on using the $F_{schedule}$ term in Equation (1). Further, A=1 and B=C=D=0 in Equation (1), which means the weather dependence of infiltration was ignored. In the ASHRAE 90.1-2013 versions of the prototype building models, infiltration was modeled with the same $F_{schedule}$ values but with C=0.224 based on a study by Gowri et al. (2009), which as noted earlier ignores the dependence of infiltration on indoor-outdoor temperature differences. These estimation methods are limited in that they do not fully account for weather effects and greatly oversimplify the impacts of system operation on infiltration.

In NIST's effort to develop coefficients for Equation (1), simulations were performed using NIST-developed CONTAM models of the DOE reference buildings to generate whole building infiltrations rates for a range of weather conditions with the ventilation fans on and off. Correlations were performed to fit these predicted infiltration rates to weather data, i.e., outdoor temperature and wind speed, to estimate the constants in Equation (1). For the ASHRAE 90.1-2004 versions of the building models, correlations were performed for 7 of the 16 reference models using Chicago weather (Ng et al., 2015). Compared with the assumption of constant infiltration in the reference building models, the correlation-based infiltration estimates agreed 60 % better on average with the CONTAM predictions. An example of the agreement between these infiltration correlations and the CONTAM predictions is shown for the Medium Office in Fig. 1a. The values for A, B and D for these 7 buildings were then correlated with building height, exterior surface area to volume ratio, and net system flow (i.e., design supply air minus design return air minus mechanical exhaust air) normalized by exterior surface area in order to predict these coefficients for any given building based on these three parameters (height, surface to volume ratio and net system flow). This generalized method resulted in an average improvement of 50 % when compared to the constant infiltration rates in the reference building models. Figure 1b compares the predictions using the suggested constants from DOE-2 and BLAST in the EnergyPlus Engineering Reference document, which results in much poorer agreement with the CONTAM predictions than seen using the correlation approach.



(a)



(b)

Fig. 1 EnergyPlus infiltration rates vs. CONTAM infiltration rates for Medium Office building using (a) NIST correlations and (b) DOE-2 and BLAST coefficients

In order to make these correlation-based estimation methods more accessible, they were incorporated into an Open Studio Measure called “Adding infiltration correlated for weather and building characteristics” (https://bcl.nrel.gov/node/83101). When the ASHRAE 90.1-2013 versions of the prototype building models were released, NIST updated the corresponding CONTAM models and expanded the infiltration correlations to eight cities (Ng et al., 2018). This work is continuing with the inclusion of more building types.

4.2 Energy-Airflow Model Coupling

Airflow and heat transfer are closely coupled processes in buildings, particularly in multizone buildings and in applications of natural ventilation. Basically, airflow models need zonal air temperatures to calculate airflows, and energy models need these airflows to calculate zonal temperatures. These calculations have historically been handled by separate software tools, with the inputs of each tool entered by the user “manually.” However, increased computer power and more widespread application of building simulation in design is making both building energy analysis and airflow modeling more accessible, as well as enabling more direct coupling between these two types of modeling tools. The CONTAM-based methods employed by Han et al. (2015) utilized loose coupling between the energy and airflow analysis software, i.e., the outputs from one program were used as inputs to another but not during runtime. More recent advancements have enabled tight coupling or co-simulation between CONTAM and energy modeling tools, i.e., EnergyPlus and TRNSYS (Dols et al., 2015; Dols et al., 2016). Co-simulation allows for the runtime exchange of simulation results between energy and airflow programs at each time step. Currently available coupling allows the complex interaction between building-specific thermal, wind and system effects to be addressed simultaneously.

5 SUMMARY AND CONCLUSIONS

The estimation of infiltration rates in commercial and institutional buildings is more complex than in low-rise residential buildings given the larger size and multi-zone configuration of these buildings, the complexity of their HVAC systems and the lack of infiltration and airtightness measurements to validate estimation methods. As a result, there has been slower progress in infiltration estimation compared with low-rise residential buildings. This paper described the history of infiltration estimation in commercial buildings, with a focus on how energy analysis tools (i.e., EnergyPlus) treat infiltration. At this time, there are basically three options for estimating infiltration rates in commercial buildings: multizone modeling, empirical formulas (i.e., Equation 1) in which the coefficients are all non-zero and have a sound technical basis, and coupled energy-airflow modeling (which is essential an application of multizone modeling). While there has been progress in these estimation methods, it is unclear how simple such methods can be given the complexity of airflow and pressure in large, multizone buildings. Nevertheless, infiltration rates are needed for commercial building energy and IAQ analyses or other applications, and if an estimated rate is to be used it must be based on a sound technical approach and data, which need to be reported along with the estimate.

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