Evaluating Potential Benefits of Air Barriers in Commercial Buildings using NIST Infiltration Correlations in EnergyPlus

Lisa C. Ng[1]
W. Stuart Dols[1]
Steven J. Emmerich[1]

[1] *Building, Energy and Environment Division*
Engineering Laboratory

Content submitted to and published by:
Building and Environment (2021): 107783
https://doi.org/10.1016/j.buildenv.2021.107783

March 2021

U.S. Department of Commerce
Gina M. Raimondo, Secretary

National Institute of Standards and Technology
James K. Olthoff, Performing the Non-Exclusive Functions and Duties of the Under Secretary of Commerce for Standards and Technology & Director, National Institute of Standards and Technology

ABSTRACT

According to the U. S. Department of Energy (DOE), infiltration accounts for 6 % of the energy use and $11 billion in energy cost for U. S. commercial buildings. One strategy to reduce infiltration in commercial buildings is to provide more supply airflow than return and exhaust in order to "pressurize the building". DOE has developed EnergyPlus models of several prototype buildings which assume that pressurization results in system-on infiltration rates that are 75 % less than the system-off rates. However, airflow simulations of these buildings using the CONTAM multizone airflow software showed that pressurization reduced infiltration by an average of 44 % only. To improve the infiltration rates calculated by the EnergyPlus models of prototype buildings, CONTAM infiltration rates were used to develop coefficients that can be input into EnergyPlus. CONTAM captures the effects of wind, temperature difference, and system operation on infiltration rates. Coefficients were developed for 11 prototype buildings, eight cities, and two levels of building envelope airtightness. Comparisons of the predicted infiltration rates were made between using the DOE prototype model inputs and the NIST infiltration correlations. Using the NIST correlations resulted in an average HVAC-EUI (HVAC-related energy use intensity) savings of 6 % or 1.4 kBtu/ft^2 due to airtightening. These results indicate that the effects of infiltration on HVAC energy use are important and that infiltration can and should be better accounted for in whole-building energy modeling.

Keywords: airflow modeling, commercial buildings, CONTAM, energy modeling, EnergyPlus, infiltration, building envelope airtightness

1. INTRODUCTION

Heating, ventilating, and air conditioning (HVAC) systems in buildings are designed and operated to maintain acceptable thermal comfort and indoor air quality (IAQ). These HVAC systems account for about 31 % of the primary energy consumed by commercial and residential buildings in the U. S. (EIA 2019). One method to reduce this energy consumption is to reduce thermal loads, and these loads can be reduced by building a tight exterior envelope in order to reduce unintentional leakage of outside air (i.e., infiltration) into a building. The U. S. Department of Energy (DOE) estimates that infiltration through building envelopes accounted for 13 % of the energy consumed by residential buildings and 6 % of the energy consumed by commercial buildings (DOE 2014). It is commonly assumed that over-supplying air (or "pressurization") in commercial buildings can significantly reduce infiltration and the associated heating and cooling loads. However, several factors can affect the impact of system operation on infiltration rates including differences in HVAC system air distribution to and from building spaces, the amount and distribution of exterior envelope leakage, the airflow resistance between building spaces, and weather. Furthermore, the interaction between these factors can be complex. For example, if stack effect is not properly accounted for in the building static pressure measurement of the building monitoring system, parts of a building may actually be negatively pressurized (Fahnline 2016). Fahnline (2016) recommends maintaining positive pressurization on lower floors to mitigate infiltration entering and rising through the building due to the stack effect. ASHRAE recognizes that pressurization can reduce or eliminate infiltration, but only in buildings with tight envelopes (ASHRAE 2017). The authors also came to this same conclusion in previous work (Ng et al. 2018).

One set of building models used to evaluate the impacts of energy-saving construction and technologies, including building envelope airtightening, are the DOE prototype commercial building models. These models were created for EnergyPlus, a whole-building energy simulation program (DOE 2019). In these models, infiltration is accounted for using the `ZoneInfiltration:DesignFlowRate` object. This object provides zone infiltration rates based on user inputs of a "design flow (infiltration) rate" and empirically based coefficients (A, B, C and D in Eq. (1)). This was based on the work by Coblenz and Achenbach (1963).

$$\text{Infiltration rate} = I_{\text{design}} \cdot F_{\text{schedule}} \left[A + B|\Delta T| + C \cdot W_{\text{s}} + D \cdot W_{\text{s}}^2\right] \quad (1)$$

where I_{design} is the infiltration rate under design conditions in units of $m^3/s \bullet m^2$ of envelope surface area. F_{schedule} is scheduled between 0.0 and 1.0 to account for the impacts of fan operation on infiltration. $|\Delta T|$ is the absolute difference between indoor temperature (T_{in}) and outdoor temperature (T_{out}) in °C, and W_{s} is the wind speed in m/s. In the DOE prototype models, the DOE-2 coefficients were implemented: $A = B = D = 0$ and $C = 0.224$ resulting in Eq. (2), referred to henceforth as the *InfiltrationDesign* model.

$$\textit{InfiltrationDesign}\ \text{model} = I_{\text{design}} \cdot F_{\text{schedule}} \left[0.224 \cdot W_{\text{s}}\right] \quad (2)$$

In the EnergyPlus documentation, BLAST coefficients are also listed. No references are provided for the DOE-2 or BLAST 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 (Persily et al. 2019).

When the HVAC system is scheduled to be on, infiltration is reduced 75 % (i.e., $F_{\text{schedule}} = 0.25$) of the design value to account for the assumption that the HVAC system positively pressurizes the building. The basis for this assumption is not described in the EnergyPlus or prototype building models documentation. This reduction in system-on infiltration rates in the

InfiltrationDesign model also oversimplifies the effects of the HVAC system on infiltration rates. The *InfiltrationDesign* model in the prototype buildings does not account for temperature effects on infiltration (i.e., stack effect) or for the variation of infiltration among different building zones. Thus, if the *InfiltrationDesign* model cannot fully capture infiltration rates as HVAC operation and weather changes, it cannot fully capture the potential benefits of building envelope airtightening.

Users of the DOE prototype buildings who want to improve upon the *InfiltrationDesign* model could use the *AirflowNetwork* model in EnergyPlus. It executes AIRNET (Walton 1989), which is a predecessor of CONTAM (Dols and Polidoro 2015) with several limitations (DOE 2018). The *AirflowNetwork* model can account for wind direction and stack effect when determining infiltration. However, the EnergyPlus user is responsible for making the connections between pressure nodes, including connections between interior zones, between interior zones and the outdoors, or between interior zones and the HVAC system. This can be cumbersome to implement without a graphical interface.

To overcome the limitations of the *InfiltrationDesign* model, the DOE prototype models were created in CONTAM (Ng et al. 2012), a multizone airflow simulation software developed at the National Institute of Standards and Technology (NIST) (Dols and Polidoro 2020). CONTAM accounts for room-to-room, infiltration and exfiltration airflows driven by temperature-induced pressures (i.e., stack effect), wind pressures acting on the building exterior, and mechanically-driven pressure differences, i.e., HVAC system flows. CONTAM is able to perform whole-building simulations for periods of up to one year, and its computational time is not as intensive as other airflow simulation methods (e.g., computational fluid dynamics). CONTAM has been validated in terms of program integrity (Haghighat and Megri 1996), laboratory experiments (Haghighat and Megri 1996) and field studies in residential buildings (Chung 1996; Emmerich 2001; Emmerich et al. 2004; Haghighat and Megri 1996). There have also been studies using CONTAM to compare measured and simulated tracer gas concentrations in three large commercial buildings (Black and Price 2009).

While the *InfiltrationDesign* model in the DOE prototype buildings accounts for wind speed effects on infiltration, CONTAM has the advantage that it can also model infiltration that is unevenly distributed around the building envelope as a function of wind direction. In CONTAM, the user can assign a wind pressure coefficient profile to each airflow path through the building envelope, so that wind pressure coefficients (C_P) vary as a function of wind direction (θ) impinging on a building surface. Taking Figure 1 as an example, at $\theta = 0$ °, the wind is impinging on the surface and C_P is the largest. In contrast, when the wind is impinging on the opposite surface, C_P is negative, resulting in a negative wind pressure. These wind pressure impacts, captured by CONTAM but not by the *InfiltrationDesign* model, are important when estimating infiltration rates.

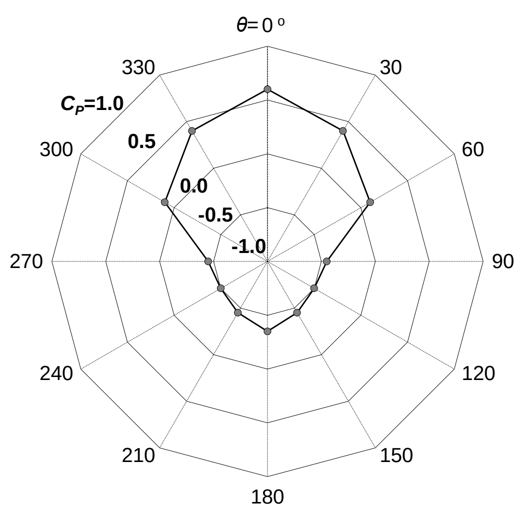


Figure 1 Example of a wind pressure coefficient profile that can be implemented in CONTAM

The authors have used CONTAM infiltration rates to develop values for the coefficients in Eq. (1) (Ng et al. 2018; Ng et al. 2015) (referred to henceforth as the "NIST infiltration correlations").The use of the NIST infiltration correlations performed much better than other coefficients provided in the EnergyPlus manual (Ng et al. 2015), specifically the coefficients associated with the DOE-2 and BLAST approaches. In this study, the authors will analyze potential benefits of building envelope airtightening (e.g., energy savings) using both the NIST infiltration correlations and the *InfiltrationDesign* model.

Since the DOE prototype buildings are not actual buildings, no measured data is available to validate the airflow or energy use. Thus, CONTAM will be used to benchmark the airflow rates and EnergyPlus will be used to benchmark the energy use.

2. OBJECTIVES

The objectives of this study are to demonstrate through CONTAM and EnergyPlus simulations of the DOE prototype buildings (Gowri et al. 2009) that (1) buildings designed to be positively "pressurized" are still likely to exhibit leakage in the form of infiltration through the building envelope, and (2) the NIST infiltration correlations reveal greater potential benefits of airtightening in commercial buildings than the *InfiltrationDesign* approach included in the DOE prototype models. A clarification on how "pressurization" was achieved in the building models will also be given.

3. METHODS

In this study, the infiltration rates and the energy use of 11 DOE prototype buildings in eight cities were simulated for a year. In EnergyPlus, the infiltration rates were simulated using both the *InfiltrationDesign* and NIST infiltration correlations approach. The DOE prototype buildings used in this study are described in Sec. 3.1, along with a clarification on how "pressurization" was (or was not) achieved in the building models. The approaches used to calculate infiltration rates in the EnergyPlus model, the *InfiltrationDesign* model and NIST infiltration correlations, are described in Sec. 3.2. The simulations performed are described in Sec. 3.3.

3.1. Prototype commercial buildings

DOE developed 16 prototype commercial buildings, 11 of which are used in this study: Highrise Apartment, Hospital, Large Hotel, Medium Office, Midrise Apartment, Primary School, Secondary School, Small Hotel, Small Office, Stand Alone Retail, and Strip Mall. These buildings were first developed to support the development of ASHRAE Standard 90.1-2004 (ASHRAE 2004; DOE 2011). A full report on the EnergyPlus models of the buildings can be found in Deru et al. (2011). CONTAM models of the prototype buildings were developed, as documented in Ng et al. (2013). The EnergyPlus models were later updated from their original versions to comply with ASHRAE Standard 90.1-2013 (ASHRAE 2013b; DOE 2016). The building geometry and layout of the updated EnergyPlus models were the same, with minor changes (such as the addition of zones, e.g., computer rooms, that did not add to the total floor area of the building) described in Goel et al. (2014). Subsequently, the CONTAM models were also updated and documented in Ng et al. (2019). The specifications of the ASHRAE Standard 90.1-2013 versions of the 11 building models used in this study are listed in Table 1, along with their building height, volume, and exterior surface areas. Both 5-sided envelope area (A_{s5}) and 6-sided envelope area (A_{s6}) terms are provided in Table 1 since airtightness values can be specified in both 5-sided and 6-sided terms. The *InfiltrationDesign* model uses a 5-sided airtightness value. In contrast, some commercial building envelope airtightness requirements, such as that from the U. S. Army Corps of Engineers (USACE 2012), ASHRAE Standard 90.1-2109 (ASHRAE 2019), and ASHRAE Standard 189.1-2020 (ASHRAE 2020), uses a 6-sided value.

Table 1 also lists the general operating schedule of the HVAC systems, whether or not the systems were modeled to be "pressurized" in CONTAM, and the normalized net system airflow rates, F_n (Eq. (33)).

$$F_n = \frac{\left(\sum F_{\text{supply}} - \sum F_{\text{return}} - \sum F_{\text{local exhaust}}\right)}{A_{s5}} \quad (3)$$

where F is the airflow rate (m^3/s).

If the *InfiltrationDesign* model of a building implemented HVAC systems that were always on and the infiltration was maintained at 100 % of the design value, it was assumed that these buildings would operate at neutral pressure. On the other hand, if the *InfiltrationDesign* model of a building implemented a reduction in infiltration when the HVAC system was on, it was assumed that these buildings were "pressurized". It should be noted that the EnergyPlus models of the prototype commercial buildings did not have HVAC systems that were modeled as "pressurized". Intended pressurization (or neutral pressurization) was determined only by the parameters in the *InfiltrationDesign* model of each building.

If a building were determined to be "pressurized", the HVAC system in CONTAM would be modeled such that the total return airflow was about 10 % less than the total supply airflow. If there was an exhaust fan in a zone, the return airflow would be reduced further in order to ensure enough makeup air for the exhaust fan. See Ng et al. (2019) for more details. Thus, a more accurate description of "pressurization" is "over-supply". Only two buildings were modeled in CONTAM to have equal supply and return airflow rates, the Highrise and Midrise Apartments (i.e., neutral pressure). The other 9 prototype commercial buildings (Hospital, Large Hotel, Medium Office, Primary School, Secondary School, Small Hotel, Small Office, Stand Alone Retail, and Strip Mall) were modeled in CONTAM as over-supplied (i.e., “pressurized”). It should be noted that the Large Office is listed in Table 1 as having a negative F_n value even though it was modeled in CONTAM as over-supplied. Restrooms were added to the CONTAM model to make the model more realistic since there were no restrooms in the EnergyPlus model. Because restrooms were added, exhaust fans were also added in order to comply with ASHRAE 62.1-2013 (ASHRAE 2013a).

Table 1. Summary of 11 DOE prototype buildings and their characteristics

	Highrise Apartment	**Hospital**	**Large Hotel**	**Medium Office**	**Midrise Apartment**	**Primary School**	**Secondary School**	**Small Hotel**	**Small Office**	**Stand Alone Retail**	**Strip Mall**
Height (m)	30	24	19	12	12	4	8	12	3	6	5
Floor area (m^2)	7837	22436	11345	4982	3135	6871	19592	4014	511	2294	2090
A_{s5} (m^2)	4639	8937	6005	3638	2326	9383	18286	2698	282	3471	3274
A_{s6} (m^2)	5422	13107	8429	5299	3109	16254	30188	3702	643	5765	5365
Volume (m^3)	23884	79802	30359	19741	9554	27484	95216	11622	1559	13984	10828
General HVAC operation											
Weekdays	24 h	24 h	24 h	6 a.m. to 10 p.m.	24 h	7 a.m. to 9 p.m.*	7 a.m. to 9 p.m.*	24 h	6 a.m. to 7 p.m.	7 a.m. to 9 p.m.	7 a.m. to 9 p.m.
Saturdays	24 h	24 h	24 h	6 a.m. to 10 p.m.	24 h	Off	Off	24 h	Off	7 a.m. to 10 p.m.	7 a.m. to 7 p.m.
Sundays & Holidays	24 h	24 h	24 h	Off	24 h	Off	Off	24 h	Off	9 a.m. to 7 p.m.	8 a.m. to 6 p.m.
Pressurized (Y/N)	N	Y	Y	Y	N	Y	Y	Y	Y	Y	Y
F_n ($m^3/s\bullet m^2$) $\times 10^{-4}$	0.0	5.8	-0.6	3.2	0.0	1.9	2.6	0.0	3.4	2.5	1.9

* Note that Primary and Secondary Schools have reduced operating hours in the summer.

3.2. Modeling of infiltration in DOE prototype models

EnergyPlus contains several empirical equations to model infiltration, all of which were developed using studies in low-rise residential buildings. Eq.(1) above is how EnergyPlus calculates infiltration rates in the DOE prototype commercial building models. As discussed earlier, the coefficients used in Eq.(1) for the prototype buildings are from DOE-2 and are $A = B = D = 0$ and $C = 0.224$ resulting in Eq. (2). A partial screenshot of how this was implemented in EnergyPlus IDFeditor is shown in Figure 2 and labeled the *InfiltrationDesign* model. In Figure 2, the EnergyPlus IDF editor identifies A as the "Constant Term Coefficient", B as the "Temperature Term Coefficient", C as the "Velocity Term Coefficient", and D as the "Velocity SquaredTerm Coefficient". The EnergyPlus results using the DOE prototype models will be referred to as the "EnergyPlus (orig)" results.

As will be described below, the NIST infiltration correlations were developed using the CONTAM models of the DOE prototype buildings and weather files. The values for A, B, and D in Eq.(1) (and assuming $C = 0$) were determined using least squares analysis (Figure 3). A screenshot of how the NIST infiltration coefficients were implemented in EnergyPlus is shown in Figure 2. The EnergyPlus results using the NIST infiltration correlations will be referred to as the "EnergyPlus (correl)" results. Other terminology in Figure 2 are described next. Note that in both screenshots of the IDFeditor, the "Flow per Exterior Surface Area" or I_{design}, are the same value in the *InfiltrationDesign* model and when using the NIST infiltration correlations.

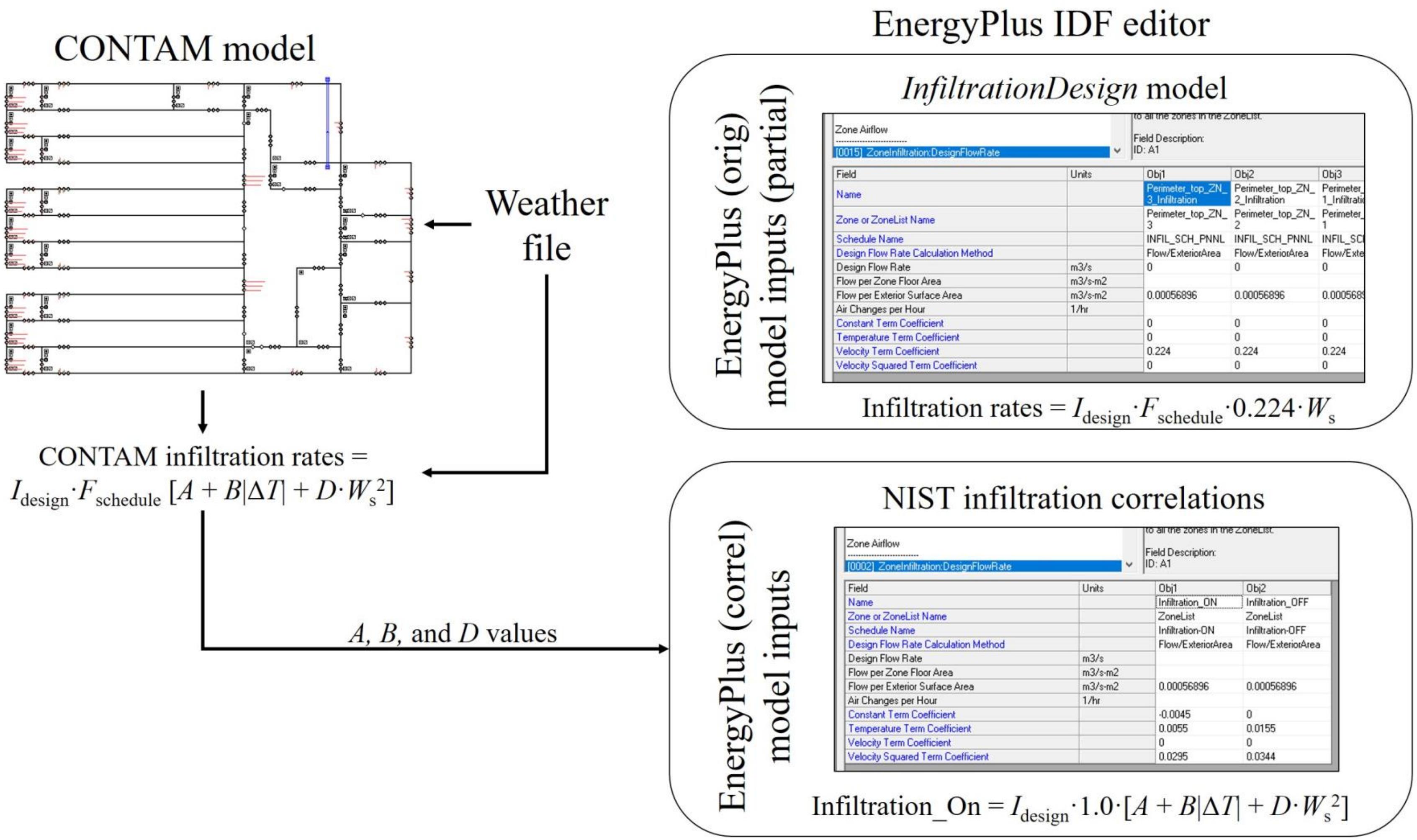


Figure 2 Diagram showing relationship between CONTAM, EnergyPlus, *InfiltrationDesign* model, and NIST infiltration correlations. Inputs for the Medium Office shown as an example.

_ENREF_8Weather-correlated infiltration correlations were developed by NIST for the 11 prototype buildings listed in Table 1. Because wind pressure on the building surface is a function of the square of the wind speed, the coefficient C was set to zero (Walton and Dols 2013). Values for A, B, and D in Eq. (1**Error! Reference source not found.**) were calculated for each building in eight cities representing eight climate zones (CZ) for HVAC system-on and off conditions. The process was shown briefly in Figure 2 and in more detail in Figure 3. It shows that weather file information (specifically, outside temperature and wind speed) and EnergyPlus HVAC system inputs are used to simulate airflow rates in CONTAM. The hourly, annual infiltration rates are then normalized by A_{s5} (Table 1) and correlated to $|\Delta T|$ and Ws in Eq. (**Error! Reference source not found.**1) where $F_{schedule} = 1$ and $C = 0$. This was done for system-on and system-off hours. It was assumed that $A = 0$ when the HVAC system was off because when $|\Delta T|$ and W_s are zero, the system-off infiltration rate should be zero. During system-on hours, A is nonzero. Additional details can be found in Ng et al. (2015) and Ng et al. (2018).

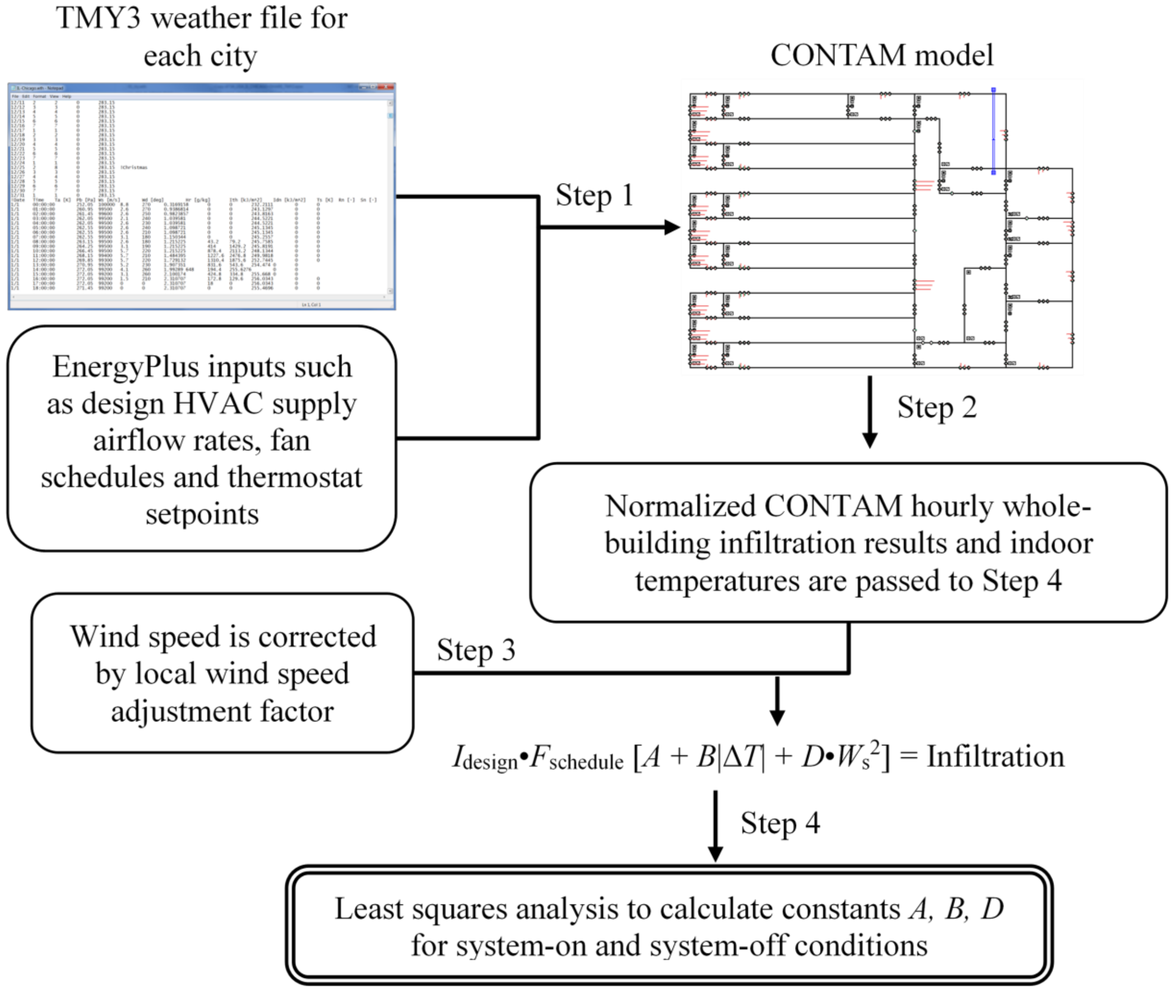


Figure 3 Infiltration correlation process from Ng et al. (2018).

The correlation coefficients for all 11 buildings for Chicago weather (CZ5) and a 5-sided building envelope airtightness of 13.8 $m^3/h{\cdot}m^2$ @ 75 Pa are listed in Table 2. This was the airtightness in the ASHRAE Standard 90.1-2013 versions of the DOE prototype models. The correlation values for the seven other cities (Miami (CZ1), Phoenix (CZ2), Memphis (CZ3), Baltimore (CZ4), Helena (CZ6), Duluth (CZ7), and Fairbanks (CZ8)) and models "with air barriers" can be found in a downloadable spreadsheet on the NIST Multizone Modeling Website (Case Study 14).

The building envelope airtightness of 13.8 $m^3/h \cdot m^2$ @ 75 Pa is converted to a value at 4 Pa to be used as I_{design} in Eq. (1**Error! Reference source not found.**). Gowri et al. (2009) assumed a 4 Pa difference when discussing the *InfiltrationDesign* model in the prototype commercial buildings. I_{design} is calculated as:

$$I_{\text{design}} = Q_{ref} \cdot \Delta p^n / p_{\text{ref}}^n \tag{4}$$

where n is the flow exponent (0.65 in this study), p_{ref} is the reference pressure (75 Pa), Q_{ref} is the leakage rate (m^3/s) at p_{ref}, and Δp is the pressure difference of 4 Pa. Thus, I_{design} for the EnergyPlus models will be 5.7 x 10^{-4} $m^3/s \cdot m^2$ at 4 Pa. The models (both CONTAM and EnergyPlus) with this building envelope airtightness will be referred to in this paper as the models "without air barriers". It should be noted that many factors contribute to how tight a building envelope is and does not solely depend on an air barrier. Sealing joints and other measures are also necessary to achieve a continuous air barrier as required in building standards and codes. Nevertheless, the terms "without air barriers" and "with air barriers" are used in this study to represent the building models with two different building envelope airtightness values.

Table 2. NIST infiltration correlation coefficients for Chicago and 5-sided building envelope airtightness of 13.8 $m^3/h{\bullet}m^2$ @ 75 Pa

	Highrise Apartment	**Hospital**	**Large Hotel**	**Medium Office**	**Midrise Apartment**	**Primary School**	**Secondary School**	**Small Hotel**	**Small Office**	**Stand Alone Retail**	**Strip Mall**
A_{on}	0.1302	0.0477	0.3330	-0.0445	0.0917	0.0025	0.1019	0.0403	0.0431	-0.0441	0.0164
B_{on}	0.0129	0.0028	0.0049	0.0055	0.0059	0.0034	0.0077	0.0079	0.0074	0.0066	0.0054
D_{on}	0.0206	0.0107	0.0262	0.0295	0.0328	0.0340	0.0877	0.0078	0.1096	0.0376	0.0360
A_{off}	N/A	N/A	N/A	0.0000	N/A	0.0000	0.0000	N/A	0.0000	0.0000	0.0000
B_{off}	N/A	N/A	N/A	0.0155	N/A	0.0066	0.0156	N/A	0.0164	0.0100	0.0090
D_{off}	N/A	N/A	N/A	0.0344	N/A	0.0423	0.1050	N/A	0.1173	0.0493	0.0471

The approach using the NIST infiltration correlations to model infiltration in EnergyPlus differs from that originally used in the DOE prototype models. First, the NIST correlations include three coefficients for Eq. (1**Error! Reference source not found.**): *A* to account for a constant term, *B* associated with temperature difference, and *D* associated with the square of wind speed. In contrast, the DOE prototype models included only the coefficient *C* to account for wind speed. Second, the NIST correlations have separate values for HVAC system-on and system-off conditions. In contrast, the DOE prototype models reduced infiltration by 75 %, i.e., to $0.25 \cdot I_{design}$, for HVAC system-on conditions. The differences were illustrated in Figure 2.

3.3. Simulations

EnergyPlus simulations with the original infiltration inputs and with the NIST infiltration correlations were performed for a year with timesteps that were either 10 min or 15 min in eight U.S. cities (eight different climate zones), and two levels of building envelope airtightness. An explanation in the difference in timestep was not provided in the documentation associated with the prototype models (Deru et al. 2011; Goel et al. 2014). As mentioned in Sec. **Error! Reference source not found.**, an envelope leakage value of 13.8 $m^3/h \cdot m^2$ @ 75 Pa was used to model buildings without air barriers. An airtightness of 5 $m^3/h \cdot m^2$ @ 75 Pa was selected to correspond to commercial buildings that were built with significant attention to airtightness (Emmerich and Persily 2014) referred to herein as models “with air barriers”. The “with air barrier” value presented in Emmerich and Persily (2014) was based on a 6-sided normalization, which was converted to a 5-sided value for this study. The 5-sided airtightness was calculated by multiplying the 6-sided airtightness by the ratio of the 6-sided surface area (above grade walls, roof, plus the floor area) to the 5-sided surface area (above grade walls and roof).

For the EnergyPlus models using the NIST infiltration correlations, two `ZoneInfiltration:DesignFlowRate` objects, "Infiltration_On" and "Infiltration_Off", were created and populated with the weather-correlated *A*, *B*, and *D* values in the following equations:

$$\text{Infiltration\_On} = I_{\text{design}} \cdot F_{\text{schedule}} \left[A_{on} + B_{on} \cdot |\Delta T| + D_{on} \cdot W_s^2\right] \tag{5}$$

$$\text{Infiltration\_Off} = I_{\text{design}} \cdot F_{\text{schedule}} \left[0 + B_{off} \cdot |\Delta T| + D_{off} \cdot W_s^2\right] \tag{6}$$

For the buildings with 24 h HVAC operation (Highrise Apartment, Hospital, Large Hotel, Midrise Apartment, and Small Hotel), F_{schedule} is always set to 1.0 in Eq. (5). For the other buildings (Medium Office, Primary School, Secondary School, Small Office, Stand Alone Retail, and Strip Mall), F_{schedule} is set to 1.0 in Eq. (5) when the HVAC system was scheduled to be on. When the HVAC system was scheduled to be off, F_{schedule} is set to 0.0 in Eq. (5) and F_{schedule} is set to 1.0 in Eq. (6).

For each of the eight cities, Typical Meteorological Year 3 (TMY3) weather data (NREL 2015) was used. In the EnergyPlus simulations, setpoint schedules were used to control the indoor temperature, T_{in}, within the thermostatically controlled zone; however, these setpoint schedules were assumed to be perfectly maintained within all zones in the CONTAM simulations.

3.4. Metrics for evaluating results

Comparisons between infiltration rates calculated using CONTAM (I_{CONTAM}) and EnergyPlus ($I_{EnergyPlus}$) were performed based on the fractional bias, defined in ASTM Standard D5157-19 (ASTM 2019). The fractional bias between I_{CONTAM} and $I_{EnergyPlus}$ was:

$$\text{Fractional bias } (FB) = \frac{2\times(I_{EnergyPlus} - I_{CONTAM})}{I_{EnergyPlus} + I_{CONTAM}} \quad (7)$$

Values within the range ±1.636 mean that I_{CONTAM} and $I_{EnergyPlus}$ are within one order of magnitude of one another. Absolute values above 1.96 mean they differ by more than an order of magnitude.

The annual average system-on infiltration rate is divided by the system-off infiltration rate (or “on/off infiltration ratio”) for the buildings that had both system-on and system-off hours. The ratio is calculated using the CONTAM, EnergyPlus (orig) and EnergyPlus (correl) results for each building.

The annual heating, cooling, and fan energy use from the EnergyPlus (correl) and EnergyPlus (orig) simulations were obtained from the results. All the buildings used gas for heating, electricity for cooling, and had fan usage. Some buildings also utilized electricity for heating, e.g., heat pumps in the Highrise Apartment and Small Office; variable air volume reheat in the Hospital and Medium Office; and electric heating coils in packaged terminal air-conditioners serving guestrooms and common areas of the Small Hotel. The annual site energy use intensity (EUI) related to HVAC operation will be reported (HVAC-EUI) in kBtu/ft^2. This is a unit commonly referenced in the literature when reporting energy use and is useful for benchmarking against other buildings. To convert these values to GJ, multiply by the floor area (ft^2) in Table 1 and then divide by 947.817 (EPA 2015). To convert from GJ to MWh, multiply by 0.2778.

4. RESULTS AND DISCUSSION

The simulation results described here were analysed in terms of the annual mean infiltration rates and HVAC energy use. A discussion of the differences between the predicted infiltration rates using the *InfiltrationDesign* method and NIST infiltration correlations is presented in Sec. 4.1 using fractional bias. To demonstrate that buildings designed to be positively "pressurized" are still likely to exhibit leakage in the form of infiltration, on/off infiltration ratios are discussed for the two simulated levels of airtightness in Sec. 4.2. To demonstrate that the NIST infiltration correlations reveal greater potential benefits of airtightening in commercial buildings compared with using the *InfiltrationDesign* approach, discussions of HVAC-EUI is presented in Sec. 4.3 and Sec. 4.4.

4.1. Simulated infiltration rates

Across 11 building models without air barriers and eight cities, the fractional bias between the annual average CONTAM and EnergyPlus (orig) predictions was 0.43 and between CONTAM and the EnergyPlus (correl) predictions was 0.13. These differences account for both system-on and system-off conditions. In other words, the differences reduced by a factor of three when using the EnergyPlus (correl) models. The differences depended on factors including type of building, HVAC system operation, and weather.

Figure 4 shows the annual average CONTAM infiltration rates (left axis) for five building models without air barriers and with HVAC systems that operated continuously (Midrise Apartment, Hospital, Highrise Apartment, Large Hotel, and Small Hotel). The right axis is the fractional bias between the annual average infiltration rates predicted by EnergyPlus ("orig" and "correl") and CONTAM. The horizontal line on the graphs show where the fraction bias equals 0.0. In these five building models, the graphs show that the infiltration rates predicted by EnergyPlus (correl) (circles) have fractional biases closer to 0 when compared with the fractional biases of the EnergyPlus (orig) results (triangles). The improvement is more consistent across the eight cities using the EnergyPlus (correl) models compared with using the EnergyPlus (orig) models. This is due in part to the EnergyPlus (correl) models taking into account both temperature and wind effects when predicting infiltration, while the EnergyPlus (orig) models only took into account wind effects.

For three of the building models (Highrise Apartment, Midrise Apartment, and Small Hotel), the fractional bias trends from positive to negative for the EnergyPlus (orig) results as the weather gets colder (CZ1 → CZ8). This could be expected since the EnergyPlus (orig) models employed a wind speed coefficient in the *InfiltrationDesign* model that did not vary with climate zone. As a result, the *InfiltrationDesign* model overestimated infiltration rates in the milder climates and underestimated in the colder climates.

That trend was not found in the Hospital and Large Hotel. For the Hospital, in CZ2 to CZ4, the fractional bias of the EnergyPlus (orig) results were negative, though > -0.10. This corresponded to absolute differences in infiltration rate less than 0.01 h^{-1}, which is likely due to the normalized net system flow (or pressurization) being highest for the Hospital (Table 1). For the Large Hotel, no matter the climate zone, the fractional bias of the EnergyPlus (orig) results was always negative and greater in magnitude than the EnergyPlus (correl) results. This was due to the Large Hotel having a negative normalized net system flow (Table 1) resulting in higher infiltration in the CONTAM model. This was not accounted for in the EnergyPlus (orig) model because the effects of HVAC system operation on infiltration were a constant 75 % reduction and did not consider the airflow physics involved.

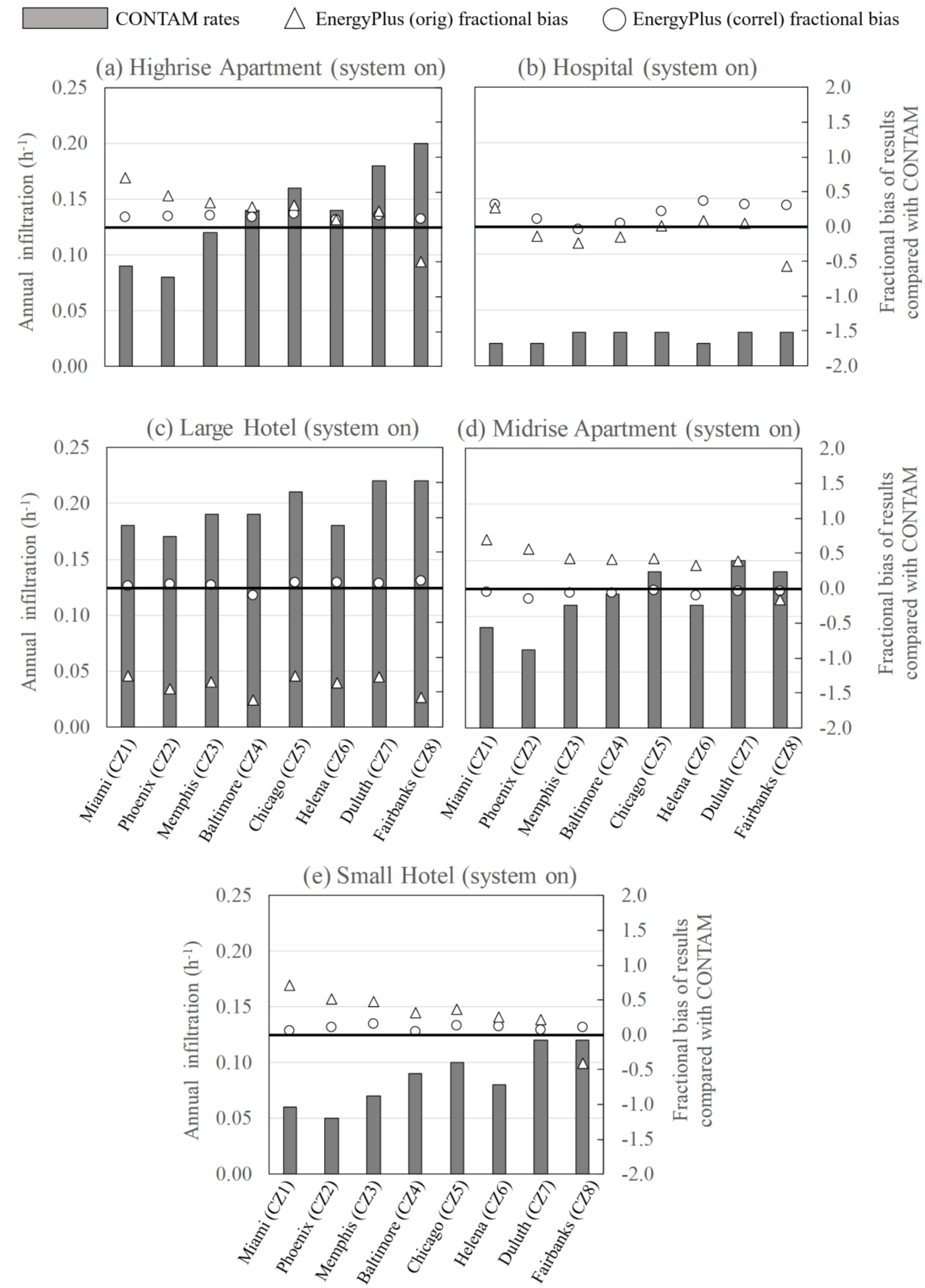


Figure 4. Comparison between annual average infiltration rates for buildings without air barriers having continuously operating HVAC systems

Figure 5 shows the same information as the previous figure for building models where the HVAC systems did not operate continuously. Whether the systems were on or off, the fractional biases of the EnergyPlus (correl) results were smaller in magnitude than the EnergyPlus (orig) results. The fractional biases of the EnergyPlus (correl) results were generally more consistent across the eight cities compared with the EnergyPlus (orig) results.

In summary, the magnitudes of the fractional biases using the NIST infiltration correlations were smaller across the 11 buildings and eight cities when compared with the EnergyPlus (orig) results. The fractional biases for building models with air barriers were on average similar to the building models without air barriers. In general, for all the buildings, the fractional biases were more consistent across the eight cities for the EnergyPlus (correl) results because these models accounted for HVAC operation, stack and wind effects. In contrast, the fractional biases for the EnergyPlus (orig) results varied with climate because the *InfiltrationDesign* method did not properly account for HVAC operation and ignored stack effects.

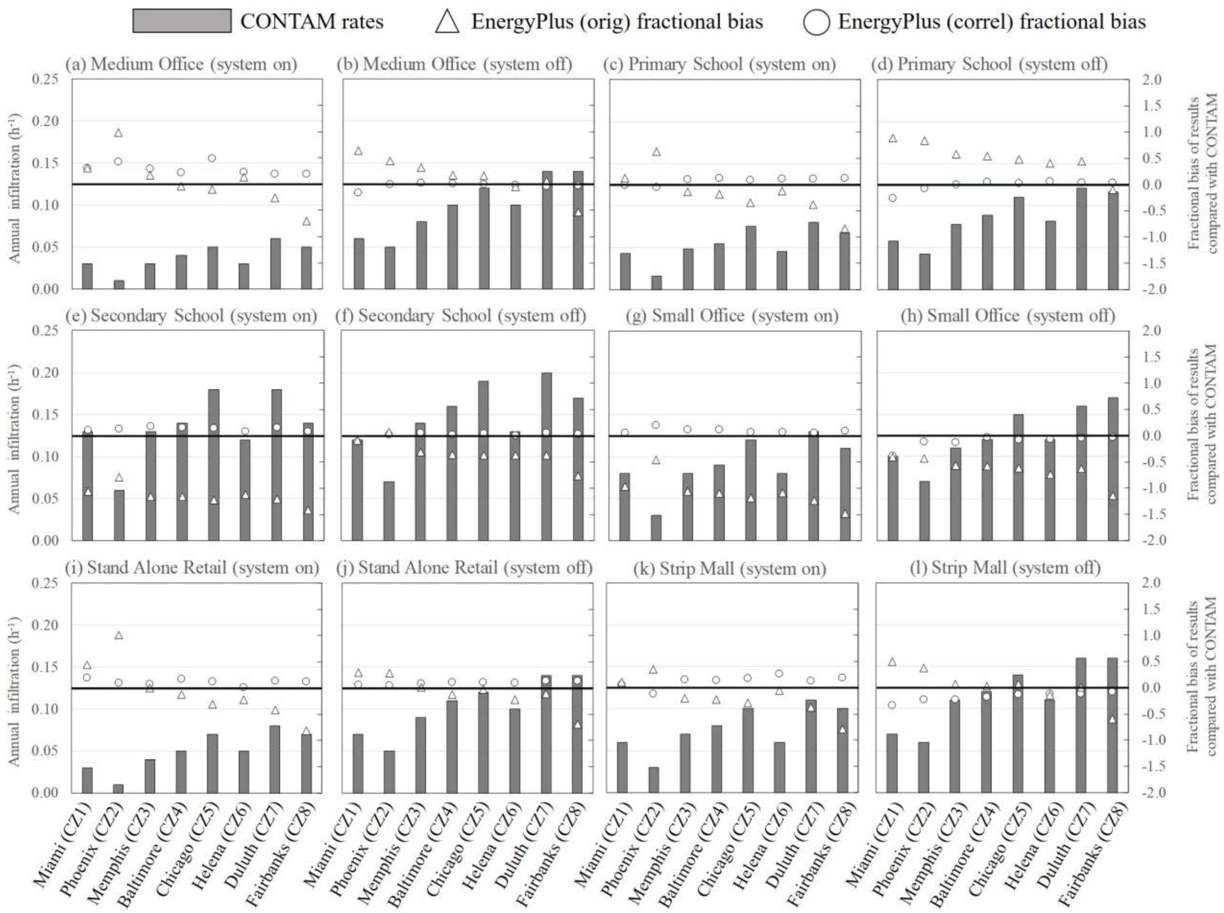


Figure 5. Comparison of annual average infiltration rates for building models with system-on and system-off operation schedules

4.2. Infiltration rates in pressurized buildings

Table 3 shows the annual average on/off infiltration ratio for the buildings without air barriers that had both system-on and system-off hours. All the buildings in Table 3 are modeled in CONTAM as being oversupplied or "pressurized." The EnergyPlus (orig) models tried to account for this by reducing the system-off infiltration rate by 75 % when the HVAC system was on.

Table 3 shows that the on/off infiltration ratios calculated using the EnergyPlus (orig) results without an air barrier (average ratio equal to 0.39 across all buildings and climates) were on average about 37 % lower than the average ratio calculated using CONTAM (average ratio equal to 0.62). The average on/off infiltration ratio calculated using the EnergyPlus (correl) results for the models without air barriers was 0.77.

For the building models with air barriers, unsurprisingly, Table 3 shows that the on/off infiltration ratio for the EnergyPlus (orig) models remained 0.39 because the "without air barrier" and "with air barrier" models only have different I_{design} values. In contrast, CONTAM accounts for the effect of airtightness on indoor-outdoor pressure differences and thus infiltration rates (average ratio equal to 0.51). These effects are reflected (with limitations) in the EnergyPlus (correl) models (average ratio equal to 0.61).

For all of the buildings except the Medium Office, Secondary School, and Stand Alone Retail, Table 3 shows that the CONTAM results predict that the system-on infiltration rate should only be reduced by 35 % compared with the system-off value. For the Secondary School, the system-on infiltration rate may not need to be reduced at all. Finally, for the Medium Office and Stand Alone Retail, the system-on infiltration rate should only be reduced by 58 % compared with the system-off value.

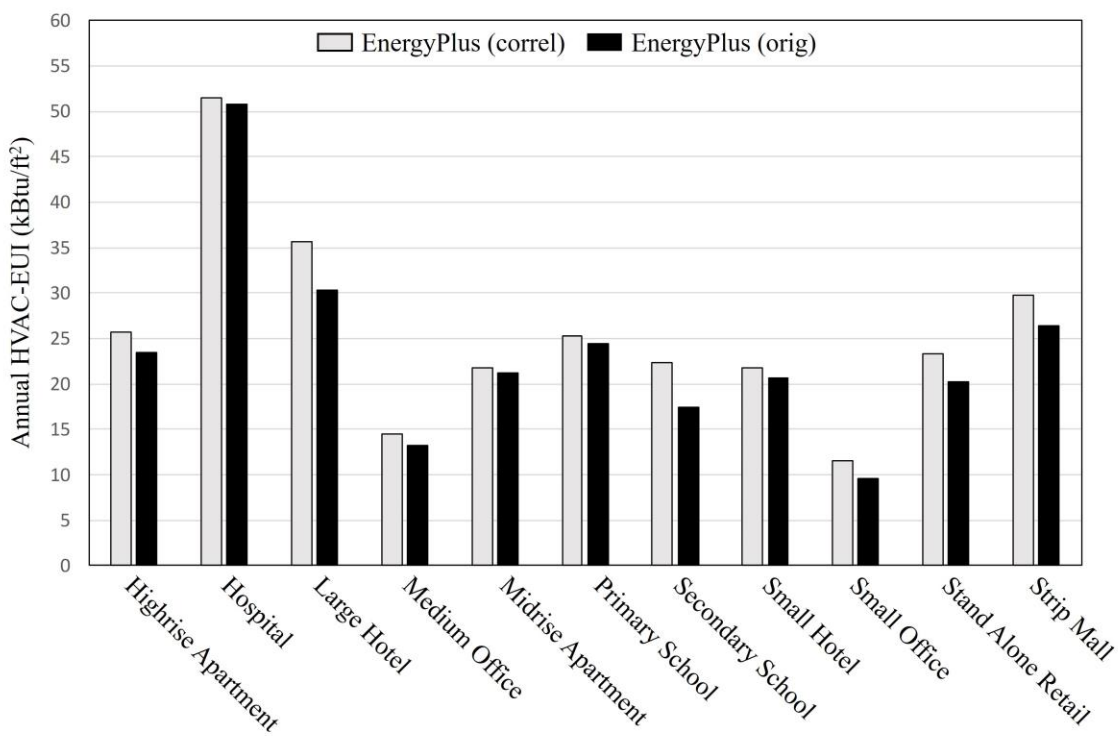
These results show that the pressurized buildings, as modeled by CONTAM, on average can be expected to leak more than is assumed in the DOE prototype models. The CONTAM models showed that pressurization is more effective with tighter building envelopes during system-on hours, but the difference is typically not as much as assumed in the EnergyPlus prototype models. That is, the HVAC system does not reduce infiltration by 75 % of the system-off rate and that reducing infiltration during system-on hours should not be generalized across all building types. These differences in predicted infiltration rates will have impacts on the predicted annual heating and cooling energy as presented in the next section.

Table 3. Average on/off (± standard deviation) infiltration ratios for buildings without and with air barrier

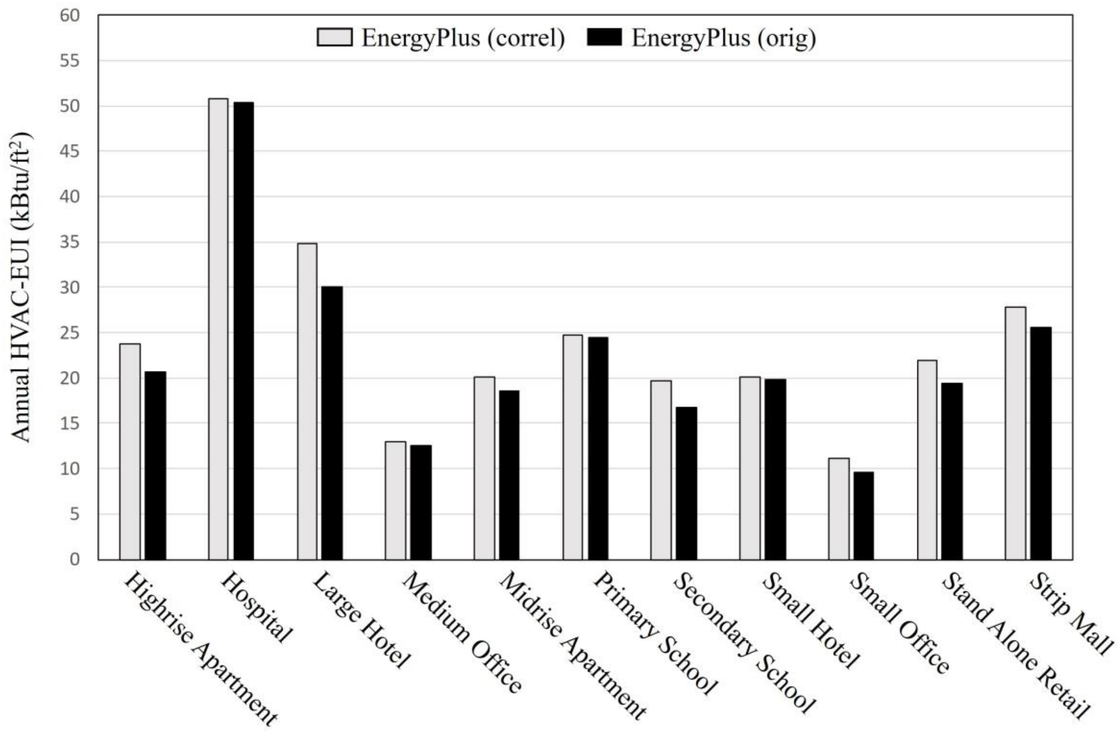
Average ratio across eight climate zones	Medium Office	Primary School	Secondary School	Small Office	Stand Alone Retail	Strip Mall	Average
	Without air barrier						
CONTAM	0.37±0.09	0.61±0.11	0.92±0.08	0.70±0.13	0.46±0.12	0.65±0.11	0.62±0.19
EnergyPlus (correl)	0.52±0.16	0.67±0.16	1.03±0.14	0.87±0.19	0.61±0.16	0.89±0.20	0.77±0.20
EnergyPlus (orig)	0.33±0.03	0.30±0.02	0.34±0.02	0.40±0.03	0.45±0.03	0.52±0.04	0.39±0.08
	With air barrier						
CONTAM	0.15±0.11	0.44±0.10	0.92±0.11	0.73±0.13	0.21±0.10	0.63±0.11	0.51±0.30
EnergyPlus (correl)	0.22±0.07	0.39±0.21	1.03±0.14	0.84±0.19	0.32±0.12	0.89±0.15	0.61±0.35
EnergyPlus (orig)	0.33±0.03	0.30±0.02	0.34±0.02	0.40±0.03	0.45±0.03	0.52±0.04	0.39±0.08

4.3. Energy use estimated using NIST infiltration correlations

Figure 6 shows that in all the buildings, the HVAC-EUI calculated using the EnergyPlus (correl) results were greater than those calculated using the EnergyPlus (orig) results. The differences for the buildings without air barriers ranged from 1 % to 22 %, with an average of 10 %. The differences for the buildings with air barriers ranged from 1 % to 15 %, with an average of 8 %. The smallest difference was for the Hospital, which was to be expected since it had the highest normalized net system flow (F_n) (Table 1). The largest differences were for the Large Hotel, Secondary School, and Small Office. Larger differences existed in the Large Hotel because it had a negative F_n, which was not accounted for by the EnergyPlus (orig) *InfiltrationDesign* model. Larger differences existed in the Secondary School and Small Office because the differences in on/off infiltration ratio (Table 3) between the EnergyPlus (correl) and EnergyPlus (orig) were on average the largest of the buildings.



(a) Without air barrier



(b) With air barrier

Figure 6. Annual HVAC-EUI for 11 prototype buildings – without and with air barrier

Though the differences in the annual HVAC-EUI between the buildings without and with air barrier in Figure 6 are not visually apparent, the buildings with air barriers saved an average of 6 % in HVAC-EUI when using the EnergyPlus (correl) models. Savings were as large as 12 % in the Stand Alone Retail and as small as 1 % in the Hospital. Energy savings are not the only benefit of airtightening and additional potential benefits may include improvements in IAQ, reductions in moisture problems, reduced material degradation, and improved thermal comfort. Additional discussion on the energy impacts of airtightening will be presented in Sec. 4.4.

Figure 7 shows that a general trend in colder climates was for the differences between the EnergyPlus (correl) and EnergyPlus (orig) HVAC-EUI to increase. There was also a general trend that the differences were larger for the buildings without air barriers compared to the buildings with air barriers. This was expected since the tighter the building envelope, the lower the infiltration rates and the smaller the differences would be between the EnergyPlus (correl) and EnergyPlus (orig) results. Except for Miami, the standard deviation of the differences was smaller for the buildings with air barriers than for the buildings without. The exception in Miami was attributed to the Stand Alone Retail, which will be discussed in the next section.

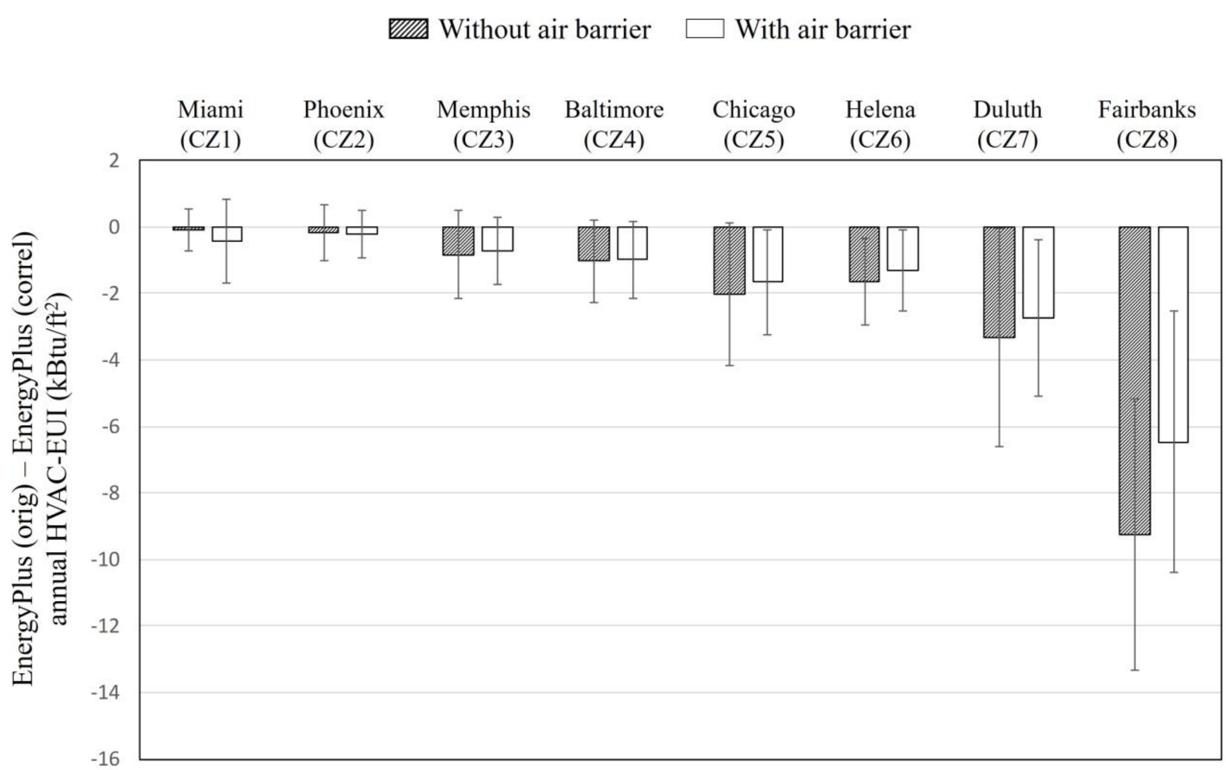


Figure 7. Average difference in HVAC-EUI by climate zone – without and with air barrier – bars showing standard deviation

4.4. Energy impacts of air-tightening

Figure 8 shows that airtightening on average resulted in energy savings whether using the EnergyPlus (correl) or EnergyPlus (orig) models, except for Miami (CZ1). In Miami (CZ1), the

EnergyPlus (correl) models predicted an average increase of 0.1 kBtu/ft^2, which was driven by an increase of 3 kBtu/ft^2 in the Stand Alone Retail. While the heating energy decreased after airtightening, the fan energy increased 15 % in the EnergyPlus (correl) model.

Figure 8 shows that except for Miami (CZ1) and Phoenix (CZ2), the EnergyPlus (correl) models calculated more HVAC-EUI savings with airtightening than the EnergyPlus (orig) models. The savings were on average 1.4 kBtu/ft^2 for the EnergyPlus (correl) models, ranging from an increase of 0.1 kBtu/ft^2 in Miami (CZ1) to a savings of 3.9 kBtu/ft^2 in Fairbanks (CZ8). In contrast, the savings were on average 0.9 kBtu/ft^2 for the EnergyPlus (orig) models, ranging from a savings of 0.2 kBtu/ft^2 in Miami (CZ1) to a savings of 2.2 kBtu/ft^2 in Duluth (CZ7).

These results demonstrate the need to more accurately account for infiltration in energy modeling in order to generate more accurate estimates of energy savings when evaluating the potential benefits of building envelope airtightening, HVAC system controls, and other measures.

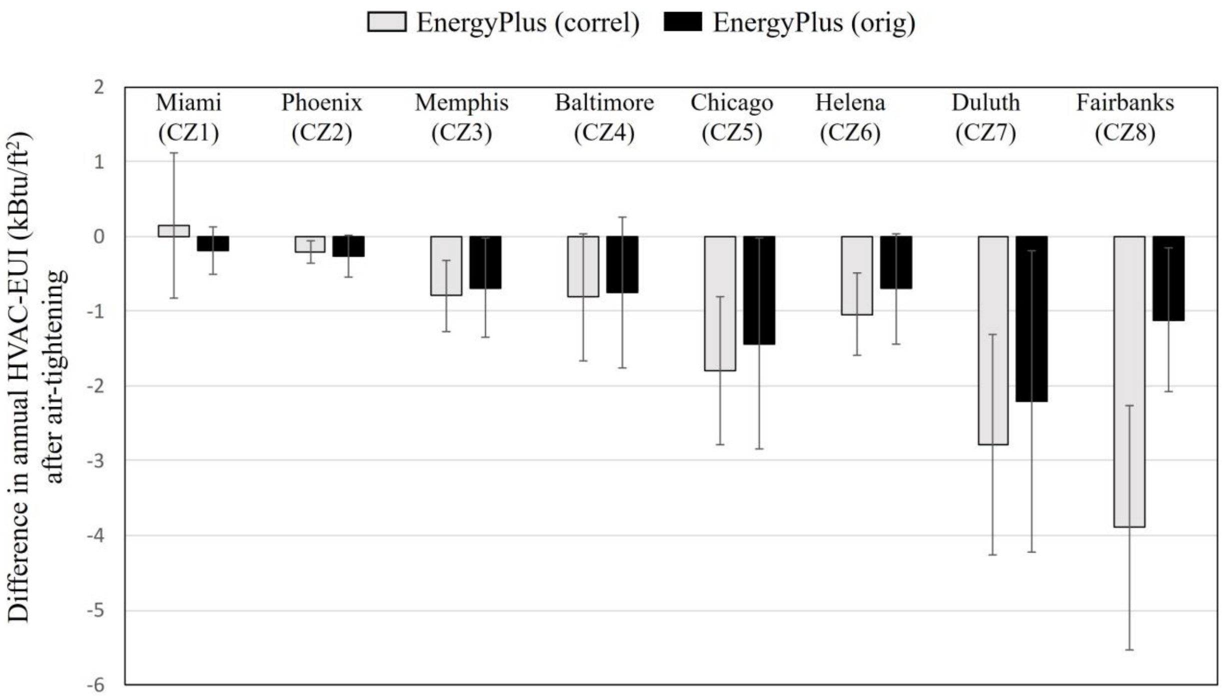


Figure 8. Annual HVAC-EUI savings with airtightening calculated using the EnergyPlus (correl) and EnergyPlus (orig) models – bars showing standard deviation

5. LIMITATIONS

The NIST infiltration correlations were developed using whole-building infiltration rates. These rates were normalized over the exterior surface area of the building and then correlated with temperature, wind speed, and HVAC system operation in the form of Eq. (1**Error! Reference source not found.**). This enables the correlations to be readily incorporated into EnergyPlus but does not capture the full effects of infiltration. Eq. (1**Error! Reference source not found.**) does not account for variations in wind direction, which will affect infiltration as discussed in the Introduction.

This study did not study the impacts that airtightening can have on moisture transport through the building envelope. However, studies using CONTAM and EnergyPlus showed that envelope airtightening can reduce the amount of moisture transported via infiltration by as much as 90 % in Chicago (Shrestha et al. 2016). This reduction in moisture transport can result in energy savings for dehumidification, improved durability of building materials, reduced risk of condensation on building surfaces, and reduced risk that condensation that could lead to IAQ issues such as mildew and mold growth.

6. CONCLUSIONS

EnergyPlus includes several methods to model infiltration. The DOE prototype models use a model developed for low-rise residential buildings that includes parameters for wind speed but not for wind direction. Those models also assumed that the HVAC system reduces infiltration by 75 % of the system-off rate. These simplified assumptions are not consistent with the relevant airflow physics embodied in CONTAM, which captures the dynamic interaction of HVAC systems, weather, and infiltration. CONTAM results showed that on average, between the buildings without and with an air barrier, the system-on infiltration rate was reduced by 44 % of the system-off rate.

In this study, CONTAM infiltration rates were correlated with temperature, wind speed, and HVAC system operation in 11 prototype buildings and in eight cities. The infiltration correlations were then input into EnergyPlus and results compared with those for the original infiltration inputs. The use of the NIST infiltration correlations resulted in an average 9 % greater annual HVAC-EUI across the 11 buildings and eight cities compared to using the EnergyPlus original inputs. Nevertheless, the potential benefits of airtightening were greater when using the NIST infiltration correlations, especially in the colder climates. On average, energy savings due to airtightening were 1.4 kBtu/ft^2 for the EnergyPlus (correl) models and only 0.9 kBtu/ft^2 for the EnergyPlus (orig) models. Though limitations exist when using these correlations, they are an improvement over the assumptions made in the DOE prototype models because the correlations are based on CONTAM results which accounts for stack effect, wind direction, and HVAC system operation. These findings indicate that the effects of infiltration on HVAC energy use are important and that infiltration can and should be better accounted for in whole-building energy models.

REFERENCES

ASHRAE (2004). ANSI/ASHRAE/IESNA Standard 90.1-2004: Energy Standard for Buildings Except Low-Rise Residential Buildings. Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE (2013a). ANSI/ASHRAE Standard 62.1-2013: Ventilation for Acceptable Indoor Air Quality. Atlanta, ASHRAE.

ASHRAE (2013b). ANSI/ASHRAE/IES Standard 90.1-2013: Energy Standard for Buildings Except Low-Rise Residential Buildings. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE (2017). ASHRAE Handbook Fundamentals. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE (2019). ANSI/ASHRAE/IES Standard 90.1-2019: Energy Standard for Buildings Except Low-Rise Residential Buildings. Atlanta, ASHRAE.

ASHRAE (2020). ANSI/ASHRAE/ICC/USGBC/IES Standard 189.1-2020: Standard for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings. Atlanta, ASHRAE.

ASTM (2019). ASTM D5157-19 Standard Guide for Statistical Evaluation of Indoor Air Quality Models. West Conshohocken, PA: American Society of Testing and Materials.

Black, D. R. and P. N. Price (2009). Contam airflow models of three large buildings: Model descriptions and validation. Berkeley, CA: Lawrence Berkeley National Laboratory. https://escholarship.org/uc/item/8sb495jq.

Chung, K. C. (1996). Development and validation of a multizone model for overall indoor air environment prediction. HVAC&R Research 2(4): 376-385.

Coblenz, C. W. and P. R. Achenbach (1963). Field Measurement of Ten Electrically-Heated Houses. ASHRAE Transactions 69(1): 358-365.

Deru, M., K. Field, D. Studer, K. Benne, B. Griffith, P. Torcellini, B. Liu, M. Halverson, D. Winiarski, M. Rosenberg, M. Yazdanian, J. Huang and D. Crawley (2011). U.S. Department of Energy Commercial Reference Building Models of the National Building Stock. Colorado: National Renewable Energy Laboratory. NREL/TP-5500-46861.

DOE (2011). Commercial Reference Buildings from http://energy.gov/eere/buildings/commercial-reference-buildings.

DOE (2014). Windows and Building Envelope Research and Development: Roadmap for Emerging Technologies. Washington, D. C.: U. S. Department of Energy.

DOE (2016). Commercial Prototype Building Models from https://www.energycodes.gov/development/commercial/prototype_models.

DOE (2018). EnergyPlus Input-Output Reference. Washington, D. C.: U. S. Department of Energy.

DOE (2019). EnergyPlus 9.2. Washington, D. C., U. S. Department of Energy.

Dols, W. S. and B. Polidoro (2015). CONTAM User Guide and Program Documentation. Gaithersburg, MD: National Institute of Standards and Technology. Technical Note 1887.

Dols, W. S. and B. Polidoro (2020). CONTAM User Guide and Program Documentation Version 3.4. Gaithersburg, MD: National Institute of Standards and Technology. Technical Note 1887 Revision 1.

EIA (2019). Annual Energy Outlook 2019 with projections to 2050. Washington, D.C.: U. S. Energy Information Administration.

Emmerich, S. J. (2001). Validation of Multizone IAQ Modeling of Residential-Scale Buildings: A Review. ASHRAE Transactions 107(2): 619-628.
Emmerich, S. J., S. J. Nabinger, A. Gupte and C. Howard-Reed (2004). Validation of multizone IAQ model predictions for tracer gas in a townhouse. Building Services Engineering Research and Technology 25(4): 305-316.
Emmerich, S. J. and A. K. Persily (2014). Analysis of U. S. Commercial Building Envelope Air Leakage Database to Support Sustainable Building Design. International Journal of Ventilation 12(4): 331-343.
EPA (2015). EPA Energy Star Portfolio Manager Technical Reference: Thermal Energy Conversions. Washington, D. C.: U. S. Environmental Protection Agency.
Fahnline, R. (2016). Impact of Stack Effect on Building Static Pressure Measurement. ASHRAE Journal **58**(10): 26-32.
Goel, S., R. Athalye, W. Wang, J. Zhang, M. Rosenberg, Y. Xie, R. Hart and V. Mendon (2014). Enhancements to ASHRAE Standard 90.1 Prototype Building Models. Richland, WA: Pacific Northwest National Laboratory. PNNL-23269.
Gowri, K., D. Winiarski and R. Jarnagin (2009). Infiltration Modeling Guidelines for Commercial Building Energy Analysis. Richland, WA: Pacific Northwest National Laboratory. PNNL-18898.
Haghighat, F. and A. C. Megri (1996). A Comprehensive Validation of Two Airflow Models - COMIS and CONTAM. Indoor Air 6(4): 278-288.
Ng, L. C., A. Musser, S. J. Emmerich and A. K. Persily (2012). Airflow and Indoor Air Quality Models of DOE Reference Commercial Buildings. Gaithersburg, MD: National Institute of Standards and Technology. Technical Note 1734.
Ng, L. C., A. Musser, S. J. Emmerich and A. K. Persily (2019). Airflow and Indoor Air Quality Models of DOE Prototype Commercial Buildings. Gaithersburg, MD: National Institute of Standards and Technology. https://doi.org/10.6028/NIST.TN.2072. Technical Note 2072.
Ng, L. C., A. Musser, A. K. Persily and S. J. Emmerich (2013). Multizone airflow models for calculating infiltration rates in commercial reference buildings. Energy and Buildings 58(0): 11-18.
Ng, L. C., N. Ojeda Quiles, W. S. Dols and S. J. Emmerich (2018). Weather correlations to calculate infiltration rates for U. S. commercial building energy models. Building and Environment 127(Supplement C): 47-57.
Ng, L. C., A. K. Persily and S. J. Emmerich (2015). Improving infiltration modeling in commercial building energy models. Energy and Buildings 88(0): 316-323.
NREL (2015). National Solar Radiation Data Base - 1991-2005 Update: Typical Meteorological Year 3 from http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/.
Persily, A., L. Ng, W. S. Dols and S. J. Emmerich (2019). Techniques to Estimate Commercial Building Infiltration Rates. 40th AIVC - 8th TightVent & 6th venticool Conference, Ghent, Belgium.
Shrestha, S. S., L. Ng, S. Emmerich, D. Hun, A. Desjarlais and L. Dalgleish (2016). Online Infiltration Calculator for the US, Canada and China. Thermal Performance of the Exterior Envelopes of Whole Buildings XIII International Conference, Clearwater, FL.
USACE (2012). U.S. Army Corps of Engineers Air Leakage Test Protocol for Building Envelopes. Champaign, IL: U.S. Army Corps of Engineers Research and Development Center.

Walton, G. N. (1989). AIRNET - A Computer Program for Building Airflow Network Modeling. Gaithersburg, MD: National Institute of Standards and Technology. NISTIR 89-4072. NISTIR 89-4072.

Walton, G. N. and W. S. Dols (2013). CONTAM User Guide and Program Documentation. Gaithersburg, MD: National Institute of Standards and Technology. NISTIR 7251. NISTIR 7251.