An Improved Method of Modeling Infiltration in Commercial Building Energy Models

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AN IMPROVED METHOD OF MODELING INFILTRATION IN COMMERCIAL BUILDING ENERGY MODELS

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ABSTRACT

Different strategies for improving building envelope thermal performance are being implemented in commercial building design and construction as well as being incorporated into ASHRAE standards and other design requirements. The energy impacts of unintended infiltration on building energy use have been shown to be significant. As HVAC equipment and other building sytems continue to become more efficient, the energy loss asssociated with building envelope leakage is becoming an even greater percentage of the total building energy consumed. However, current energy simulation software and design methods are generally not able to accurately account for envelope infiltration and the impacts of improved airtightness. New strategies to incorporate airflow calculations into building energy calculations are proposed in this paper. These methods, based on infiltration rates calculated using detailed multizone airflow models, are more accurate than current approaches and easier to apply than multizone airflow modeling. The new strategies are based on relationships between infiltration rates calculated using multizone airflow models, weather conditions, and building characteristics, including envelope airtightness and HVAC system operation.

INTRODUCTION

Heating, ventilating, and air conditioning (HVAC) systems in buildings are designed to maintain acceptable thermal comfort and indoor air quality (IAQ). The operating cost of these HVAC systems is often a large percentage of the total energy cost of buildings, which constitutes 40 % of the primary energy consumed in the U.S. (DOE 2010). Due to the current emphasis on reducing energy consumption and greenhouse gas emissions, the use of energy simulation software has increased to investigate different design options and their impacts on building energy use. In order to comply with energy design standards, such as the California Code of Regulations, Title 24 (CEC 2008) and ASHRAE Standard 90.1 (ASHRAE 2013), energy simulation is often performed, and in some cases required. One design option to reduce building energy use is improving building envelope airtightness. However, unless efforts are made to design and build tight building envelopes, commercial buildings are actually much leakier than typically assumed (Emmerich et al. 2007; Emmerich and Persily 2013). As a result, the energy impacts of infitration can be larger than expected. Nevertheless, current energy simulation software and design methods are generally not able to accurately account for envelope infiltration (Ng and Persily 2011), and therefore the impacts of improved airtightness on energy may not be properly captured.

Multizone building airflow models are the most technically complete and accepted approaches for calculating building infiltration rates, but they do require accurate input data and familiarity with the associated software tools (Walton and Dols 2013). However, empirical approaches to estimating infiltration rates have the advantage of ease of use relative to building airflow models. These approaches employ algebraic equations that relate simple building features, such as height and envelope leakage, as well as weather conditions to calculate infiltration rates. One of the earliest such approaches was developed by Shaw and Tamura (1977), which had one equation for stack induced infiltration, one for wind driven, and another to combine the two into the total building infiltration rate. More recently, Gowri et al. (2009) proposed a method to account for infiltration in commercial buildings that was developed using a square medium office building and a building envelope airtightness value, such as one obtained by a pressurization test. Assuming a constant indoor-outdoor pressure difference of 4 Pa, Gowri calculated an infiltration rate to be input into EnergyPlus using an approach that accounts for wind speed but not temperature effects. However, temperature effects can be important particularly in taller buildings and colder climates. Gowri further recommends that this leakage rate be multiplied by a wind speed adjustment and a factor of 0.25 in EnergyPlus when the HVAC system is on and 1.0 when the HVAC system is off. Overall, such empirical methods greatly simplify the interaction of building envelope airtightness, weather, HVAC system operation, and infiltration, which reduces the accuracy of the estimated infiltration rates.

In summary, the ways in which infiltration are currently accounted for in energy simulations are not typically based on well-developed airflow theory relating building envelope airtightness, HVAC system operation, and weather (Walton 1989). In those few energy simulation programs where airflow can be more accurately modeled, the features are often limited and cumbersome to employ and are rarely used in design. New strategies to more accurately, but relatively simply, incorporate physically-based infiltration calculations into energy software are proposed in this paper. These strategies are based on relationships developed between infiltration rates calculated by multizone airflow modeling, building characteristics, HVAC system operation, weather conditions, and building envelope airtightness. The strategies are described for implementation in EnergyPlus but are applicable to other energy simulation software.

METHODS

This section describes how infiltration is currently incorporated into EnergyPlus. Two new strategies for estimating infiltration in mechanically ventilated commercial buildings based on detailed multizone airflow simulations are then described, a building-specific strategy and a generalized one. For the building-specific strategy, the results of multizone airflow simulations are fit to an empirical relationship between infiltration rates and weather conditions for a specific building. For the generalized strategy, the coefficients of the empirical relationships (calculated using the building-specific strategy) are related to general building characteristics, such as building height, in order to derive expressions for calculating empirical coefficients for any given building.

Common strategy for modeling infiltration in EnergyPlus

EnergyPlus contains three empirical equations to calculate infiltration, all of which were developed using data from low-rise residential buildings but have different functional forms. One of the equations is:

$$\text{Infiltration} = I_{\text{design}} \bullet F_{\text{schedule}} \, [A + B|\Delta T| + C \bullet W_s + D \bullet W_s^2] \qquad (1)$$

where I_{design} is defined by EnergyPlus as the "design infiltration rate", which is the airflow through the building envelope under design conditions. 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 absolute 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 user manual (DOE 2012). However, these suggested values are based on empirical data for low-rise residential buildings. Given the challenges in determining valid coefficients for each building, a common strategy used in EnergyPlus for incorporating infiltration is to assume constant infiltration rates, i.e., A=1 and B=C=D=0. This strategy does not reflect known dependencies of infiltration on outdoor weather and HVAC system operation. Therefore, new strategies are proposed that can more accurately incorporate infiltration into EnergyPlus and other energy simulation software.

Method 1 – Building Specific

Method 1 is a building-specific strategy for determining *A*, *B*, *C*, and *D* values in Equation (1). Seven commercial reference buildings (DOE 2011) were selected for testing this strategy: Full Service Restaurant, Hospital, Large Office, Medium Office, Primary School, Stand Alone Retail, and Small Hotel. These buildings include several different types of occupancies and HVAC system types and operation.

Based on the EnergyPlus models of these buildings (DOE 2011), models were created using the multizone airflow and contaminant transport model CONTAM (Walton and Dols 2013). Details of the CONTAM building models can be found in Ng et al. (2012; 2013). The number of zones in the buildings was different between the CONTAM and EnergyPlus models in instances where the CONTAM models needed additional zones to support realistic airflow and IAQ analyses. Modeling all building zones, or at least more of the zones than are typically needed for energy analyses, is generally important for airflow and IAQ analyses to properly capture pressure relationships and airflow patterns in buildings. Though the number of zones and some zone floor areas are different for the CONTAM and EnergyPlus models, the total building floor areas and volumes are consistent.

Hourly infiltration rates over one year for each of the building models were simulated using typical meteorological year (TMY2) weather data for Chicago (DOE 2011). Chicago weather was selected since there are a relatively high percentage of buildings in the U.S. in this climate zone (Deru et al. 2011) and because Chicago covers a wide range of outdoor temperatures and wind speeds. A building envelope effective leakage area of 5.27 cm^2/m^2 at a reference pressure of 4 Pa (0.00918 $m^3/s{\cdot}m^2$ at 75 Pa) was used in the CONTAM building models. This leakage area value was based on consideration of airtightness data in U.S. commercial buildings (Emmerich and Persily 2005). Assuming a constant indoor-outdoor pressure of 4 Pa and a pressure exponent of 0.65, this leakage area was converted to a building envelope leakage value of 0.00137 $m^3/s{\cdot}m^2$, using Equation (2), for use in Energy Plus (I_{design}).

$$I_{\mathrm{design}} = Q_{ref}/p_{\mathrm{ref}}{}^{n} \cdot \Delta p^{n} \qquad (2)$$

where Q_{ref} is the leakage rate (m^3/s) at a reference pressure p_{ref}, Δp is the desired pressure (Pa), and n is the flow exponent. In this discussion, infiltration includes only the outdoor air entering through unintentional building envelope leakage. It does not include any outdoor air entering the building through mechanical ventilation systems.

Hourly CONTAM infiltration rates and weather data over one year were fit to Equation (1) to calculate *A*, *B*, *C*, and *D* values for each of the seven buildings. However, since wind pressure is a function of the square of wind speed (Walton and Dols 2013), a separate set of *A*, *B*, and *D* values were calculated when *C* was set to 0.

The calculated *A*, *B*, *C*, and *D* values (details in (Ng et al. 2014)) and I_{design}=0.00137 $m^3/s{\cdot}m^2$ were input into the EnergyPlus ZoneInfiltration:DesignFlowRate object, which implements Equation (1) for calculating infiltration. It was found that the infiltration rates calculated by EnergyPlus, whether *C* was non-zero or zero, were similar. Therefore, to simplify the subsequent analyses, *C* was set equal to zero. 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.

The *A*, *B*, and *D* values (Table 2) for each building were input into the EnergyPlus ZoneInfiltration:DesignFlowRate object. Annual energy simulations were then performed using Chicago weather, and the hourly infiltration rates were compared between CONTAM and EnergyPlus.

The average system-on and system-off R^2 value for the seven buildings is 0.80 (details in (Ng et al. 2014)). Excluding the Hospital and Large Office, which have the smallest mean infiltration rates among the buildings, the average system-on relative standard error of the other buildings is 24 % and the average system-off relative standard error is 15 %. As expected, the R^2 values and relative standard error of the EnergyPlus infiltration rates compared with CONTAM are relatively good using Method 1 because different *A*, *B*, and *D* values were specifically calculated for each building. Using a common strategy for modeling infiltration in EnergyPlus, which is to assume a fixed rate (0.000302 $m^3/s{\cdot}m^2$ in the DOE reference building models), the average standard error compared to CONTAM infiltration rates was 76 % for system-on conditions and 35 % for sytem-off. Using Method 1, the average standard error compared to CONTAM infiltration rates was reduced to 39 % for system-on and 15 % for system-off.

However, using Method 1 requires infiltration rate data, such as those generated using CONTAM or perhaps measured values, which may not necessarily be available in a given building. In order to address this limitation, a method that can be used to calculate *A*, *B*, and *D* in any building is described in the next section.

Method 2 – General

Method 2 is a generalized strategy for determining *A*, *B*, and *D* values in Equation (1) based on key building characteristics. The building characteristics considered are: building height (*H* in m), exterior surface area to volume ratio (*SV* in m^2/m^3), and net system flow (i.e., design supply air minus design return air minus mechanical exhaust air) normalized by exterior surface area (F_n in $m^3/s{\cdot}m^2$). The values for these characteristics for the seven buildings are listed in Table 1. It should be noted that only the Full Service Restaurant has a large negative net system flow, due to a kitchen exhaust fan, while the other buildings have positive net system flow.

The following relationships between the constants *A*, *B*, and *D* in Equation (1) (*C*=0) and the building characteristics (*H*, *SV*, and F_n) were considered:

$$A = M_A \cdot H + N_A \cdot SV + P_A \cdot F_n \qquad (3)$$

$$B = M_B \cdot H + N_B \cdot SV + P_B \cdot F_n \quad (4)$$

$$D = M_D \cdot H + N_D \cdot SV + P_D \cdot F_n \quad (5)$$

where M, N, and P are constants, and their subscripts distinguish them between A, B, and D.

A, B and D values calculated using Method 1 and the building characteristics of the seven buildings (Table 1) were fit to Equations (3) through (5) to calculate M, N, and P values. It was assumed that $A = 0$ and the net system flow is zero ($F_n = 0$) when the system is off. The solutions to Equations (3) through (5) are:

$$A_{on} = 0.0001 \cdot H + 0.0933 \cdot SV + -47 \cdot F_n \quad (6)$$

$$B_{on} = 0.0002 \cdot H + 0.0245 \cdot SV + -5 \cdot F_n \quad (7)$$

$$D_{on} = 0.0008 \cdot H + 0.1312 \cdot SV + -28 \cdot F_n \quad (8)$$

$$A_{off} = 0 \quad (9)$$

$$B_{off} = 0.0002 \cdot H + 0.0430 \cdot SV \quad (10)$$

$$D_{off} = -0.00002 \cdot H + 0.2110 \cdot SV \quad (11)$$

The idea behind Method 2 is to use Equations (6) through (11) to determine A, B and D values for other buildings based on their characteristics. A, B, and D were recalculated for each of the seven buildings using these equations and shown in Table 3. The corresponding values are generally on the same order of magnitude as those calculated using Method 1, and in some cases are quite close to one another.

EVALUATING METHOD 2

Method 2 is a general approach to improving infiltration calculations in EnergyPlus based on key building characteristics. This section describes the performance of this method in the seven reference buildings, three other buildings, and using different building envelope effective leakage area values.

Evaluation in the seven simulated buildings

The calculated A, B, and D values in Table 3 and I_{design}=0.00137 m^3/s•m^2 were input into the EnergyPlus ZoneInfiltration:DesignFlowRate object. A_{on}, B_{on}, and D_{on} were used with $F_{schedule}$=1.0 during system-on hours and $F_{schedule}$=0.0 during system-off hours. A_{off}, B_{off}, and D_{off} were used with $F_{schedule}$=1.0 during system-off hours and $F_{schedule}$=0.0 during system-on hours. Annual EnergyPlus simulations were performed using Chicago weather for each of the seven buildings, and the hourly infiltration results were then compared between CONTAM and EnergyPlus. The mean of the CONTAM and EnergyPlus infiltration rates are listed in Table 4, along with the standard error, standard error as a percentage of the CONTAM mean rate (or "relative standard error"), and coefficient of determination, R^2, of the EnergyPlus infiltration rates compared with the CONTAM rates.

Excluding the Hospital and Large Office, which have the smallest system-on mean infiltration rates among the buildings, the average system-on difference in mean infiltration rates is 18 % and the average system-off difference is 30 %.

The Retail and Hotel generally have the lowest relative standard errors and highest R^2 of the buildings. This is also shown in Figure 1(a), where the CONTAM versus EnergyPlus infiltration rates fall close to lines of perfect agreement for the Retail. For the Medium Office, the relative standard error of the EnergyPlus infiltration rates is high, yet there is still good agreement between the CONTAM and EnergyPlus infiltration rates as shown in Figure 1(b).

For the School, Large Office, and Restaurant, the system-on and system-off relative standard error of the EnergyPlus infiltration rates and R^2 values do not reflect as good a level of agreement as seen in the Retail, Hotel, and Medium Office.

In general, buildings with the lowest infiltration rates, the Hospital and two offices, also have the highest system-on relative standard errors. However, since the absolute infiltration rates are relatively low for these three buildings, the absolute errors in the infiltration rates are also low. For all of the buildings except the Hospital and Full Service Restaurant, there is good agreement between the system-on and system-off infiltration rates calculated by CONTAM and EnergyPlus. Though the average system-on and system-off R^2 values for the seven buildings is only

0.08, the average system-on relative standard error, excluding the Hospital and Large Office, is 25 %, and the average system-off relative standard error is 17 %.

As stated earlier, using a common strategy for modeling infiltration in EnergyPlus, the average standard error compared to CONTAM infiltration rates was 76 % for system on and 35 % for sytem off. Using Method 2, the average standard error compared to CONTAM infiltration rates was reduced to 46 % for system on and 17 % for system off.

Evaluation in other buildings

Equations (6) to (11) were used to calculate system-on and system-off *A*, *B*, and *D* values for three additional buildings based only on their individual building characteristics. The buildings were the Small Office building from the DOE reference buildings, and two buildings on the campus of the National Institute of Standards and Technology (NIST), the Administration and the TRF Buildings. The building height, exterior surface area to volume ratio, and net system flow normalized by exterior surface area for these buildings are listed in Table 5. For more details on the Small Office, see Ng et al. (2012). For more details on the NIST buildings, see Persily et al. (2007).

For the Small Office using Method 2, the mean infiltration rates calculated by EnergyPlus are about 80 % less than those calculated by CONTAM. In addition to being similar in height and having similar surface to volume ratios with the Full Service Restaurant, the Small Office and Full Service Restaurant both have attic spaces that may be contributing to the low estimates of infiltration.

EnergyPlus models were not available for the NIST buildings, thus, infiltration was calculated using a spreadsheet that implemented the EnergyPlus infiltration equation. For the NIST Administration Building, the calculated mean infiltration rates are also 80 % lower than the values calculated by CONTAM. For the NIST TRF Building, there is good agreement between the calculated and CONTAM infiltration rates, with differences about 30 %.

As noted earlier, EnergyPlus models were not available for the NIST buildings, thus, calculated infiltration may not reflect the rates that EnergyPlus would calculate. This is due to the fact that EnergyPlus applies a different wind speed adjustment to each zone depending on its height. In contrast, the infiltration calculated by the spreadsheet uses a single average local wind speed adjustment for the entire building. This could explain the underestimated infiltration rates in the NIST Administration Building, which was one of the taller buildings. Using an average local wind speed adjustment may neglect the impacts of wind on infiltration on the highest floors.

Evaluation for other I_{design} values

Equations (6) through (11) were developed assuming a building envelope effective leakage area of 5.27 cm^2/m^2 at 4 Pa (i.e., I_{design} = 0.00137 $m^3/s{\bullet}m^2$). Other I_{design} values were tested to evaluate the extension of Method 2 to other airtightness values. CONTAM simulations were re-run with building envelope effective leakage area of 1.18 cm^2/m^2 at 4 Pa and 20.96 cm^2/m^2 at 4 Pa. These were respectively four times lower and higher than the original I_{design} value. EnergyPlus simulations were re-run with I_{design} values of 0.000304 $m^3/s{\bullet}m^2$ (or "low I_{design}") and 0.0054 $m^3/s{\bullet}m^2$ (or "high I_{design}") respectively, assuming a constant indoor-outdoor pressure of 4 Pa and a pressure exponent of 0.65. In these EnergyPlus simulations, the I_{design} values changed, but the *A*, *B*, and *D* values remained the same as those in Table 3. Hourly infiltration rates were compared between CONTAM and EnergyPlus. This analysis was done to assess the ability of the *A*, *B*, and *D* values in Table 3, calculated using a single building envelope leakage value, to predict infiltration for a range of building envelope leakage values.

Using the low I_{design} value resulted in comparable agreement between the EnergyPlus and CONTAM infiltration rates in most buildings tested. The exceptions were the Large and Small Offices, School, and Hospital. The level of agreement between CONTAM and EnergyPlus infiltration rates is better using the high I_{design} value relative to using the low I_{design} value for the buildings tested in this paper. No studies using different I_{design} values for the NIST buildings were performed because EnergyPlus models were not available to make those comparisons. Detailed results can be found in Ng et al. (2014).

DISCUSSION

The proposed methods for estimating infiltration rates based on weather, system operation, building envelope airtightness, and building characteristics were developed using hourly infiltration rates from CONTAM for seven commercial building models. Compared with using a constant infiltration rate, using Method 1 increases the predicted toal building annual energy use from 0.5 % to 10 %. Using Method 2, increases in the predicted total building annual energy use are between 2 % and 10 %. It is possible that these methods could be made more robust by considering other buildings, such as the complete collection of fifteen commercial building models available from DOE (2011). Also, the building models developed by DOE are based on data from real buildings, but are not actual buildings. Future work could include using building envelope airtightness values and measurements of infiltration from real buildings to further evaluate these methods. Further, it is possible that under actual system operation the normalized net system flow (F_n) deviates from the design value, thus, future work could incorporate these impacts. Also, the CONTAM simulations discussed in this paper used only Chicago weather data, so additional work using data from other cities could be performed.

Based on the results of this effort, it is important to develop guidance on how to use both methods in EnergyPlus, or other energy simulation software. However, depending on the building, occupancy use type, building envelope airtightness, and its location, the methods may still not yield infiltration rates that are sufficiently accurate. In these situations, CONTAM or other airflow simulation program may be recommended.

In developing and implementing these approaches using EnergyPlus, some issues were identified that merit program modifications . Based on the physics of airflow in mechanically ventilated buildings, as reflected in the CONTAM simulation results and obsesrved in field data, infiltration rates are not necessarily symmetrical around an indoor-outdoor temperature difference of zero when fans are on. In such cases, the EnergyPlus infiltration equation will not accurately account for infiltration at negative indoor-outdoor temperature differences. This limitation could be overcome by allowing for negative indoor-outdoor temperature differences in the calculation of infiltration in EnergyPlus. In addition, EnergyPlus assumes that the local wind speeds at various heights acting on the building can be simply calculated using a scaling factor for the wind measured at a meteorological station. However, the physics of airflow at heights close to the ground and between buildings is complex and a simple relationship of wind speed and height is not likely to capture the actual variation. Based on existing approaches to characterizing wind effects on buiding facades, supplemented by experiments or CFD simulations, local wind pressure coefficients (C_p) can be determined to more accurately calculate local wind pressure on buildings.

CONCLUSION

Due to an increased emphasis on energy consumption and greenhouse gas emissions, the potential savings from energy efficiency measures are often analyzed using energy simulation software. However, the impact of some efficiency measures can not always be accurately estimated because building envelope infiltration is not properly accounted for in this simulation programs. Many of the airflow estimation approaches implemented in energy software tools are inappropriate for large buildings or are otherwise limited in their capabilities. Based on the relationship between building envelope airtightness, building characteristics, weather, and system operation, methods are presented in this paper to calculate infiltration rates that are comparable to performing multizone calculations. These methods show better accuracy when compared with existing approaches to estimating infiltration in commercial building energy calculations.

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Table 1 Building characteristics of seven simulated buildings

	RESTAURANT	HOSPITAL	LARGE OFFICE	MEDIUM OFFICE	SCHOOL	HOTEL	RETAIL
H (m)	4.7	23.8	50.4	12	4	11.6	6.1
SV (m^2/m^3)	0.17	0.11	0.09	0.18	0.34	0.23	0.24
F_n ($m^3/s \bullet m^2$) $\times 10^{-3}$	-2.6	1.0	1.3	0.56	0.02	0.50	0.21

Table 2 Method 1: A, B, and D values of simulated buildings

	RESTAURANT	HOSPITAL	LARGE OFFICE	MEDIUM OFFICE	SCHOOL	HOTEL	RETAIL
A on	0.1413	-0.0535	-0.0412	-0.0283	0.0173	0.0374	0.0181
B on	0.0197	0.0065	0.0012	0.0031	0.0047	0.0078	0.0074
D on	0.1033	0.0151	0.0087	0.0280	0.0364	0.0275	0.0322
A off	0	NA	0	0	0	NA	0
B off	0.0255	NA	0.0141	0.0138	0.0068	NA	0.0099
D off	0.1189	NA	0.0153	0.0315	0.0433	NA	0.0364

Note: The Hospital and Small Hotel HVAC systems are always scheduled to be on.

Table 3 Method 2: A, B, and D values of simulated buildings

	RESTAURANT	HOSPITAL	LARGE OFFICE	MEDIUM OFFICE	SCHOOL	HOTEL	RETAIL
A on	0.1424	-0.0349	-0.0466	-0.0082	0.0310	-0.0008	0.0137
B on	0.0186	0.0014	0.0040	0.0036	0.0088	0.0050	0.0059
D on	0.1004	0.0049	0.0160	0.0177	0.0468	0.0256	0.0311
A off	0	NA	0	0	0	NA	0
B off	0.0086	NA	0.0155	0.0106	0.0154	NA	0.0119
D off	0.0427	NA	0.0175	0.0379	0.0710	NA	0.0515

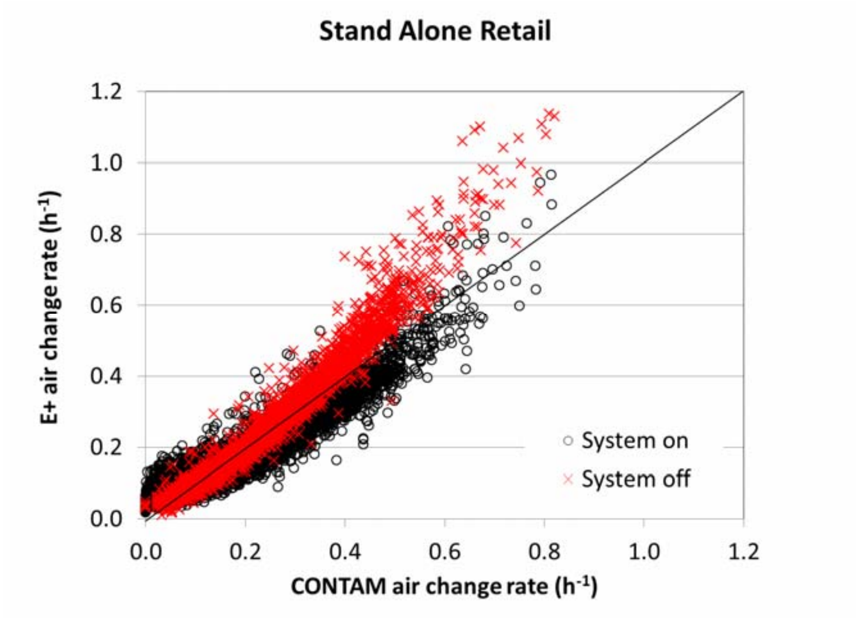
Table 4 Comparison of CONTAM and EnergyPlus infiltration rates using A, B, *and* D *values from Table 3*

	REST-AURANT	HOSPITAL	LARGE OFFICE	MEDIUM OFFICE	SCHOOL	HOTEL	RETAIL
System on values (System off values)							
CONTAM mean infiltration rate (h^{-1})	0.53 (0.50)	0.02 (NA)	0.03 (0.14)	0.11 (0.27)	0.25 (0.29)	0.26 (NA)	0.23 (0.26)
EnergyPlus mean infiltration rate (h^{-1})	0.46 (0.15)	0.01 (NA)	0.08 (0.13)	0.11 (0.23)	0.34 (0.44)	0.19 (NA)	0.21 (0.29)
Standard error of EnergyPlus rates (h^{-1})	0.09 (0.08)	0.02 (NA)	0.02 (0.02)	0.04 (0.06)	0.07 (0.15)	0.06 (NA)	0.05 (0.03)
Relative standard error of EnergyPlus rates (compared to CONTAM)	17 % (15 %)	130 % (NA)	68 % (16 %)	36 % (23 %)	26 % (18 %)	24 % (NA)	20 % (13 %)
Coefficient of determination, R^2	0.80 (-1.47)	-0.23 (NA)	-1.74 (0.81)	0.83 (0.57)	0.31 (-0.90)	0.61 (NA)	0.83 (0.78)

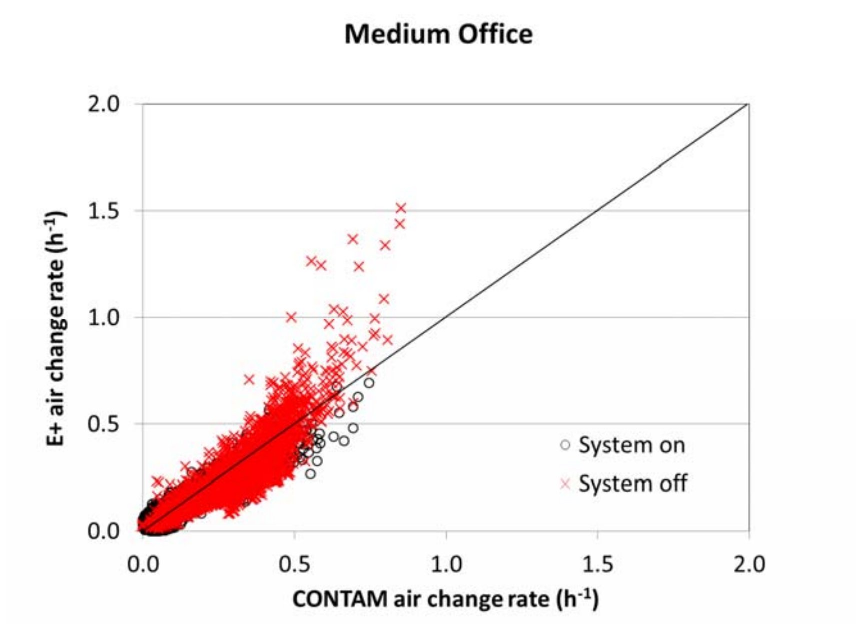
The standard error of EnergyPlus rates and R^2 values are based on the comparisons between EnergyPlus and CONTAM hourly results.

Table 5 Building characteristics of three additional buildings

	SMALL OFFICE	NIST ADMINISTRATION	NIST TRF
H (m)	4.3	46.6	4.0
SV (m^2/m^3)	0.18	0.05	0.36
F_n ($m^3/s \cdot m^2$) × 10^{-3}	0.61	0.85	0.51



(a)



(b)

Figure 1 EnergyPlus vs. CONTAM infiltration rates for (a) Stand Alone Retail and (b) Medium Office