Improving Infiltration Modeling in Commercial Building Energy Models

Lisa Ng
Andrew Persily
Steven J. Emmerich

Engineering Laboratory, National Institute of Standards and Technology
100 Bureau Drive Gaithersburg, MD 20899

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Improving infiltration modeling in commercial building energy models

Lisa C. Ng[1,2]
Andrew K. Persily[1]
Steven J. Emmerich[1]

[1] National Institute of Standards and Technology
100 Bureau Drive, MS8633, Gaithersburg MD 20899

[2]Tel: +1 301 975 4853
Fax: +1 301 975 4409
lisa.ng@nist.gov

Abstract

As building envelope performance and HVAC equipment efficiencies are increasingly improved to reduce building energy use, a greater percentage of the total energy loss of a building can occur through envelope leakage. Although the energy impacts of unintended infiltration on a building's energy use can be significant, 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, which are based on relationships between infiltration rates calculated using multizone airflow models, building characteristics, including envelope airtightness, weather conditions, and HVAC system operation. The new strategies are more accurate than current approaches in energy simulation software and easier to apply than multizone airflow modeling.

Highlights:

- Energy simulation inadequately accounts for infiltration and improved airtightness
- Methods proposed to incorporate airflow into building energy calculations
- They're more accurate than current methods in energy simulation and easier to apply

Keywords: airflow modeling, commercial buildings, CONTAM, energy modeling, EnergyPlus, infiltration

1. 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. [1]. Due to the current emphasis on reducing energy consumption and greenhouse gas emissions, the use of energy simulation software has increased for investigating 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 [2] and ASHRAE Standard 90.1 [3], energy simulation is often performed, and in some cases required. One option for reducing building energy use is to improve building envelope airtightness. Existing data show that unless efforts are made to design and build tight building envelopes, commercial buildings are actually much leakier than often assumed [4, 5]. As a result, the energy impacts of uncontrolled infiltration are also greater than assumed. Nevertheless, current energy simulation software and design methods generally do not accurately account for envelope infiltration, and therefore the impacts of improved airtightness on energy may not be fully captured.

A review of the airflow analyses capabilities of energy simulation software tools found that many of the empirical infiltration models employed in these tools are based on calculation methods developed for low-rise, residential buildings [6]. These methods are not generally appropriate for other types of buildings, particularly mechanically ventilated commercial buildings as well as taller buildings. Also, these empirical infiltration models require the user to specify air leakage coefficients that are best obtained from building pressurization tests [7], which is challenging because only limited air leakage data are available for commercial buildings [4]. Many energy simulation software users simply assume constant infiltration rates, which do not reflect known dependencies on outdoor weather conditions and ventilation system operation. Airflow calculations using existing theory and methods [8] are the only technically sound means of determining the airflow rates for predicting energy use as well as IAQ.

Empirical approaches for estimating infiltration rates have the advantage of ease of use relative to multizone building airflow models. These empirical 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 [9], which had one equation for stack induced infiltration, one wind-driven, and another to combine the two into the total building infiltration rate. More recently, Gowri et al. [10] proposed a method to estimate infiltration in commercial buildings using EnergyPlus that accounts for wind but not temperature effects. Overall, these methods tend to oversimplify the well-established interactions of building envelope airtightness, weather, and HVAC system operation that affect infiltration rates [8].

New strategies to more accurately, and more 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.

2. Methods

2.1. Current strategy for modeling of infiltration in EnergyPlus

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

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

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. It should be noted that EnergyPlus varies the outdoor temperature and wind speed by zone height for use in Equation (1) and for other calculations. How this was handled in this study is detailed in Ng et al. [11]. *A*, *B*, *C*, and *D* are constants, for which values are suggested in the EnergyPlus user manual [12]. Two sets of values are presented: DOE-2 (similar to Gowri et al. [10]) and BLAST. However, those values are based on studies in low-rise residential buildings. Given the challenges in determining valid coefficients for a given building, a common strategy used in EnergyPlus for incorporating infiltration is to assume constant infiltration rates. In other words, assume A=1 and B=C=D=0. However, this strategy does not reflect known dependencies of infiltration on outdoor weather and HVAC system operation.

2.2. Proposed strategies for improved modeling of infiltration in EnergyPlus

2.2.1. 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 [13] were selected to study this strategy:

Full Service Restaurant, Hospital, Large Office, Medium Office, Primary School, Stand Alone Retail, and Small Hotel. These particular buildings were selected based on their being representative of different types of occupancy and HVAC systems types and operation.

Models of these buildings have previously been created in the multizone airflow and contaminant transport model CONTAM [14-16]. In order to study the new strategies for modeling infiltration, Energy Plus models of the buildings were used [13]. The building zoning was different between the CONTAM and EnergyPlus models in instances where the CONTAM models needed additional zones to support realistic airflow analyses (restrooms, stairwells, elevator shafts, and storage rooms). Modeling these additional zones, relative to those that are typically needed for energy analyses, is important for airflow and IAQ analyses in order to properly capture pressure relationships and airflow patterns in buildings. Though the number of zones and some zone floor areas are different between the CONTAM and EnergyPlus models, the total building floor areas and volumes are consistent. The CONTAM and EnergyPlus models employed the same occupancy and system operation schedules and outdoor air ventilation requirements. In addition, the outdoor air economizers and night-cooling options in EnergyPlus were disabled for all of the buildings since these capabilities were not implemented in the CONTAM models.

Hourly infiltration rates for one year were simulated for each building using typical meteorological year (TMY2) weather data for Chicago [13]. The indoor temperature setpoint in the EnergyPlus models was set to 20 °C when the system was on, and in CONTAM, the setpoint was always at 20 °C. A building envelope effective leakage area (ELA) of 5.27 cm^2/m^2 at 4 Pa (0.00918 $m^3/s{\bullet}m^2$ at 75 Pa) was used in the CONTAM models. This value was based on available airtightness data in U.S. commercial buildings and is close to the average value of the data available at that time [17]. This building ELA corresponds to a building envelope leakage value of 0.00137 $m^3/s{\bullet}m^2$.

Hourly CONTAM infiltration rates and weather data over one year were fit to Equation (1) to determine *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 [14], a separate set of *A*, *B*, and *D* values were calculated with *C* set to 0. The calculated *A*, *B*, *C*, and *D* values and I_{design}=0.00137 $m^3/s{\bullet}m^2$ 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, *C* was set equal to 0 for the subsequent analyses.

The calculated *A*, *B*, and *D* values, assuming I_{design} = 0.00137 $m^3/s{\bullet}m^2$, for each of the seven buildings are listed in Table 1. It was assumed that *A* = 0 when the HVAC system was off. There are no system-off values for the Hospital and Small Hotel because the HVAC systems in these buildings were always on.

The *A*, *B*, and *D* values from Table 1 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 energy simulations were then performed using EnergyPlus for the same Chicago weather used in the CONTAM predictions. Hourly infiltration rates were then compared between CONTAM and EnergyPlus. The mean of the CONTAM and EnergyPlus infiltration rates are listed in Table 2, 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.

The average system-on and system-off R^2 value for the seven buildings shown in Table 2 is 0.80. The average system-on relative standard error of the other buildings is 39 % and the average system-off relative standard error is 15 %. Compared to the common strategy for modeling infiltration in EnergyPlus, which is to assume a fixed rate (0.000302 $m^3/s \bullet m^2$ in the DOE reference building models), Method 1 resulted in about 60 % improvement in standard error (details can be found in [11]). 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 the *A*, *B*, and *D* values were specifically calculated for each building. However, using Method 1 requires infiltration rate data, such as those generated using CONTAM or measured values, which may not necessarily be available in a given building. In order to address this limitation, a general method to calculate *A*, *B*, and *D* in any building is described in Section 2.2.2.

2.2.2. 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 $m^3/s \bullet m^2$). The values for these characteristics for each of the seven buildings are listed in Table 3. It should be noted that only the Full Service Restaurant has a large negative net system flow (Table 3), while the other buildings have positive net system flows.

In order to determine values of A, B and D for any given building, the following relationships between these constants and the building characteristics (H, SV, and F_n) were considered:

$$A = M_A \cdot H + N_A \cdot SV + P_A \cdot F_n \qquad (2)$$
$$B = M_B \cdot H + N_B \cdot SV + P_B \cdot F_n \qquad (3)$$
$$D = M_D \cdot H + N_D \cdot SV + P_D \cdot F_n \qquad (4)$$

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

Using a spreadsheet program, the building-specific A, B and D values calculated using Method 1 (Table 1) and the building characteristics of the seven buildings (Table 3) were fit to Equations (2) through (4) to calculate M, N, and P. Equations (5) through (10) show the results for system-on and system-off conditions. It was assumed that A and the net system flow, F_n, are both zero when the system is off.

$$A_{on} = 0.0001 \cdot H + 0.0933 \cdot SV + -47 \cdot F_n \qquad (5)$$
$$B_{on} = 0.0002 \cdot H + 0.0245 \cdot SV + -5 \cdot F_n \qquad (6)$$
$$D_{on} = 0.0008 \cdot H + 0.1312 \cdot SV + -28 \cdot F_n \qquad (7)$$

$$A_{off} = 0 \qquad (8)$$
$$B_{off} = 0.0002 \cdot H + 0.0430 \cdot SV \qquad (9)$$
$$D_{off} = -0.00002 \cdot H + 0.2110 \cdot SV \qquad (10)$$

A, B, and D were calculated for each of the seven reference buildings using these equations and are listed in Table 4. While there are differences between the A, B, and D values in Table 1 and Table 4, the corresponding values are generally on the same order of magnitude. In some cases they are quite close to one another.

3. Results

Method 2 was studied using the seven reference buildings and using different building envelope effective leakage area values. It was also compared with the approaches outlined in the

EnergyPlus user manual [12]. Additional studies using different buildings and comparing results with a constant infiltration approach can be found in [11].

3.1. Evaluation in the seven simulated buildings

The calculated *A*, *B*, and *D* values in Table 4 and I_{design}=0.00137 $m^3/s•m^2$ (referred to as the "original I_{design}" value since this value is changed in subsequent analyses) were input into the EnergyPlus ZoneInfiltration:DesignFlowRate object for each of the seven reference buildings simulated previously. The mean of the hourly CONTAM and EnergyPlus infiltration rates over a year are listed in Table 5. The Medium Office CONTAM and EnergyPlus system-on mean infiltration rates agree within about 1 %, and the Large Office CONTAM and EnergyPlus system-off mean infiltration rates differ by only 6 %. The average differences in the mean system-on infiltration rates for all seven buildings is 46 %, and the average system-off difference is 30 %.

The standard error, relative standard error, and R^2 of the EnergyPlus infiltration rates compared with the CONTAM rates are also listed in Table 5. Some R^2 values in Table 5 are negative because the relationship between the CONTAM and EnergyPlus rates is not linear in these cases. The Stand Alone Retail and Small Hotel have the lowest relative standard errors and highest R^2 of the buildings (averages of system-on and system-off statistics). This is also shown in Figure 1(a-b), in which the infiltration rates predicted with EnergyPlus are plotted against the rates predicted with CONTAM. Each point corresponds to a single hour in the year. Figure 1(a-b) shows that the CONTAM and EnergyPlus infiltration rates for the Stand Alone Retail and Small Hotel fall close to lines of perfect agreement. For the Medium Office, Table 5 shows that the system-on relative standard error of the EnergyPlus infiltration rates is among the highest of the buildings, but the R^2 value is also among the highest. Nevertheless, Figure 1(c) shows good agreement between the CONTAM and EnergyPlus infiltration rates for the Medium Office.

For the remaining buildings, 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 Stand Alone Retail, Small Hotel, and Medium Office. This result is also reflected in Figure 1(d-g).

The average system-on relative standard error of all the buildings in Table 5 is 46 %, and the average system-off relative standard error is 17 %. Compared to the common strategy for modeling infiltration in EnergyPlus, which is to assume a fixed rate (0.000302 $m^3/s{\bullet}m^2$ in the DOE reference building models), Method 2 resulted in about 50 % improvement in standard error [11]. Thus, the improvement in standard error using Method 2 is similar to the improvement using Method 1 (building-specific method).

3.2. Evaluation of Method 2 for other I_{design} values

Additional analyses were performed to investigate how well Method 2 performed for different envelope airtightness values than that used to derive Equations (5) through (10). As noted above, these equations were developed using a building envelope effective leakage area of 5.27 cm^2/m^2 at 4 Pa (i.e., original I_{design} = 0.00137 $m^3/s{\bullet}m^2$). Method 2 was applied using two other I_{design} values, 1.18 cm^2/m^2 at 4 Pa and 20.96 cm^2/m^2 at 4 Pa, which were respectively four times lower and four times higher than the original I_{design}. The EnergyPlus simulations used the corresponding 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. In these EnergyPlus simulations, the I_{design} values changed, but the A, B, and D values remained the same as those determined using the original I_{design} value (Table 4).

Using a value of lower I_{design} value, Method 2 resulted in the average system-on relative standard error of the seven buildings being almost 300 % due to the small infiltration rates simulated by CONTAM in the Hospital and Large Office (~10^{-3} and 10^{-4} h^{-1}). Excluding these buildings, the average system-on relative standard error for the five remaining buildings was 81 %. The average system-off relative standard error for all seven buildings was 17 %. In contrast, using a value of higher I_{design} value, Method 2 resulted in the average system-on relative standard error of the seven buildings being 23 % and the average system-off relative standard error being 18 %. Thus, on average, the high I_{design} value resulted in better agreement between the CONTAM and EnergyPlus rates compared to the low I_{design} value for the seven buildings studied in this paper. This is demonstrated using the Stand Alone Retail in Figure 2(a-b) and for the Small Hotel Figure 2(c-d). Thus, as Method 2 is developed further, it will be important to identify a range of I_{design} values over which it can be applied without introducing excessive errors.

3.3. Comparing Method 2 to other approaches

Suggestions for values for the coefficients in Equation (1) are given in the EnergyPlus user manual [12]. One set of values is A=B=D=0, C=0.224 (DOE-2 approach), and the other A=0.606, B=0.03636, C=0.1177, D=0 (BLAST approach). The DOE-2 approach accounts for wind, but not temperature effects.

The average difference in mean infiltration rates calculated using the DOE-2 approach and using CONTAM was 250 %. The average difference in mean infiltration rates calculated using the BLAST approach and using CONTAM was 775 %. In contrast, the average difference was only 38 % between Method 2 and CONTAM. Similarly, the average relative standard error was 52 % using the DOE-2 approach, 48 % using the BLAST approach, and only 32 % using Method 2. Figure 3 shows results for the Stand Alone Retail and Medium Office.

4. Discussion

Though modelers can account for infiltration and improved envelope airtightness with current energy simulation software, the simplified approaches typically employed ignore the effects of weather, system operation, and envelope leakage, or at best do not account for them very well. Oftentimes, zero, constant or scheduled infiltration rates are input into energy simulation software due to a lack of understanding of how to more accurately account for infiltration. Also, the infiltration equations currently included in energy simulation software and guidance for input variables are based largely on research for low-rise, residential buildings. However, the interaction of weather, system operation, and envelope leakage in determining infiltration rates is fundamentally related to pressure, but the physics of these interactions are not typically or easily modeled in current energy simulation software. Multizone airflow modeling is the accepted approach to calculating infiltration, however, the current means of doing so in energy simulation programs are limited and can be cumbersome to implement.

Strategies to incorporate the effects of weather, system operation, envelope leakage, and building characteristics on infiltration are presented in this paper. Method 1 is a building-specific strategy for determining coefficients in an empirical equation available in EnergyPlus to calculate infiltration. However, Method 1 requires infiltration rate data, such as those generated using CONTAM or measured values, which may not necessarily be available. In order to address this limitation, Method 2 calculates the coefficients in the EnergyPlus empirical equation using key building characteristics. It is possible that Method 2 could be made more robust by considering other buildings, such as the complete collection of fifteen commercial building models available from DOE [13], and other weather conditions. Future work could include using building envelope airtightness values and measurements of infiltration from real buildings to further evaluate these methods. Also, since under actual system operation the normalized net system flow (F_n) often deviates from the design value, future work could investigate these impacts.

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 observed 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 building 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.

Based on the results of this effort, it is also important to develop guidance on how to use Method 2 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 preferred.

5. 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 implementing some efficiency measures is oftentimes incomplete because building envelope infiltration is not properly accounted for. Many of the airflow estimation approaches implemented in current energy software tools are inappropriate for large buildings or are otherwise limited. 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. Method 1: *A*, *B*, and *D* values of simulated buildings – Method 1

	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 on.

Table 2. Comparison of CONTAM and EnergyPlus infiltration rates – Method 1

	Restaurant	Hospital	Large Office	Medium Office	School	Hotel	Retail
System on							
CONTAM mean infiltration rate (h^{-1})	0.53	0.02	0.03	0.11	0.25	0.26	0.23
EnergyPlus mean infiltration rate (h^{-1})	0.48	0.06	0.03	0.14	0.24	0.29	0.24
Standard error of EnergyPlus rates (h^{-1}) (% of CONTAM mean)	0.09 (17 %)	0.02 (87 %)	0.02 (65 %)	0.04 (35 %)	0.06 (25 %)	0.06 (22 %)	0.05 (20 %)
Coefficient of determination, R^2	0.83	0.87	0.78	0.75	0.83	0.82	0.88
System off							
CONTAM mean infiltration rate (h^{-1})	0.50	NA	0.14	0.27	0.29	NA	0.26
EnergyPlus mean infiltration rate (h^{-1})	0.43	NA	0.12	0.23	0.23	NA	0.23
Standard error of EnergyPlus rates (h^{-1}) (% of CONTAM mean)	0.07 (14 %)	NA	0.02 (15 %)	0.05 (18 %)	0.05 (18 %)	NA	0.03 (12 %)
Coefficient of determination, R^2	0.83	NA	0.76	0.75	0.68	NA	0.88

Note: The Hospital and Small Hotel HVAC systems are always on. The standard error of EnergyPlus rates and R^2 values were based on the comparison between EnergyPlus and CONTAM results.

Table 3. Building characteristics of seven simulated buildings

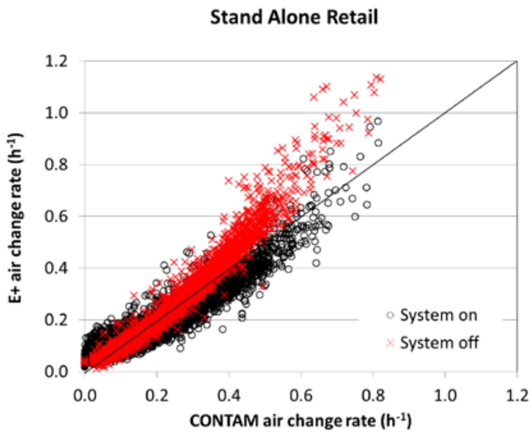
	Restaurant	Hospital	Large Office	Medium Office	School	Hotel	Retail
H **(m)**	4.7	23.8	50.4	12	4	11.6	6.1
SV **(m^2/m^3)**	0.17	0.11	0.09	0.18	0.34	0.23	0.24
F_n ($m^3/s•m^2$) × 10^{-3}	-2.6	1.0	1.3	0.56	0.02	0.50	0.21

Table 4. *A*, *B*, and *D* values of simulated buildings – Method 2

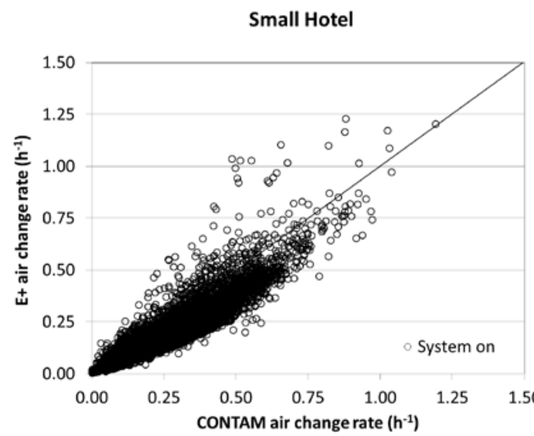
	Restaurant	Hospital	Large Office	Medium Office	School	Hotel	Retail
A **on**	0.1424	-0.0349	-0.0466	-0.0082	0.0310	-0.0008	0.0137
B **on**	0.0186	0.0014	0.0040	0.0036	0.0088	0.0050	0.0059
D **on**	0.1004	0.0049	0.0160	0.0177	0.0468	0.0256	0.0311
A **off**	0	NA	0	0	0	NA	0
B **off**	0.0086	NA	0.0155	0.0106	0.0154	NA	0.0119
D **off**	0.0367	NA	0.0175	0.0379	0.0710	NA	0.0515

Table 5. Comparison of CONTAM and EnergyPlus infiltration rates – Method 2

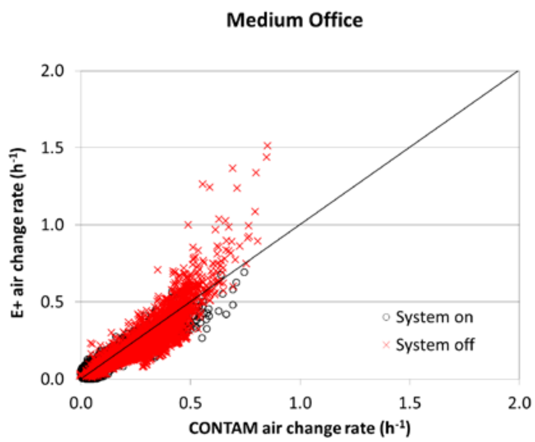
	Restaurant	Hospital	Large Office	Medium Office	School	Hotel	Retail
System on							
CONTAM mean infiltration rate (h^{-1})	0.53	0.02	0.03	0.11	0.25	0.26	0.23
EnergyPlus mean infiltration rate (h^{-1})	0.46	0.01	0.08	0.11	0.34	0.19	0.21
Standard error of EnergyPlus rates (h^{-1}) (% of CONTAM mean)	0.09 (17%)	0.02 (130%)	0.02 (68%)	0.04 (36%)	0.07 (26%)	0.06 (24%)	0.05 (20%)
Coefficient of determination, R^2	0.80	-0.23	-1.74	0.83	0.31	0.61	0.83
System off							
CONTAM mean infiltration rate (h^{-1})	0.50	NA	0.14	0.27	0.29	NA	0.26
EnergyPlus mean infiltration rate (h^{-1})	0.15	NA	0.13	0.23	0.44	NA	0.29
Standard error of EnergyPlus rates (h^{-1}) (% of CONTAM mean)	0.08 (15%)	NA	0.02 (16%)	0.06 (23%)	0.15 (18%)	NA	0.03 (13%)
Coefficient of determination, R^2	-1.47	NA	0.81	0.57	-0.90	NA	0.78


Stand Alone Retail
E+ air change rate (h-1)
CONTAM air change rate (h-1)
System on
System off

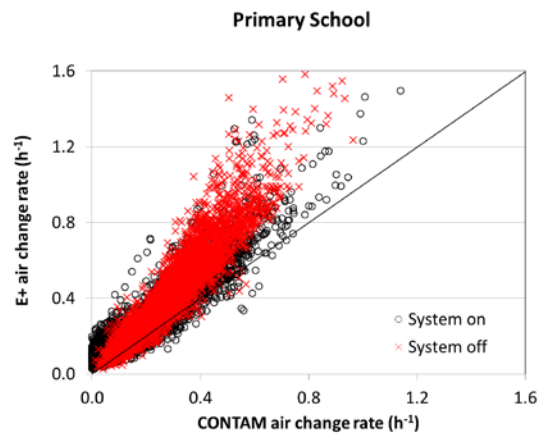
(a)


Small Hotel
E+ air change rate (h-1)
CONTAM air change rate (h-1)
System on

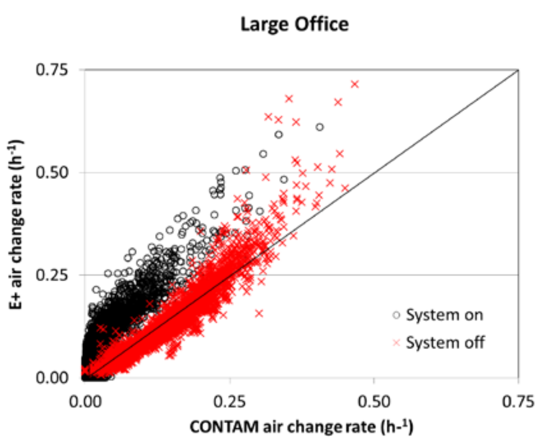
(b)


Medium Office
E+ air change rate (h-1)
CONTAM air change rate (h-1)
System on
System off

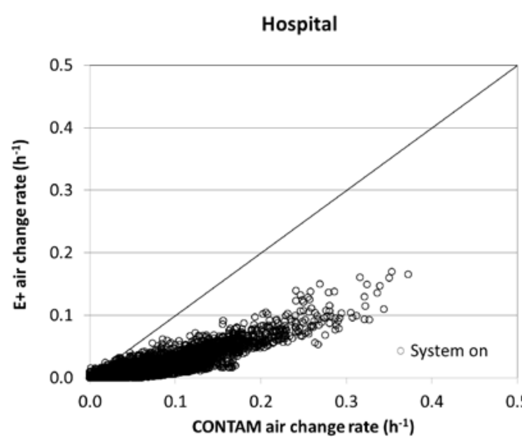
(c)


Primary School
E+ air change rate (h-1)
CONTAM air change rate (h-1)
System on
System off

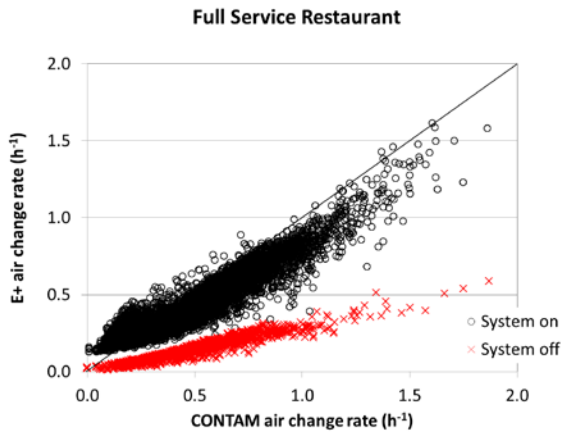
(d)


Large Office
E+ air change rate (h-1)
CONTAM air change rate (h-1)
System on
System off

(e)

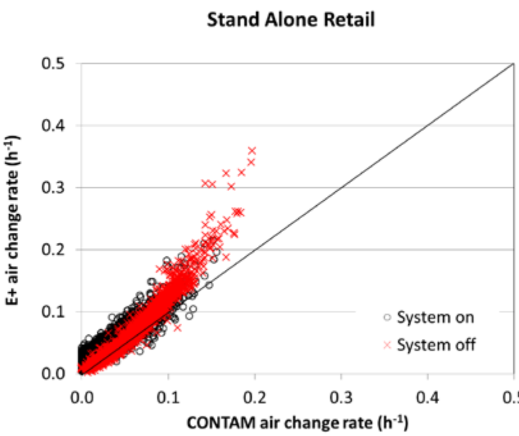

Hospital
E+ air change rate (h-1)
CONTAM air change rate (h-1)
System on

(f)

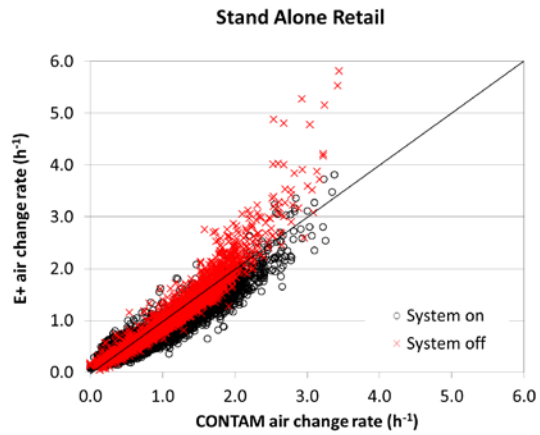


(g)

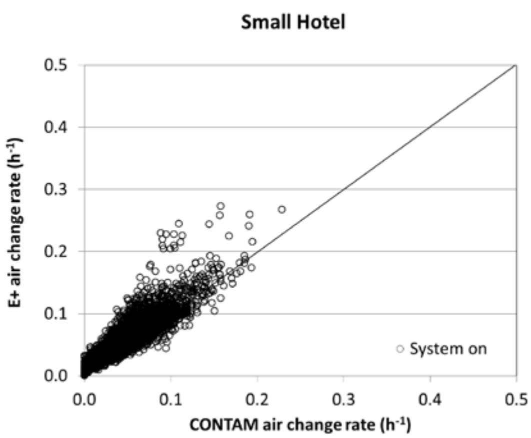
Figure 1: EnergyPlus vs. CONTAM infiltration rates for (a) Stand Alone Retail (b) Small Hotel (c) Medium Office and (d) Primary School (e) Large Office (f) Hospital (g) Full Service Restaurant (original I_{design})



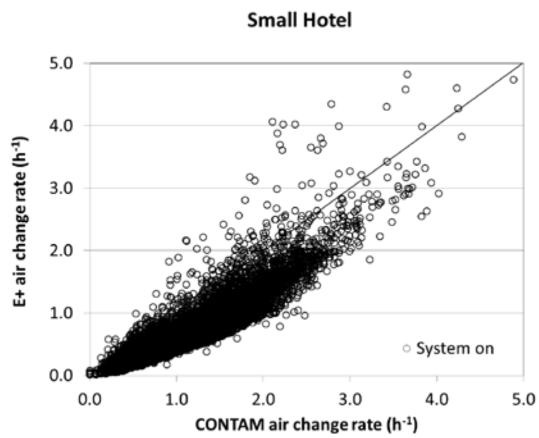
(a) Low I_{design}



(b) High I_{design}



(c) Low I_{design}



(d) High I_{design}

Figure 2: EnergyPlus vs. CONTAM infiltration rates for Stand Alone Retail (a) low I_{design} (b) high I_{design} and Small Hotel (c) low I_{design} (d) high I_{design}

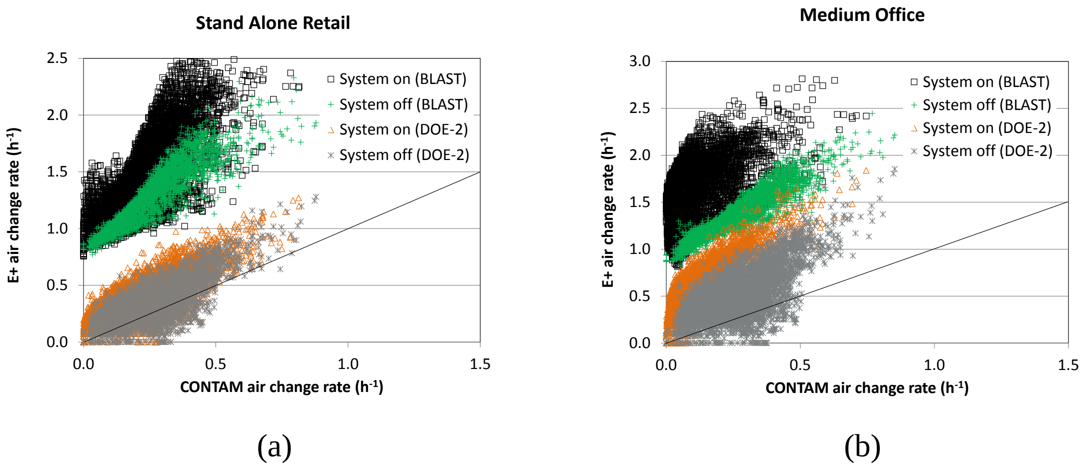


Figure 3: EnergyPlus vs. CONTAM infiltration rates for (a) Stand Alone Retail (b) Medium Office (DOE-2 and BLAST approaches, original I_{design})