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Evaluation of Existing Infiltration Models Used in Building Energy Simulation

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Abstract

Infiltration modeling is one of the major sources of uncertainty in building energy simulation. Although many infiltration models exist, their structures and assumptions vary, and many of them are inaccurate for commercial buildings. The use of these models are rarely updated or revised due to the high cost for tests that are used to determine infiltration rates. In this study, tracer gas decay and whole-building pressurization tests were performed in a full-scale, two story, unoccupied commercial building. Three different infiltration models within EnergyPlus were used to simulate infiltration rates. The pressurization test result was converted to the design infiltration rate used in each infiltration model. The simulation results were compared with the infiltration rate estimated from the field measurements. The results showed that the predicted infiltration rate and the estimated heating energy consumption can be significantly affected by the infiltration model selection.

Key Innovations

- Tracer gas decay and whole-building pressurization tests were performed in the test building to validate accurate infiltration rate.
- Actual building envelope airtightness value from whole-building pressurization tests were used in six different infiltration models available in EnergyPlus.
- Measured hourly infiltration rate and the predicted values using the six infiltration models were analysed to compare performance of different models.
- A simulation study was conducted to investigate how the selection of the infiltration model influences the predicted building heating energy consumption.

Practical Implications

This study shows that the predicted infiltration rate and the estimated heating energy consumption can be significantly affected by the infiltration model selection.

Introduction

Infiltration can have a significant impact on building loads. Studies show that infiltration can account for 15 to 40% of annual space conditioning needs in commercial buildings (Emmerich et al., 2019; Younes et al., 2012). The driving force of infiltration is the pressure difference across the building envelope caused by wind, stack effect known as buoyancy effect, and operation of mechanical equipment. Wind pressure is governed by direction, velocity and building shape and other structures around the buildings, while the stack effect is a function of the building height, air density differences between the indoor air ambient air, and the vertical distribution of envelope leakage (Han, 2015). The infiltration rate is determined based on the combination of these effects; however, the effect of wind is often dominant in low-rise residential buildings, and the effect of stack is more dominant in high-rise buildings (ASHRAE, 2017).

Currently, the available methods for estimating infiltration range from assuming a fixed air change rate to using a detailed physical model. In building energy simulation programs such as EnergyPlus, different empirical infiltration models are available such as effective leakage area, flow coefficient, and those based on temperature difference and wind speed.

This study aims to evaluate the existing infiltration models in EnergyPlus by comparing their simulation results with the infiltration rate estimated from field measurements. Tracer gas decay and fan pressurization tests were performed in a full-scale, two story, unoccupied commercial building. Three infiltration models within EnergyPlus, one with various sets of coefficients, are used to simulate infiltration rates. A fan pressurization test result was converted to the design infiltration rate for use in each infiltration model.

EnergyPlus infiltration models

In EnergyPlus, the infiltration models are available in the following objects: (1) ZoneInfiltration:DesignFlowRate, (2) ZoneInfiltration:EffectiveLeakageArea, and (3) ZoneInfiltration:FlowCoefficient. Four different sets of coefficients are tested using the ZoneInfiltration:DesignFlowRate object (default, DOE-2, BLAST, and Regression). It should be noted that the default, DOE-2, and BLAST coefficients do not account physically or empirically for depressurization effects due to HVAC, exhaust fan or other equipment operation. Figure 1 shows the six different infiltration models and their required input parameters. The fan pressurization test result (typically reported as volumetric airflow rate (m^3/h) at 75 Pa for commercial buildings) needs to be converted to a design infiltration rate (m^3/s), an effective leakage area (cm^2), or a flow coefficient ($m^3/(sPa^n)$) before it is used in one of the infiltration models.

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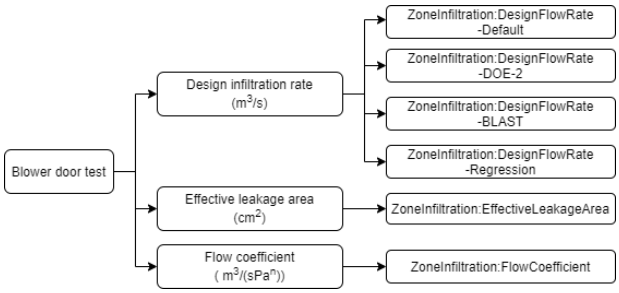

Figure 1: Infiltration models in EnergyPlus

The ZoneInfiltration:DesignFlowRate model uses the following empirical equation:

$$I = I_{design}(C_0 + C_1|\Delta T| + C_2 V + C_3 V^2) \quad (1)$$

where I is the infiltration rate (m^3/s), I_{design} is the design infiltration rate, C_0 to C_3 are regression coefficients, $|\Delta T|$ is the absolute difference between indoor and outdoor dry-bulb temperatures, and V is the wind speed. The default coefficients in EnergyPlus are C_0=1, C_1=0, C_2=0, and C_3=0 meaning that infiltration is a constant volumetric flow rate, and the wind and stack effects are not taken into consideration (EnergyPlus, 2018). The DOE-2 and BLAST coefficients are derived from these EnergyPlus predecessors. The DOE-2 coefficients are C_0=0, C_1=0, C_2=0.224, and C_3=0, which consider only wind effects; the BLAST coefficients are C_0=0.606, C_1=0.03636, C_2=0.1177, and C_3=0, which account for both wind and stack effects but have not been validated for use in all building types. The regression model coefficients are C_0=0.13026, C_1=0.00110, C_2=0.01834, and C_3= 0.004200 (refer to Experiment section for details).

The ZoneInfiltration:EffectiveLeakageArea model uses a modified Sherman and Grimsrud model (ASHRAE, 2017), which was developed for low-rise residential buildings:

$$I = \frac{A_L}{1000}\sqrt{C_s|\Delta T| + C_w(V)^2} \quad (2)$$

where I is the infiltration rate (m^3/s), A_L is the effective air leakage area at 4 Pa (cm^2), C_s is the stack coefficient ((L/s)^2/(cm^4·K)), and C_w is the wind coefficient ((L/s)^2/(cm^4·(m/s)^2)). The default values of C_s are assigned based on building story and C_w is determined based on building story and shelter class as shown in Table 1-3. For this study, the local shelter class of the building is set to 3. Considering the height of the building (8.56 m), the coefficients are linearly interpolated for two-story and three-story building. The calculated C_s and C_w are 0.000363 and 0.000251, respectively.

Table 1 Stack coefficient C_s

	Building height (Stories)		
	One-story	**Two-story**	**Three-story**
Stack coefficient	0.000145	0.000290	0.000435

Table 2 Local shelter classes

Shelter Class	Description
1	No obstructions or local shielding
2	Typical shelter for an isolated rural house
3	Typical shelter caused by other buildings across street from building under study
4	Typical shelter for urban buildings on larger lots where sheltering obstacles are more than one building height away
5	Typical shelter produced by buildings or other structures immediately adjacent (closer than one house height)

Table 3 Wind coefficient C_w

Shelter class	Building height (Stories)		
	One	**Two**	**Three**
1	0.000319	0.000420	0.000494
2	0.000246	0.000325	0.000382
3	0.000174	0.000231	0.000271
4	0.000104	0.000137	0.000161
5	0.000032	0.000042	0.000049

The ZoneInfiltration:FlowCoefficient model uses the following modified AIM-2 model:

$$I = \sqrt{(cC_s|\Delta T|^n)^2 + (cC_w(s * V)^{2n})^2} \quad (3)$$

where I is the infiltration rate (m^3/s), c is the flow coefficient (m^3/(sPa^n)), s is the shelter factor coefficient, and n is the pressure exponent. The default values of C_s and C_w are different from those used in the previous Effective Leakage Area model and are determined based on building story, shelter factor, and the existence of a flue. Default values for the building with no flue and basement slab are shown in Table 4-5. The coefficients are linearly interpolated for two-story and three-story building, and C_s, C_w, n, and s are set to 0.088, 0.17, 0.65, and 0.7 in this study.

Table 4 Stack coefficient (C_s) and wind coefficient (C_w)

	One-story	**Two-story**	**Three-story**
Stack coefficient	0.054	0.078	0.098
Wind coefficient	0.156	0.170	0.170

Table 5 Shelter factor (s)

	1	**2**	**3**	**4**	**5**
Shelter class	1.00	0.90	0.70	0.50	0.30

Experiment

Testing was conducted at the two-story Flexible Research Platform (FRP) (Figure 2), which is a slab-on-grade steel superstructure with a footprint of 13.4 m × 13.4 m that is representative of light commercial buildings common to the existing US building stock.

The FRP is an unoccupied research apparatus in which occupancy is emulated by process control of lighting, humidifiers for human-based latent loading, and heater for Miscellaneous Electrical Loads (MELs) to minimize human-occupancy-based interference with the building, which is one of the main sources of uncertainty in building

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modeling input data. The building is exposed to natural weather conditions for research and development leading to system- and building-level advanced energy efficiency solutions for new and retrofit applications. In addition, a dedicated weather station (Figure 3) is installed on the roof of the two-story FRP so that actual weather data can be used in performance analysis and energy modeling.

Figure 2 ORNL flexible research platforms (FRP)

Figure 3 Weather station on the roof of the two-story FRP.

The FRP has 10 conditioned zones and two unconditioned zones (e.g., staircase) with a 0.4 m thick exterior wall. The windows are evenly distributed, except on the east and north sides of the first floor, with a 28 % window-to wall-ratio.

Fan pressurization tests

Commercial blower door equipment was used to perform fan pressurization tests for determining the building envelope airtightness. During this test, the heating, ventilating, and cooling (HVAC) system was off and all interior doors were open. The airflow rates (m^3/s) required to maintain differential pressures of 30 to 75 Pa in accordance with ASTM E779 (ASTM International, 2019) were determined. The building envelope airtightness (I_{75P}) was 0.9817 m^3/s at 75 Pa.

For the ZoneInfiltration:DesignFlowRate model, this I_{75P} value is converted to I_{design} using Equation (4)

$$I_{design} = (\alpha_{bldg} + 1) \cdot I_{75P} \left(\frac{0.5 C_s \rho U_H^2}{75}\right)^n \quad (4)$$

where the wind speed at building height (U_H), the density of air (ρ), the average surface pressure coefficients (C_s), the urban terrain environment coefficient (α_{bldg}), and the flow exponent (n) are set to 4.47 m/s, 1.18 kg/m^3, 0.1617, 0.22, and 0.65, respectively (Gowri et al., 2009). The calculated I_{design} for the FRP is 0.11 m^3/s.

For the ZoneInfiltration:EffectiveLeakageArea model, I_{75P} needs to be converted to effective leakage area (A_L) using Equation (5)

$$A_L = \sqrt{\frac{\rho}{2(\Delta p_{r,1})}} I_{75P} \left(\frac{\Delta p_{r,1}}{\Delta p_{r,2}}\right)^n \quad (5)$$

where $\Delta p_{r,1}$ and $\Delta p_{r,2}$ are two reference pressure differences. The calculated A_L at 4 Pa for the FRP is 590 cm^2.

For the ZoneInfiltration: FlowCoefficient model, I_{75P} needs to be converted to a flow coefficient (c) shown in Equation (6)

$$c = \frac{I_{75P}}{(\Delta p)^n} \quad (6)$$

where n is the pressure exponent (set to 0.65). The calculated c for the FRP is 0.0617613 $m^3/(s \cdot Pa^n)$.

Tracer gas test

The tracer gas test was performed with a multichannel doser and sampler and a photoacoustic gas monitor. The tracer gas (R134a/tetrafluoroethane) is a nonflammable refrigerant. As shown in Figure 4, it was injected in six locations, and the tracer gas tests were carried out five times from March 2019 to June 2019.

Figure 4 Test locations

The tracer gas was injected into the return duct with the HVAC system operating until the indoor concentration reached 600 mg/m^3 in all measured locations (5 min to 6 min). Assuming that the gas mixes thoroughly and instantaneously within the building, the average outdoor air change rate occurring between two measurements taken at times t_i and t_{i+1} was estimated using (ASTM International, 2017):

$$\bar{A}(t_i, t_{i+1}) = \frac{(\ln C(t_i) - \ln C(t_{i+1}))}{t_{i+1} - t_i} \quad (7)$$

where $\bar{A}(t_i, t_{i+1})$ *is* the average air change rate (1/h), and $C(t_i)$ and $C(t_{i+1})$ are the average concentrations (mg/m^3) at times t_i and t_{i+1} (h), respectively. The uncertainty in the estimation of the average air change rate was estimated using (ASTM International, 2017):

$$S^2_{A(t_i,t_{i+1})} = \frac{1}{(t_{i+1}-t_i)^2} \frac{S^2_{C(t_{i+1})}}{C(t_{i+1})^2} + \frac{S^2_{C(t_i)}}{C(t_i)^2} \quad (8)$$

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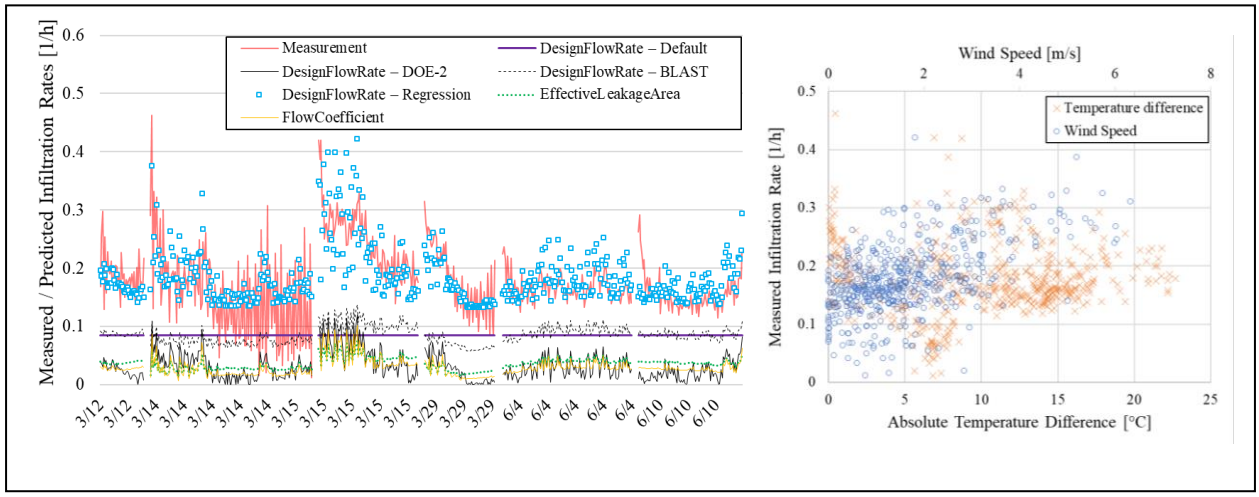

Figure 5: (a) Measured and predicted infiltration rates (timeseries); (b) scattered plot showing the relationship between the measured infiltration rate versus wind speed and indoor/outdoor absolute temperature difference

where $S^2_{C(t_i)}$ and $S^2_{C(t_{i+1})}$ are the variances of the measured concentrations at times t_i and t_{i+1}, respectively. The 1st quartile, median, and 3rd quartile values of the estimated uncertainty over the tracer gas tests were 0.0196, 0.0321, and 0.0429, respectively. It should be noted that ASTM E741-11 recommends minimum durations between initial and final tracer measurements to determine an average air change rate that ranges from 4 h for a building that is relatively tight (0.25 1/h) and 15 min for a building that is not as tight (4 1/h). For simulation studies, an infiltration model for EnergyPlus was developed for the FRP with the estimated outdoor air change rate (or "infiltration rate") and the measured indoor-outdoor temperature difference and wind speed. Equation (1) was used as the model structure, and C_0 to C_3 were estimated for the FRP based on the test conditions: 0.13026, 0.00110, 0.01834, and 0.004200 respectively. It should be noted that these coefficients may not be applicable to other conditions, such as different weather or HVAC operation.

Results

Infiltration model comparison

The left graph in Figure 5 shows the measured hourly infiltration rate (red line) and the predicted values using the six infiltration models explained in the previous section. The predicted infiltration rate for all models, except DesignFlowRate – Regression, was reduced by 75 % when the HVAC system was on based on Gowri et al. (2009) but this assumption is overly simplified and has not been validated with data.

By comparing the measured infiltration rate and the weather conditions in Figure 5b, we can see that the infiltration rate is positively correlated with the wind speed (the Pearson correlation coefficient is 0.55). However, the correlation between the estimated infiltration rate and the temperature difference between indoor and outdoor is smaller (the Pearson correlation coefficient is -0.01). Based on this result, the stack effect is inferred to not be a significant driving factor in the infiltration rates of the test building. Thus, models overestimating the stack effect would overestimate the infiltration for this building.

Except for the ZoneInfiltration:DesignFlowRate model that uses the regression coefficients, and which was trained using the measured data, the remaining models -- especially "DOE-2," "EffectiveLeakageArea," and "FlowCoefficient"-- show significantly large differences from the measurements. For example, the median value of the predicted infiltration rates using the "DOE-2" model was only 15.4 % of the median value of the measured rates. However, the absolute predictive error in the infiltration rate was small because the building is

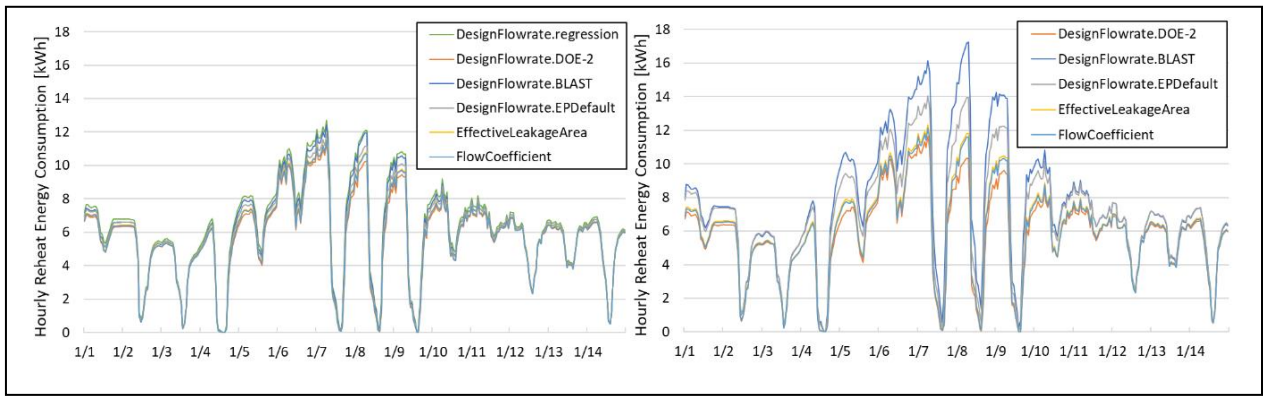

Figure 6: Hourly reheat energy consumption with different infiltration models using (a) measured building envelope airtightness of the FPR and (b) 2.95 times leakier building.

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relatively airtight. If the airtightness of the target building is low (i.e., leaky), then the absolute predictive error would also increase.

Influence on HVAC energy consumption

To investigate how the selection of the infiltration model influences the predicted building heating energy consumption, a simulation study was conducted with a validated EnergyPlus building model that reflects the thermal behavior of the test building (Im et at., 2020).

The left graph in Figure 6 shows the hourly reheat energy consumption during the simulation period with the six different infiltration models. Differences between the model results look small. This is due to the small differences in the infiltration rates (Figure 5), i.e., because the building is relatively tight. Nevertheless, the total reheat energy consumption during the simulation period in the "Regression" case is 10.8 % higher than that for the "DOE-2" case, which reveals that the energy impact of different infiltration models is not negligible even in a relatively tight building. The right plot in Figure 6 illustrates the effect of the infiltration models when used for a leakier building. When using the default design infiltration rate from the *DOE Commercial Prototypical Building Model* (USDOE, 2020), 0.4353 m^3/s (i.e., 2.95 times leakier that the test building), the reheat energy use shows significant differences among the five non-constant infiltration models. For example, the total reheat energy consumption in the "BLAST" case is 30.4 % higher than that in the "DOE-2" case.

Conclusions

In this study, different infiltration models that are used by building energy modelers were evaluated. The results show that the selection of the infiltration model can significantly affect the estimated heating energy consumption, even in a relatively airtight building. The significance of the infiltration model selection increases in leakier buildings, as expected. The results of this study indicate that current practices in infiltration modeling in building energy simulation may not provide accurate or reliable results, which is essential for accurate energy predictions. Therefore, comprehensive and systematic infiltration modeling research for different building types is required to provide better modeling guidelines for building energy modelers and researchers.

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