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# The limitations of multi-zone infiltration algorithms in whole building energy simulation engines

Cara H. Lozinsky[1], Marianne F. Touchie[2,3]

[1] Sense Engineering Ltd., North Vancouver, Canada
[2] Department of Civil Engineering, University of Toronto, Canada
[3] Department of Mechanical and Industrial Engineering, University of Toronto, Canada

***Abstract:*** *The algorithm used within EnergyPlus for multi-zone infiltration computations consists of a multivariable regression equation based on limited data collected from single-family homes, which do not accurately represent airflow patterns in MURBs. Depending on the coefficient scheme used with the regression equation, the resulting infiltration rates may or may not appropriately account for the effects of wind and/or air buoyancy. This paper compares the infiltration profiles for a 40-m and a 10-m building, calculated using three coefficient schemes recommended by EnergyPlus with the zone infiltration algorithm, and the theoretical infiltration profiles calculated from first principles using the Power Law Equation. The analysis was conducted for cities in each of North America's eight climate zones. Depending on the coefficient scheme selected, the resulting infiltration profiles varied considerably, especially for the 40-m building in cold climate regions. These limitations need to be considered during model development, to ensure that infiltration is accurately accounted for.*

***Keywords:*** *building infiltration, whole-building energy simulation, calibration*

## INTRODUCTION

The physical forces driving infiltration in buildings are incredibly complex, exhibit high spatial and temporal variability and are heavily dependent on the local climate. Infiltration also has the potential to greatly impact building energy consumption. Recent modeling studies have shown that infiltration accounts for anywhere from 15 to 45% of annual space conditioning loads, depending on building type (Jokisalo et al., 2009; Ren and Chen, 2015; Scanada Consultants Ltd., 1997). The use of whole-building energy models has increased drastically in recent years, both in new construction to verify code compliance (ASHRAE, 2016; City of Vancouver, 2017) and in retrofit applications to assess energy savings associated with various energy conservation measures (ECMs). Accurately accounting for air infiltration is key to model reliability.

A recent study that compared the airflow modeling capabilities of the most common whole-building energy simulation programs found that while all the programs could account for infiltration, the multi-zone models were based on empirical models for single-family homes, which have limited external validity to large, multi-zone structures such as commercial or multi-unit residential buildings (Ng and Persily, 2011).

Several studies have demonstrated that the existing multi-zone algorithms within most whole-building energy simulation programs are lacking; however, these studies have been limited to a specific building type and/or climate, limiting the generalization of the findings. Ren and Chen compared three infiltration models within a benchmarking energy simulation program for single-family homes in Australia (2015). They compared a simple empirical model; a modified version of the Sherman-Grimsrud model; and a multi-zone model based on the Power Law. The empirical model, which relied on coefficients to characterize wind- and buoyancy-induced infiltration, was not as sensitive to changes in temperature and wind speed, compared to the multi-zone model based on the Power Law. Similarly, Ng et al., found that the mean infiltration rates computed using the *DesignFlowRate* empirical model within EnergyPlus was up to 775% greater than mean infiltration rates computed using airflow network models for the same buildings (2015); however, this comparison was limited to two commercial building types in Chicago.

Specialized airflow simulation software, such as CONTAM, can model multi-zone airflow using pressure network models, thus improving the characterization of infiltration (Ng and Persily, 2011). Despite improvements in recent years, these models are still difficult to implement and have not achieved mass adoption in industry. This leaves most energy modeling practitioners to work within the existing constraints of the simplified, empirical models. It is important to fully understand the limitations of the infiltration models within whole-building energy simulation programs, and how they may affect results.

This paper compares infiltration profiles computed using EnergyPlus' multi-zone, empirical model with those calculated from first principles using the Power Law. We selected EnergyPlus for the analysis as it is a widely-used simulation engine in North America that has been


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extensively validated and incorporated into several user interfaces.

## ENERGYPLUS INFILTRATION ALGORITHMS

Air infiltration in EnergyPlus can be simulated using one of three models: *ZoneInfiltration:EffectiveLeakageArea*, *ZoneInfiltration:FlowCoefficient* and *ZoneInfiltration:DesignFlowRate*. The first two models compute airflow due to wind and air buoyancy differences separately and then combine them via simple quadrature superposition (Sherman and Grimsrud, 1980; Walker and Wilson, 1998). These models are intended for smaller buildings with a single, well-mixed zone and little-to-no internal resistance to airflow. The final model, *DesignFlowRate*, is the only model that EnergyPlus classifies as a multi-zone model, where internal resistance to airflow cannot be assumed negligible.

### *ZoneInfiltration:DesignFlowRate*

The *ZoneInfiltration:DesignFlowRate* model uses a multi-variable regression equation of the following form, which is based on the residential model developed by Coblenz and Achenbach (1963):

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

Where $I_{design}$ is the baseline infiltration rate ($m^3/s$); $F_{schedule}$ is a fractional value between 0 and 1.0, meant to account for the balancing effects from building heating, ventilation and air conditioning (HVAC) systems; $\Delta T$ is the difference between zone temperature and the outdoor dry-bulb temperature; $U_H$ is the wind speed at the height of the zone centroid; and *A*, *B*, *C* and *D* are regression coefficients. $I_{design}$, $F_{schedule}$ and the regression coefficients are all specified by the user. Zone temperature is calculated within the model, while outdoor dry-bulb temperature and $U_H$ are adapted from the model weather file.

*ASHRAE 90.1: Energy Standard for Buildings Except Low-Rise Residential Buildings* specifies that commercial buildings must be modeled with an $F_{schedule}$ value of 0.0 when the HVAC system is on and with a value of 1.0 when the HVAC systems are off. This $F_{schedule}$ configuration would be consistent with a balanced HVAC system, where infiltration is offset by the HVAC operation. In MURB applications, *ASHRAE 90.1* requires an $F_{schedule}$ value of 1.0 at all times (ASHRAE, 2016).

### Coefficient Schemes for *ZoneInfiltration:DesignFlowRate*

EnergyPlus currently uses default coefficients of *A=1, B=C=D=0* for the *ZoneInfiltration:DesignFlowRate* calculations, meaning that building infiltration is constant and does not take into account effects from air buoyancy differences and wind. This is problematic, as infiltration is heavily dependent on indoor-outdoor temperature differences and wind. Ignoring the physical processes that affect infiltration will definitely affect the validity of the model.

The *EnergyPlus Input-Output Reference* also lists the coefficient schemes used by EnergyPlus predecessors BLAST and DOE-2 (2016). BLAST used coefficients that accounted for both air buoyancy differences and wind in infiltration rate computations, while DOE-2 used coefficients that only accounted for the effects of wind. A comparison of the three coefficient schemes is provided in Table 1. The baseline conditions – and coefficients – for the BLAST and DOE-2 models can be traced back to a study by Bahnfleth et al., where infiltration measurements were taken in two single-family test homes near the University of Illinois (1957). The average air exchange rate between the two homes was 0.15 ach at an indoor-outdoor ΔT of 0°C and 0 m/s wind speed. On average, a 1°C increase in the indoor-outdoor ΔT resulted in a 0.009 increase in ach. Similarly, a 1.0 m/s increase in wind speed resulted in a 0.028 increase in ach.

The baseline pressure differentials were calculated based on the reference wind speeds, in accordance with the procedure developed by Gowri et al. (2009), which assumes an average, positive whole-building wind pressure coefficient of 0.1617.

*Table 1: Regression Coefficients for* ZoneInfiltration:DesignFlowRate *Model*

| Coefficient | | Default | BLAST | DOE-2 |
|---|---|---|---|---|
| A | Constant (dim.) | 1 | 0.606 | 0 |
| B | Temperature ($^\circ C^{-1}$) | 0 | 0.03636 | 0 |
| C | Wind Speed (s/m) | 0 | 0.1177 | 0.224 |
| D | Wind Speed-squared ($s^2/m^2$) | 0 | 0 | 0 |
| Baseline Conditions | | - | ΔT: 0°C<br>$U_H$: 3.35 m/s<br>$\Delta P_{tot}$: 1.07 Pa | $U_H$: 4.47 m/s<br>$\Delta P_{tot}$: 1.91 Pa |

The DOE-2 coefficient scheme has been adopted by *ASHRAE 90.1* (2016). Within the methodology for the Building Envelope Trade-Off Option, the building infiltration rate for energy simulations is calculated assuming a baseline pressure differential of 1.91 Pa, consistent with the DOE-2 infiltration model coefficients.

Even though the DOE-2 coefficients have been widely adopted by energy modeling guidelines and standards for commercial and multi-unit residential new construction,


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the coefficients do not provide an accurate representation of infiltration in these building types. The temperature and wind relationships measured in the Bahnfleth et al. study do not provide the same level of predictive power for commercial and multi-unit residential buildings, which vary from single-family homes in both size and level of compartmentalization.

## SIMULATIONS

To compare the three coefficient schemes against each other, zone-level infiltration was calculated using the *ZoneInfiltration:DesignFlowRate* equation for each of the coefficient schemes for a zone at the top of a 10-m tall building and a 40-m tall building, both located in Toronto, Ontario. Infiltration was also calculated using the power law equation:

$$Q = C\Delta P^n \quad (2)$$

Where $Q$ ($m^3/s$) is the infiltration rate at a given pressure difference, $\Delta P$ (Pa); $C$ is the flow coefficient ($m^3/s/Pa^n$); and $n$ is the flow exponent (dim.).

For this analysis, we assumed $\Delta P_{tot}$ is the sum of pressure differentials due to both wind and air buoyancy differences. The flow exponent, $n$, was assumed at 0.65, consistent with other studies (ASHRAE, 2013; Sherman and Chan, 2004; Younes et al., 2011). The flow coefficient, $C$, was back-calculated based on the pressure differential at baseline conditions for the BLAST and DOE-2 models. The analysis used the CWEC weather file for Toronto Pearson International Airport. For infiltration due to differences in air buoyancy, we assumed a thermal draft coefficient, γ, of 0.4 and a neutral pressure plane height ($H_{NPP}$) of 50 % total building height. γ is a measure of building compartmentalization. Previous studies have measured γ between 0.63 and 0.82 (Tamura and Wilson, 1973) for commercial buildings and anywhere between 0 and 1.0 for multi-unit residential buildings, depending on building configuration and time of year (Jo et al., 2007; Proskiw and Phillips, 2008). $H_{NPP}$ also exhibits high seasonal variability. The values selected for the analysis are meant to represent annual averages. Remaining input parameters for the calculations are summarized in Table 2.

This analysis was repeated for cities in each of North America's eight climate zones: Fairbanks, Alaska (Sub-Arctic/Arctic Climate); Calgary, Alberta (Very Cold Climate); Vancouver, British Columbia (Marine Climate); Los Angeles, California (Hot-Dry Climate); Phoenix, Arizona (Mixed-Dry Climate); Houston, Texas (Hot-Humid Climate); and Nashville Tennessee (Mixed-Humid Climate), to examine the effect of climate on modeled and calculated infiltration rates.

## RESULTS

Figure 1 and Figure 2 show the five infiltration profiles calculated at 1-hour time steps for Toronto, Ontario. For clarity, the data were filtered using a 24-hour rolling average.

Between the *DesignFlowRate* profiles, the BLAST coefficients yielded higher infiltration rates across the entire year at zone heights of 10 m and 40 m; however, the DOE-2 coefficients resulted in a larger spread of values. At $H_{zone}$ = 10 m, the annual mean infiltration rates from the BLAST and DOE-2 models were 49% higher and 32% lower, respectively, when compared to the constant EnergyPlus profile and 61% higher and 8% lower, respectively at $H_{zone}$ = 40 m.

The gap between the BLAST and DOE-2 models was largest during the winter months, when infiltration was dominated by the effects of differences in air buoyancy. As the DOE-2 model does not account for air buoyancy-induced infiltration, it is unsurprising that this model estimates chronically low infiltration rates when compared to the BLAST model.

*Table 2: Input Parameters for Infiltration Rate Computations*

| | **Calculated (Power Law)** | | ***ZoneInfiltration:DesignFlowRate*** | | |
|---|---|---|---|---|---|
| | **BLAST** | **DOE-2** | **EnergyPlus** | **BLAST** | **DOE-2** |
| Site Terrain | | | Suburbs | | |
| Zone Height ($H_{zone}$) (m) | | | 10, 40 | | |
| $T_{zone}$ (°C) | | | 21 | | |
| Wind Pressure Coefficient, $C_p$ | | | 0.1617 | | |
| Height of Neutral Pressure Plane ($H_{NPP}$) (m) | 0.5H | 0.5H | - | - | - |
| Thermal Draft Coefficient, γ | 0.4 | 0.4 | - | - | - |
| C ($m^3/sPa^n$) | 0.96 | 0.66 | - | - | - |
| n | 0.65 | 0.65 | - | - | - |
| $I_{design}$ ($m^3/s$) | - | - | 1.0 | 1.0 | 1.0 |


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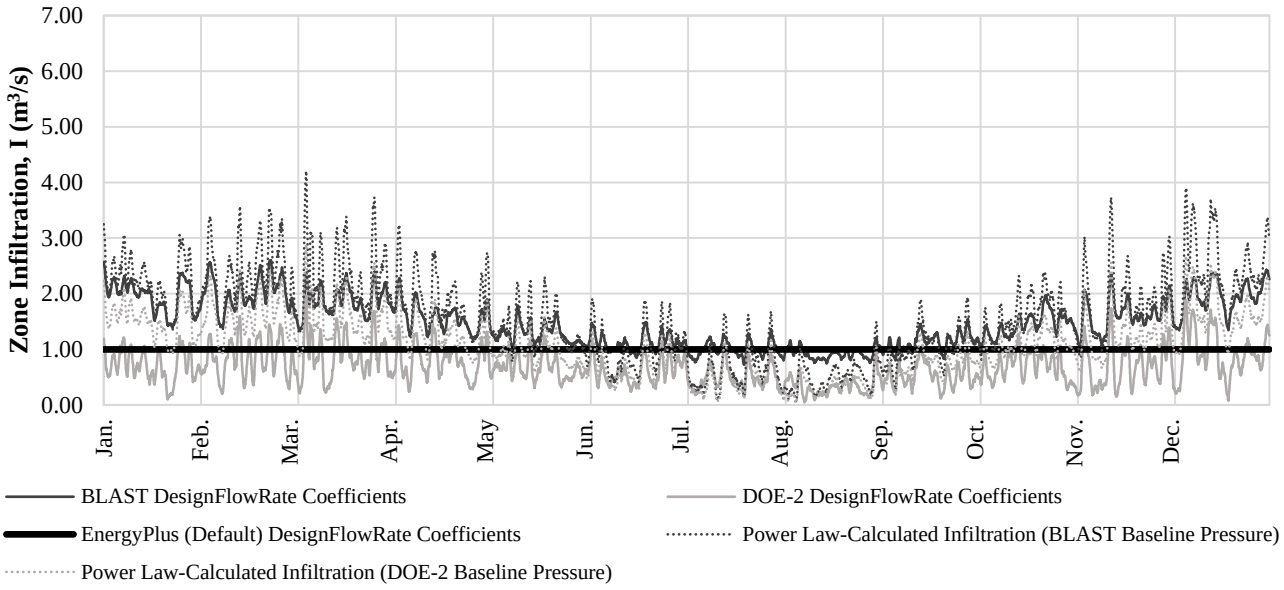


*Figure 1 Infiltration Profiles for Toronto (Cold Climate Zone) at $H_{zone}$ = 10 m*

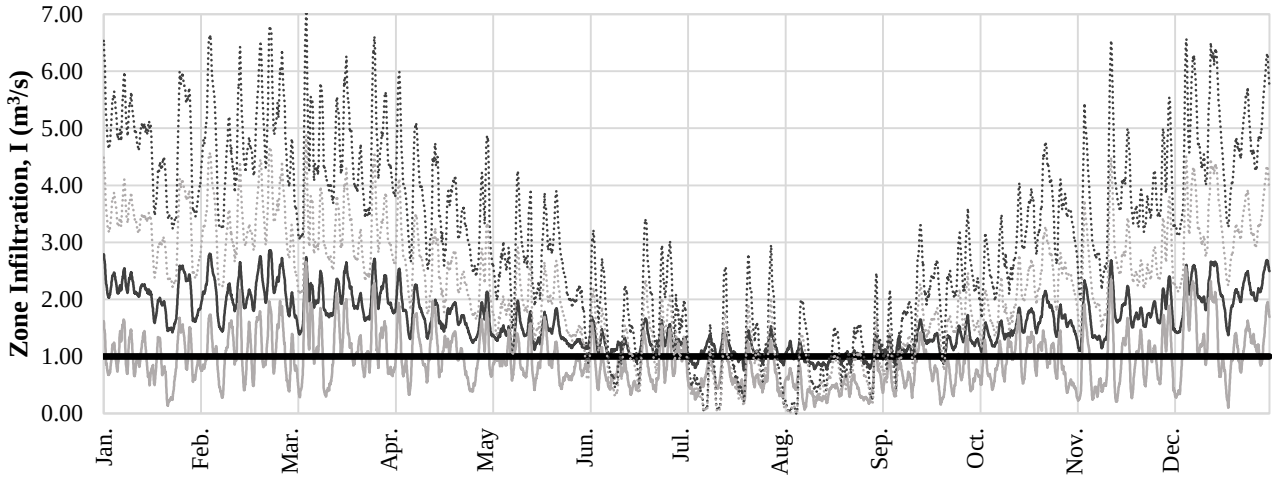


*Figure 2: Infiltration Profiles for Toronto (Cold Climate Zone) at $H_{zone}$ = 40 m*

When compared to the Power Law-calcualted infiltration rates, the BLAST and DOE-2 models were both lower. At a zone height of 10 m, the annual mean infiltration rates from the BLAST and DOE-2 *DesignFlowRate* computations were 7% and 38% lower, respectively. At 40 m, the differences jump to 49% and 58%, respectively. This suggests that even the BLAST model underestimates the effect of air buoyancy on infiltration. Again, underestimation of air buoyancy is unsurprising, considering the model coefficients were developed from data collected in single-family homes, where buoyancy-induced infiltration is typically dwarfed by wind-induced infiltration.

The Power Law-calculated infiltration rates made certain assumptions about the leakage characteristics of the building, namely the $H_{NPP}$ and $\gamma$. A sensitivity analysis of the Power Law-calculated rates to these parameters revealed that a reduction of the $H_{NPP}$ to 1.0 m or $\gamma$ to 0.0 was required for the *DesignFlowRate* models and Power Law-calculated values to converge. While both $H_{NPP}$ and $\gamma$ demonstrate seasonal variability (Proskiw and Phillips, 2008), both adjustments are well outside the range of expected average values for $H_{NPP}$ and $\gamma$. As such it is reasonable to assume that the BLAST and DOE-2 models will always underestimate the effect of differences in air buoyancy on infiltration in tall buildings.

Figure 3 shows box and whisker plots for the hourly zone infiltration rates for all eight cities (minimum, first quartile, median, third quartile and maximum).


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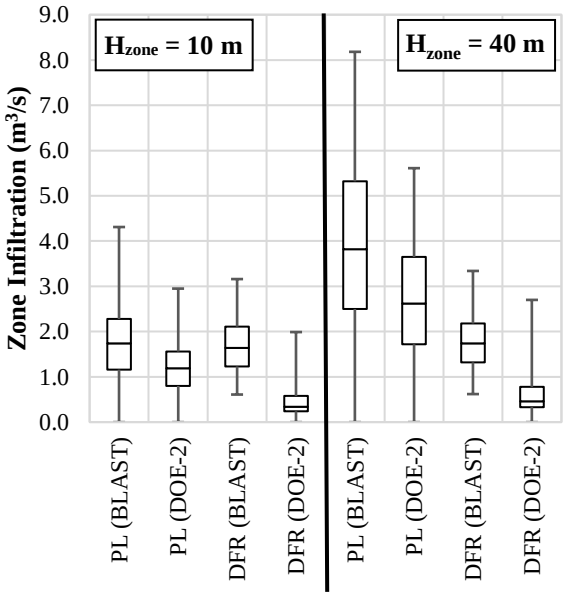
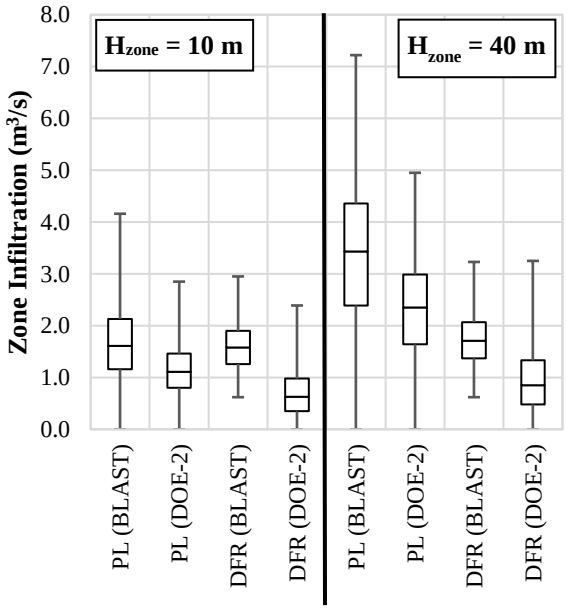
Note that the Default EnergyPlus model was not included in the graphs, as the Default model assumes a constant infiltration rate. As expected, the divergence between *DesignFlowRate* and Power Law-calculated infiltration rates is greatest for Fairbanks (Sub-Arctic/Arctic climate zone) at $H_{zone}$ = 40 m, where winter-time indoor-outdoor temperature differences are typically 25°C and larger. Houston (Hot-Humid climate zone) demonstrated the best agreement between *DesignFlowRate* and Power Law-calculated rates among the eight cities, though the Power Law-calculated infiltration was still larger than the BLAST and DOE-2 *DesignFlowRate* infiltration rates during the winter months.

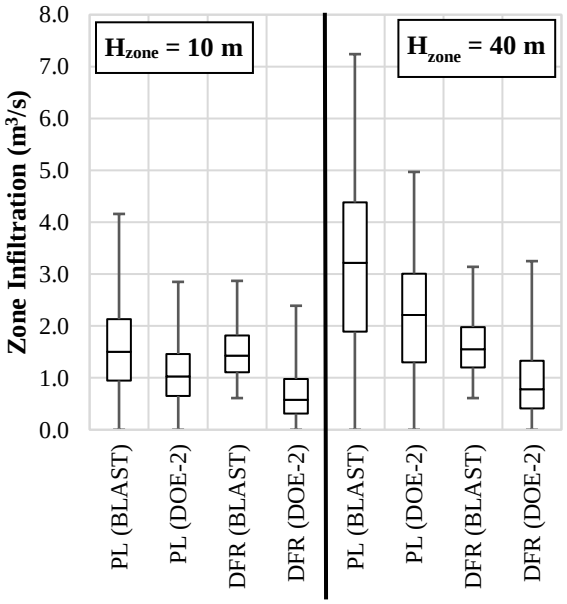
This analysis emphasizes the strong effect that climate exerts over infiltration rates. None of the *DesignFlowRate* coefficient schemes provided valid infiltration profiles across all climates and building types. Depending on the climate zone and the building size, the BLAST and DOE-2 *DesignFlowRate* model coefficients may over- or under-estimate zone infiltration.



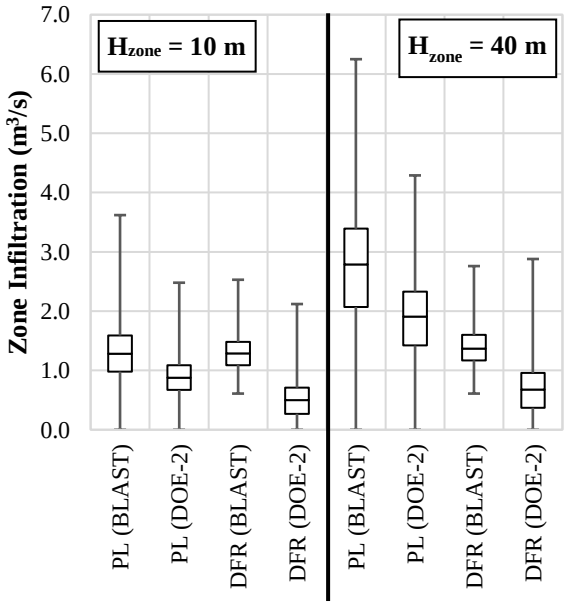

**(a) Fairbanks (Sub-Arctic, Arctic)**




**(b) Calgary (Very Cold)**




**(c) Toronto (Cold)**




**(d) Vancouver (Marine)**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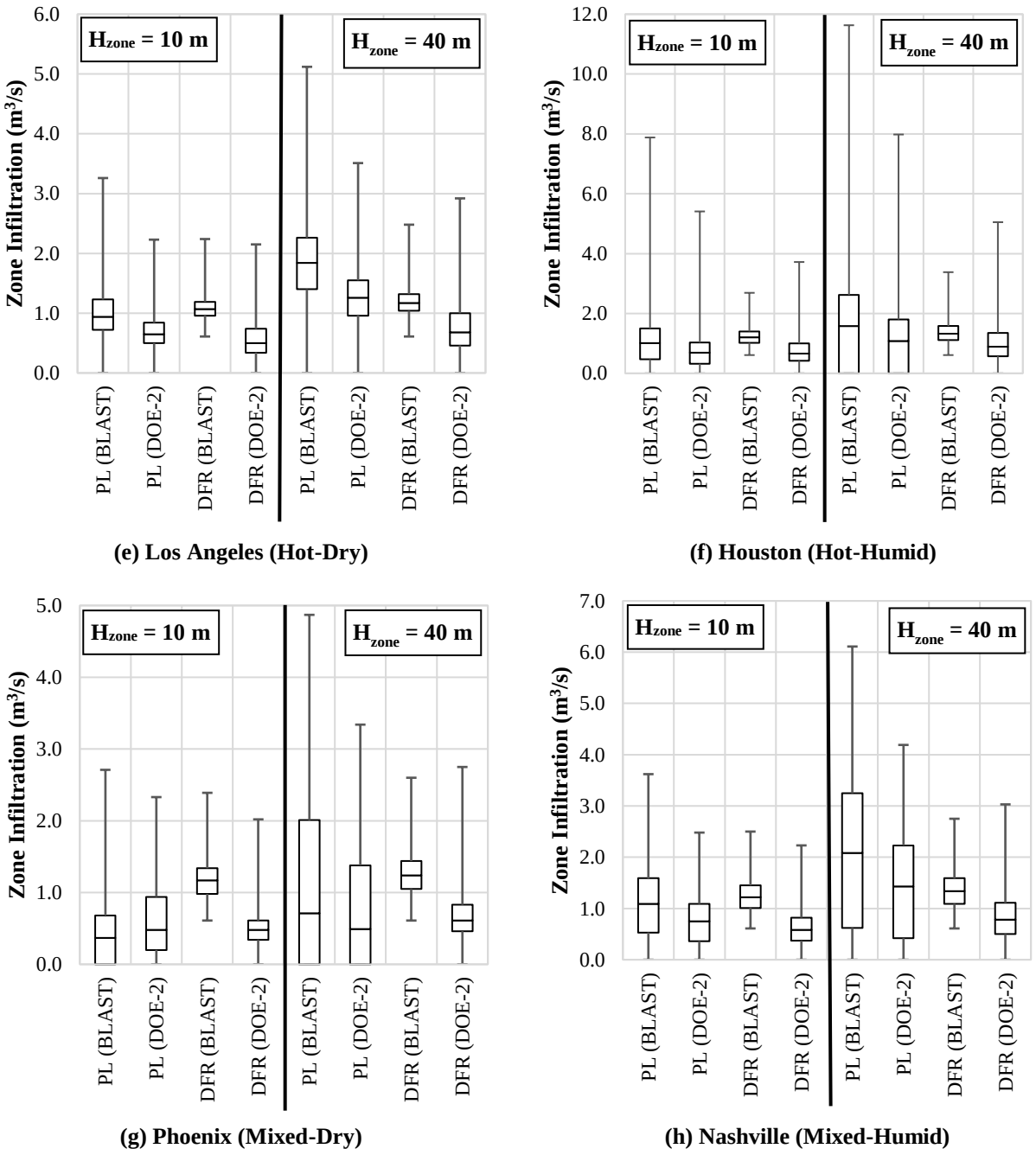


*Figure 3: Box plots of zone infiltration (Power Law (PL) vs.* ZoneInfiltration:DesignFlowRate *(DFR)) for each of the eight North American climate zones*

## LIMITATIONS OF ANALYSIS

This analysis was intended to be preliminary in nature. The Power Law is an admittedly static way of quantifying building air infiltration, which is highly dynamic. The results of this analysis should be viewed within the context of these limitations.

Pressures induced by differences in air buoyancy assumed a static $H_{NPP}$ and $\gamma$. As previously mentioned, $H_{NPP}$ and $\gamma$ vary significantly based on season and general building operation. The $\gamma$ and $H_{NPP}$ values were meant to represent average, annual conditions. The values do not accurately capture seasonal variations.


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Another major limitation of this study is the fact that pressures from mechanical systems were not accounted for. The pressure differential induced by mechanical systems will heavily depend on the building type and the type and configuration of the mechanical system. This analysis was originally completed for multi-unit residential buildings where mechanical pressures are typically small in magnitude, especially compared to buoyancy- and wind-induced pressures. In multi-unit residential buildings ventilations systems have been found to pressurize suites by 5 to 10 Pa, relative to the corridors (Cooke-, 2005).

## IMPLICATIONS FOR WHOLE-BUILDING ENERGY SIMULATIONS

The limitations inherent with EnergyPlus' *DesignFlowRate* algorithm have several implications for the overall utility of energy models.

In new construction applications, energy models are essentially used as a benchmarking tool to confirm code compliance. It is well established that the models are not necessarily representative of actual in-service performance. Despite this very large qualifier for model reliability, the primary goal of energy efficient legislation and elective programs is to improve the energy efficiency of our building stock. If benchmarking tools, such as whole-building energy models, are flawed from the start, design and construction stakeholders at all levels are not receiving accurate information required to make key design decisions.

This shortcoming is even more critical for whole-building energy models used in retrofit applications, where accurate representation of in-service performance is imperative to assess ECMs. If energy models do not accurately describe building function, the resulting model estimates will have a low level of reliability. Models calibrated using heuristic methods often vary high-uncertainty parameters, such as the infiltration rate, to achieve calibration. In this case, the final "calibrated" infiltration rate is simply the value that results in overall model calibration. The calibrated infiltration rate ends up absorbing the error from the infiltration model.

The *EnergyPlus Input-Output Reference* recommends completing a detailed infiltration analysis to determine custom coefficients; however, this is onerous as it requires constructing a separate airflow network model. It is unlikely that the average practitioner would undertake the analysis required to develop robust coefficients. Ng et al. recently developed an empirical technique to calculate building-specific coefficients to use with the *DesignFlowRate* model, using three building characteristics (2015). The technique resulted in improved agreement with CONTAM airflow models, compared to the standard BLAST and DOE-2 coefficients; however, the study was limited to a small subset of commercial reference buildings and were only modeled for the Chicago climate. The technique has not been rigourously validated for other building types and climates.

## CONCLUSION

This paper compared zone infiltration profiles calculated using EnergyPlus' standard multi-zone infiltration model, *DesignFlowRate*, for building zones in different climates against infiltration rates calculated using first principles (Power Law). The relative agreement between the EnergyPlus models and the Power Law calculations varied considerably, depending on climate, building height and coefficient scheme selected.

At low zone elevations, the DOE-2 coefficients exhibited better agreement with the Power Law for warmer climates, while the BLAST coefficients worked better for colder climates. At higher zone elevations, both the BLAST and DOE-2 coefficient schemes underestimated zone infiltration. This was most pronounced in colder climates, where air buoyancy-induced infiltration dominates.

Alternatives to the standard *DesignFlowRate* coefficients listed in the *EnergyPlus InputOutput Reference* include potentially labour-intensive computations to calculate building-specific coefficients for the empirical model, or development of airflow network models using CONTAM. While inroads have been made to simplify both alternatives, industry conventions still defer to the limited capabilities of the empirical models.

Whether we are using whole-building energy simulation software for new construction or retrofit applications, the limitations of existing infiltration models need to be accounted for during model development and interpretation of the results.

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