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Different modeling strategies of infiltration rates for an office building to improve accuracy of building energy simulations

Guiyuan Han [a,*], Jelena Srebric [b,**], Elena Enache-Pommer [c]

[a] Department of Architectural Engineering, Pennsylvania State University, University Park, PA, USA
[b] Department of Mechanical Engineering, University of Maryland, College Park, MD, USA
[c] Dow Building Solutions R&D at Dow Chemical, Midland, MI, USA

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ABSTRACT

Air infiltration rates directly impact building energy consumption to a larger or smaller degree depending on the tightness of building enclosure and heating ventilation and air conditioning system operation. The relative importance of infiltration airflows has been increasing in total building energy consumption due to the improvements in building insulation and window products. The objective of this study is to compare the accuracy of building energy simulations associated with different air infiltration rates calculation approaches. This study used different sources of infiltration rate: time-dependent simulated data, AIVC database, and default settings in building energy simulations. A coupled framework associated with time-dependent infiltration rates is used by integrating computational fluid dynamics and multi-zone airflow modeling results into energy simulations. This framework is demonstrated with a case study for an office building in Michigan. The case study also uses the infiltration rates obtained from the database and default settings in energy simulation program. The comparison between simulation results and utility data shows that time-dependent infiltration rates could increase the accuracy of energy simulations with 3–11% reduction in the coefficient of variation of the root mean square error (CVRMSE), and 2–11% reduction in the normalized mean bias error (NMBE).

1. Introduction

Air infiltration is the unintentional airflow into a building through different openings in building enclosure. Infiltration rates can have a significant effect on the building energy consumption [1,2]. In a study conducted during 1980s, the energy loss due to infiltration was estimated to be between 6% and 9% of the total energy budget for the US [3]. The relative importance of infiltration airflows has been increasing in the total building energy consumption due to the improvements of building insulation and window products. Another more recent study shows that infiltration is responsible for approximately 13% of the heating loads and 3% of the cooling loads for the US office buildings. Specifically, for newer buildings, infiltration is responsible for about 25% of the heating loads and 4% of the cooling loads due to the higher levels of insulation [4]. The problem is worldwide, for example, according to a study in 2009, infiltration causes about 15–30% of the energy use for space heating including ventilation in a typical Finnish detached house. In this case, the average infiltration rate and heat energy use was increasing almost linearly with the building leakage rate [5].

The air infiltration rates in buildings are driven by the pressure difference across the building envelope caused by wind and air density differences due to temperature differences between inside and outside air. Mechanical systems also contribute to pressure differences across the envelope. The indoor/outdoor pressure difference at a location depends on these driving mechanisms as well as on the characteristics of the openings in the building envelope.

The actual wind pressure distribution profile, as one of the important infiltration driving mechanisms, depends on the wind direction, wind speed, air density, surrounding terrain, and building layout. The data sources of wind pressure coefficients (C_p) are classified as primary and secondary sources. The primary sources include full-scale measurements, reduced-scale measurements in wind tunnels and computational fluid dynamics (CFD), while the secondary sources of wind pressure coefficients mainly include databases and analytical models. A study provided an overview of different pressure coefficient data in building energy simulation and airflow network programs [6]. The overview shows that

* Corresponding author. Tel.: +1 814 753 2821; fax: +1 814 863 4789.
** Corresponding author. Tel.: +1 301 405 7276.
E-mail addresses: goh5067@psu.edu, hanguiyuan@gmail.com (G. Han), jsrebric@umd.edu (J. Srebric).

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the pressure coefficients from different data sources show large variations when applied to the same building.

The building construction quality is another significant factor influencing building infiltration rates. The accuracy of infiltration rate calculations directly depends on the construction quality represented as the building leakage areas. Ideally, the size, location and characteristics of all leakage areas should be known. However, these properties are difficult to quantify. Besides, the uncertainty of building leakage areas could be greatly increased by different manufacturing and installation processes [7].

Currently, available methods for evaluating the building air leakage area and associated infiltration rates range from simple air change methods to complex physical modeling methods. The previous studies have been using different sources of the infiltration rates in building performance simulation. Infiltration rates could be set up as certain air change rates according to an estimation of building envelope tightness [8] [9]. Infiltration rates could also be calculated according to numerical equations [10] and correlations with wind speed [11]. Multi-zone modeling simulation is employed in building performance analyses to consider building detailed configurations and provide relatively accurate infiltration rates [4]. In building energy simulation tools, such as EnergyPlus, the calculation methods of infiltration rates typically use default infiltration rates depending on different leakage properties of the buildings such as: leaky, normal, and tight. These three categories of building leakage do not account for the infiltration driving mechanisms and other building characteristics. Consequently, the assumed infiltration rates in EnergyPlus do not reflect the direct impacts of outdoor weather conditions [12]. Therefore, the default settings for infiltrate rates do not directly reflect the actual infiltration rates in building energy simulations. However, to the authors' knowledge, there has been no study analyzing the uncertainty of building performance simulation correlated with different infiltration rates calculation methods.

To more directly reflect the actual weather conditions, a study by the Pacific Northwest National Laboratory (PNNL) proposed a simplified approach to account for wind-driven infiltration rates into buildings [13]. The method uses an average wind speed coefficient for a square office building to calculate a base infiltration rate that is further varied with the incoming average wind speed using a capability within EnergyPlus. Even though this approach addresses wind-driven infiltration, it is not accounting for the infiltration rates due to the stack effect. Furthermore, another research study on airflow rate calculations indicated that the underestimation and overestimation due to surface-averaged pressure coefficients are not negligible [14]. Therefore, the simplified methods may not be sufficiently accurate for energy simulation tools required to satisfy high accuracy levels as defined by ASHRAE guideline 14-2002 [15].

Among the physical modeling methods, a recent research study developed a roadmap for performing full 3-D envelope simulations to calculate air leakage in buildings [16]. This physical modeling method realistically depicts the various cracks common in an envelope in terms of shape, location, and quantity, so it is very computationally demanding. Another group of models focuses on better representation of specific building enclosure elements know to make significant impact on the total building infiltration rates, such as windows [17], doors with air curtains [18], and revolving doors [19]. However, the existing studies do not focus on comparing the influence of different infiltration rate calculation methods on the accuracy of building energy simulation results for commercial buildings.

Overall, there have been many different calculation strategies of infiltration rates in both theoretical and practical studies. Therefore, it is important to understand the accuracy level of building performance analysis associated with different methods of infiltration rate calculations. The purpose of the present study is to compare the impact of infiltration rates from different data sources on the accuracy of building energy simulations, and discuss the uncertainty of simulated energy consumption associated with the infiltration rates.

2. Methodology

The methodology focuses on the wind pressure coefficients and building leakage areas because the heating ventilation and air conditioning (HVAC) imposed pressures are predefined by the building design/operation already accounted in energy simulations, while the wind pressures depend on the weather and surroundings.

The major data sources of wind pressure coefficient (C_p) include measurements [20], computational fluid dynamics (CFD) simulations [21], databases and analytical models [22]. Measurements include full-scale measurements and reduced-scale measurements in wind tunnels. Generally, measurements are complex, time-consuming and expensive. Both full-scale and wind-tunnel measurements are limited by high equipment costs, intense labor, and demanding time requirement for data collection [6]. Therefore, the present study focuses on comparing energy simulation accuracy resulting from infiltration calculations using wind pressure coefficients (C_p) from CFD modeling and Air Infiltration and Ventilation Centre (AIVC) database as relatively inexpensive data sources when compared to measurements as a data source.

CFD has been employed to study airflow and contaminant dispersion around and in buildings for a few decades [23–25]. More recently, CFD is also used to simulate the wind pressure on building envelope [26–28]. CFD is able to consider all major factors in development of pressure coefficients, including local wind profile, building orientation and shape, terrain and sheltering effects of surrounding buildings [29]. A popular tool that uses these pressure coefficients to calculate infiltration rates is multi-zone modeling based on a simplified macro-representation of the bulk airflow in and around a building [30]. The advantages of multi-zone modeling are simple problem definition, straight forward representation, and clear calculation procedure. However, due to the perfect-mixing assumption of air in each zone, multi-zone modeling is not able to provide detailed temperature, airflow and pressure distributions within a single space [31]. Therefore, an integration of the airflow multi-zone modeling and CFD methods provides a balance between complementary information on building physics and required simulation resources. As a result, the combination of CFD and multi-zone models has been investigated and applied in several studies [32].

The building energy simulation framework accounting for infiltration rates by integrating CFD and multi-zone modeling is shown in Fig. 1.

CFD provides detailed model to simulation airflow pattern around the building and also provides wind pressure distribution profile. A multi-zone model uses this wind pressure distribution profile and building leakage area as inputs. The output of the multi-zone modeling, infiltration rates, together with the weather files and building thermal properties, are important inputs to building energy simulation. EnergyPlus is employed as building energy simulation tool in this framework due to its capability to modify every detailed parameter in open source architecture.

Besides the coupled CFD/multi-zone modeling approach, databases are also employed as an alternative data source of wind pressure coefficients (C_p). The two widely used databases often found in the ventilation and infiltration literature include the AIVC database [33] and ASHRAE database [34].

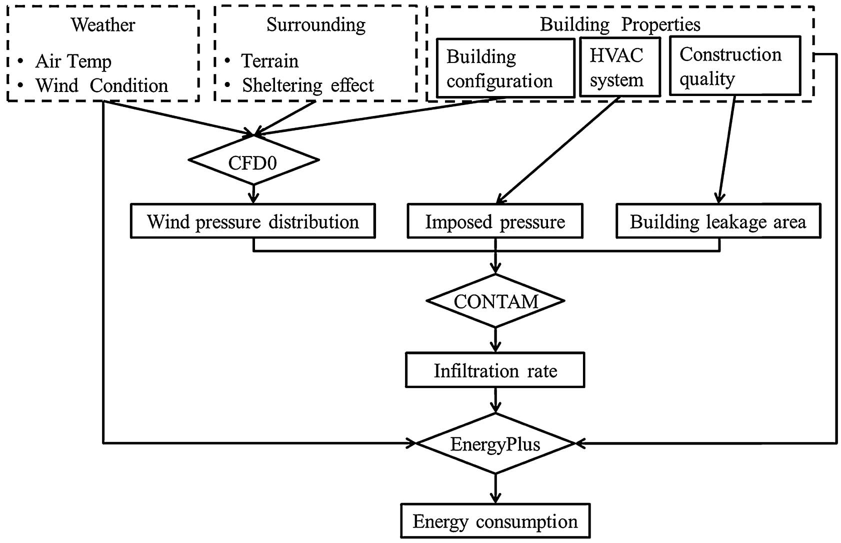


Fig. 1. Framework of building energy simulation based on time-dependent infiltration rates.

The Air Infiltration and Ventilation Centre (AIVC) is an international information center on air infiltration and ventilation, providing online technical notes and guides and free search in databases with over 18,000 references. In 1986, AIVC published a compilation of C_p data as a part of a comprehensive guide [33]. The guide has been used as an important reference in the ventilation studies since its publication. Both low-rise (up to 3 stories) and high-rise buildings are presented in the database. The data for low-rise buildings are based on wind-tunnel data published in a workshop on wind pressure coefficients [35], while the data for high-rise buildings are reproduced from the literature [36]. The database for low-rise buildings consists of surface-averaged C_p data for rectangular buildings with selected aspect ratios and for three shielding levels including: exposed, semi-sheltered, and sheltered buildings.

ASHRAE handbook also provides surface-averaged C_p data for both low-rise and high-rise buildings. The wind pressure coefficients are provided in 2001 ASHRAE Fundamentals Handbook, page 16.5, Figure 7, "Surface Averaged Wall Pressure Coefficients for Tall Buildings" [37]. ASHRAE does not present data for sheltered buildings, although it provides correction factors for the reference wind speed based on sheltering factors.

Both databases are established through experiments, but the literature focuses on the pressure coefficients and does not present information about the wind profiles used in the experiments. Table 1 summarizes the infiltration modeling capabilities of three different models deployed to derive the C_p data for energy simulations in the present study.

Another critical element of infiltration rates estimation is actual building leakage area, which is usually represented by effective air leakage at a certain pressure difference. The effective leakage areas in this case study will be estimated using data available in the literature and/or existing industry standards [10,11].

Table 1
Summary of infiltration modeling capabilities for different C_p data sources.

	CFD0	AIVC	ASHRAE
Wind condition/angle	F	P	P
Terrain effect	F	N	N
Sheltering effect	F	P	P
Building configuration	F	N	N

F: fully able to model; P: partially able to model; N: not able to model.

Fig. 2. The case study building in Saginaw, Michigan, US.

Table 2
R-value of building enclosure system.

Enclosure	*R*-value ((m^2 K)/W)
Roof	43
Wall	14
Slab/stem wall	12

3. Case study building

The selected case study building is a commercial office building located in Saginaw, Michigan, US. It is a two-story building, shown in Fig. 2, with a total conditioned floor area of 1579 m^2 (16,992 ft^2). The building shape is nearly rectangular with an aspect ratio of 3 and the long façades having north/south orientation. Table 2 shows the *R*-value of building envelope, which is also the value used in energy simulations. Window properties in the energy model are replicating to the actual construction, double glazing with aluminum frame.

For the conditioned building spaces, HVAC system is a single duct multi-zone variable air volume type, while the half of the second floor area is unoccupied and therefore conditioned to different temperature set points. Table 3 shows the building

Table 3
Set-points for different building areas.

Area	Set-point (°C)
Unoccupied cooling set-point	29.4
Unoccupied heating set-point	12.8
Interior temperature set-point	22.2

Table 4
Occupancy profile (M–F).

Time slots	Fraction
6:00 pm–6:30 am	0
6:30 am–8:00 am	0.25
8:00 am–9:00 am	0.5
9:00 am–12:00 pm	1
12:00 pm–2:00 pm	0.75
2:00 pm–4:00 pm	1
4:00 pm–5:00 pm	0.5
5:00 pm–6:00 pm	0.25

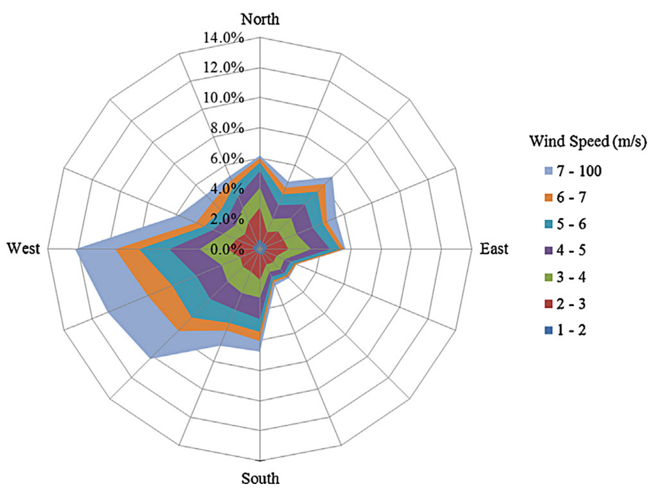


Fig. 3. Wind rose of Saginaw, MI.

set-point temperatures for both occupied and unoccupied spaces. The total office occupancy is 57 people with a maximum density of 5/100 m^2 which is modulated at each simulation time step to represent typical hourly occupancy schedules. Electric lighting system has a power density of 10.9 W/m^2, and this study assumed the same electric plug loads of 10.9 W/m^2. The main occupancy schedule is Monday–Friday, 6:30 am–6:00 pm. The occupancy, electrical equipment and lighting schedules are all corresponding to the occupancy profile shown in Table 4.

This building is considered as an exposed building according to the local surrounding environment. The energy simulation model uses local environmental boundary conditions (44°N/84°W), which is classified as ASHRAE Climate Zone 5A. This climate zone is heating dominated with cool and humid weather conditions and the annual heating and cooling degree days of 3966 and 580, respectively (18 °C baseline). Fig. 3 shows the wind rose according to the typical meteorological year (TMY) weather data. The annual average value of wind speed is 4.4 m/s, and maximum value is 17.5 m/s. The local prevailing wind direction is west.

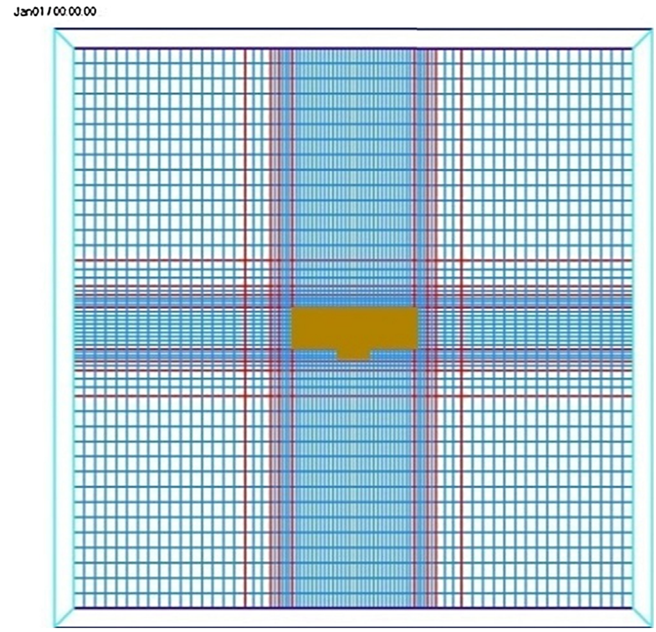


Fig. 4. Computational grids in the horizontal cross section.

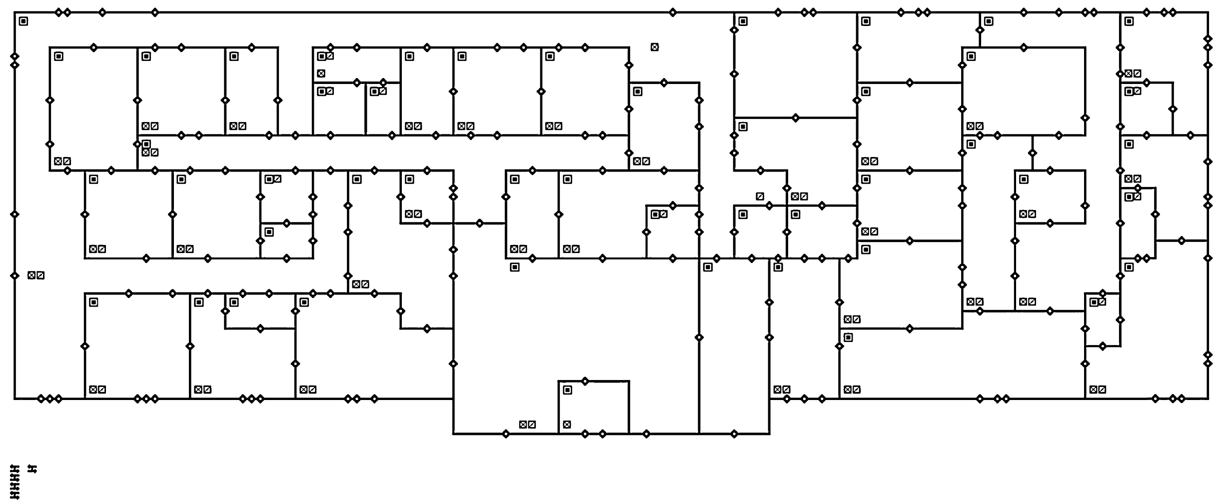
4. Simulation scenarios

The study is to compare the energy simulation results based on different sources of air infiltration calculations. In this study, there are four simulation scenarios shown in Table 5. Scenario 1 simply uses the default setting of infiltration rates in the energy simulation program, considering three envelope tightness levels (leaky, medium, and tight). DesignBuilder uses the EnergyPlus AIRNET method [38] to calculate air flow rates. Scenario 2 simulates building infiltration rates using CONTAM, in which data sources of wind pressure loads is AIVC database. Scenarios 3 and 4 are using simulation procedure with time-dependent infiltration rates outlined in Fig. 1. Wind pressure loads are simulated by CFD0 coupled in CONTAM. Furthermore, yearly-averaged and monthly-averaged infiltration rates are calculated and inputted in energy simulation program [39].

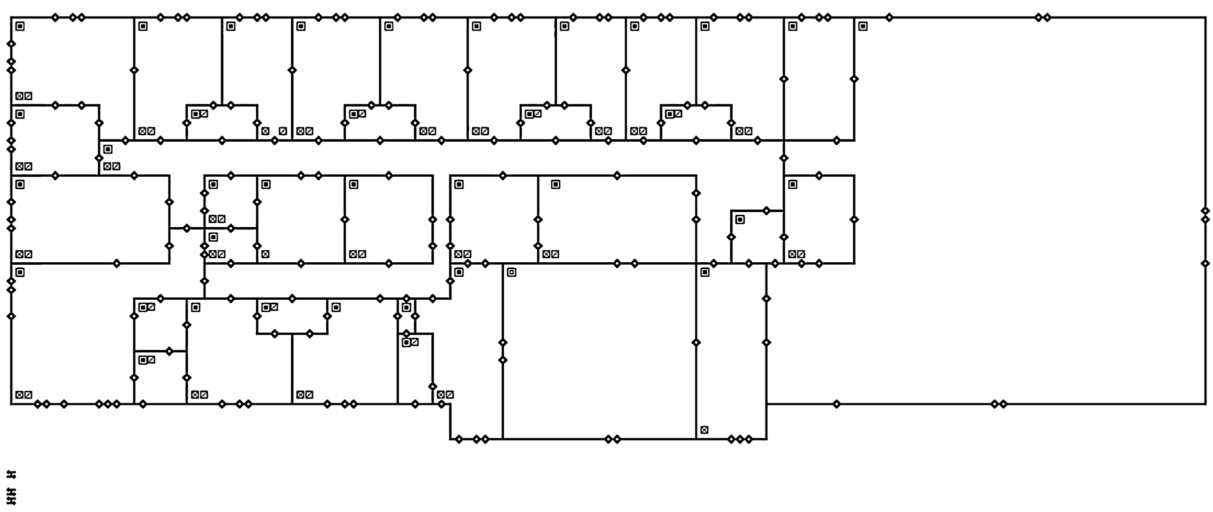
Time-dependent infiltration calculations are conducted by combining CFD and multi-zone airflow modeling approaches. Fig. 4 shows the CFD computational grid in the horizontal cross section. The study region is 250 m × 250 m × 24 m in the X, Y and Z dimensions, respectively. The inlet type boundaries are created on all four sides of the region according to the local TMY3 weather data. A total of 30, 50, and 12 cells are used along the width, length, and height of the building. The mesh boundaries align with the building blockages to properly identify the locations of the CONTAM airflow paths on the building surface. The results of CFD0 simulations provide wind pressure profiles to CONTAM.

Table 5
Four simulation scenarios.

	Wind pressure loads	Imposed pressure	Building leakage area
Scenario 1	Default setting of infiltration rates in DesignBuilder (leaky, medium, tight)		
Scenario 2	Wind pressure load database	Simulated by CONTAM, input yearly-averaged infiltration rates	
Scenario 3	CFD0	Simulated by CONTAM, input yearly-averaged infiltration rates	
Scenario 4	CFD0	Simulated by CONTAM, input monthly-averaged infiltration rates	



(a)



(b)

Fig. 5. Building floor layout in the multi-zone airflow model, CONTAM, for (a) the first floor and (b) the second floor.

Fig. 5 illustrates the multi-zone airflow model built in CONTAM. The symbols on the external and internal walls represent the airflow paths. The wind pressure profiles provided by CFD0 are imported and selected in the models. Every envelope airflow paths are defined with the information of actual locations.

The effective air leakage areas of three different air-tightness levels are used in the calculation of infiltration rates, shown in Table 6 [34]. The major influential building components of air infiltration are considered in the case study, including doors, windows, window frames, and wall leakage paths.

To demonstrate the impact of an infiltration calculation procedure on building energy simulations, the results of different simulations are compared to the monthly power usage of the building.

Table 6
Estimated building leakage area.

Building components	Effective air leakage (at 4 Pa)
Door, double	11 cm^2/m^2
Window framing, wood	1.7 cm^2/m^2
Windows, double horizontal slider	1.1 cm^2/m
Exterior wall, concrete panel	4.0 cm^2/m^2

5. Results

The case study aims to compare the building energy simulation results based on different sources of infiltration rates. To illustrate the accuracy of different scenarios, the simulation results are compared to the actual utility bills.

Fig. 6 shows the comparison of monthly electricity use between utility bills and building energy simulation results associated with different sources of infiltration rates. Table 7 shows the percentage differences between simulation results and utility data.

According to the simulations, energy consumption due to air infiltration contributes 12% on average to the total annual energy consumption (standard deviation: 3.3%). According to Fig. 6, the monthly electricity use is well predicted by the calculation based on time-dependent infiltration rates. The comparison indicates that energy simulations with time-dependent infiltration rates could

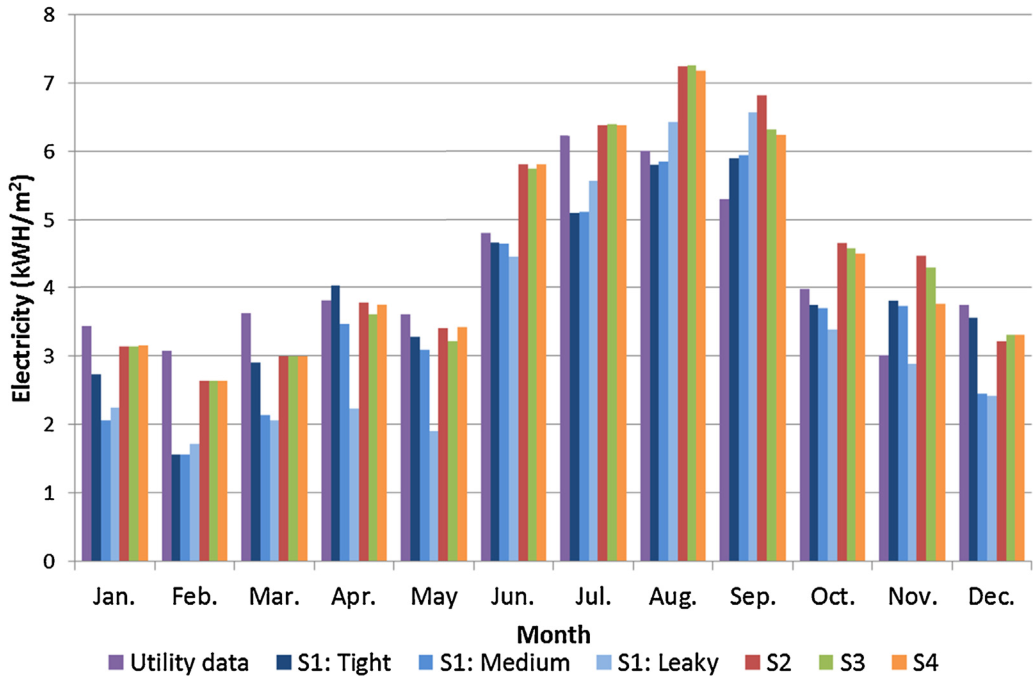


Fig. 6. Comparison of monthly electricity use with different sources of infiltration rates.

Table 7
Percentage differences between simulated data and utility data.

	S1: tight	S1: medium	S1: leaky	S2 (database)	S3 (CFD0, yearly)	S4 (CFD0, monthly)
January	−20%	−40%	−35%	−9%	−9%	−8%
February	−50%	−49%	−44%	−14%	−14%	−14%
March	−20%	−41%	−43%	−17%	−17%	−17%
April	6%	−9%	−41%	−1%	−5%	−2%
May	−9%	−14%	−47%	−6%	−19%	−5%
June	−3%	−3%	−7%	21%	20%	21%
July	−18%	−18%	−10%	3%	3%	3%
August	−3%	-3%	7%	21%	21%	2%
September	11%	12%	24%	29%	19%	18%
October	−6%	−7%	−15%	17%	15%	12%
November	27%	24%	−4%	49%	43%	25%
December	−5%	−34%	−35%	−14%	−12%	−11%

provide more accurate monthly energy use than the ones with the default infiltration rates from databases.

6. Discussion

The measurement of infiltration rates has high uncertainties and standard measurement approach for commercial buildings does not exist. Specifically, the accuracy of measurement is influenced by many factors when it comes to commercial buildings [40]. According to ASHRAE guideline 14-2002, the utility bills could be used to examine accuracy of simulation results [15]. Therefore, this study used building energy consumption as a metric for assessing the accuracy.

To analyze the simulation results, coefficient of variation of the root mean square error (CVRMSE) and normalized mean bias error (NMBE) are used as indicators to represent how well the mathematical model describes the variability in measured data. These indices should be computed for the single mathematical model used to describe the baseline data from all operating conditions. ASHRAE guideline 14-2002 describes these indicators as following [15]:

$$\mathrm{CVRMSE} = 100 \times \left[\sum (y_i - \hat{y}_l)^2/(n-p)\right]^{1/2}/\bar{y} \qquad (1)$$

$$\mathrm{NMBE} = \frac{\sum^n y_i - \hat{y}_l}{(n-p)\times \bar{y}} \times 100 \qquad (2)$$

where y_i is the utility data used for calibration; $\hat{y}_l$ is the simulation predicted data; $\bar{y}$ is the arithmetic mean of the sample of n observations; $p = 1$ for calibrated simulations.

For calibrated simulations, the CVRMSE and NMBE of modeled energy use should be determined by comparing simulation-predicted data ($\hat{y}_l$) to the utility data used for calibration (y_i), with $p = 1$ [15].

Table 8 presents CVRMSE and NMBE values of monthly energy simulation results based on different calculation methods of

Table 8
CVRMSE and NMBE of different calculation methods of infiltration rates.

	Coefficient of variation of the root mean square error (CVRMSE)	Normalized mean bias error (NMBE)
S1 (DB default): tight	17.4%	7.6%
S1 (DB default): medium	21.5%	12.8%
S1 (DB default): leaky	26.2%	16.8%
S2 (database)	20.8%	8.5%
S3 (CFD0, yearly)	18.4%	6.3%
S4 (CFD0, monthly)	14.9%	5.4%

infiltration rates. The ASHRAE guideline 14-2002 requires that the simulation model should have an NMBE of 5% and a CVRMSE of 15% relative to monthly calibration data [15]. Scenario 4, employing monthly-average infiltration rates simulated by multi-zone modeling and wind pressure loads calculated by CFD, achieves the smallest CVRMSE and NMBE values among all simulation scenarios. In simulation scenario 1, the default setting of tight envelope has the CVRMSE and NMBE values which are closest to the ASHRAE guideline requirement. Inputting yearly-average infiltration rates, scenario 3 can only improve the value of NMBE. However, the CVRMSE in scenario 3 is higher than the one of scenario 1 with appropriate estimation of envelope tightness. Simulation in scenario 2 has larger errors than the results in scenario 1 with tight envelope quality, which indicates that in this case study appropriate estimation of envelope tightness is crucial to the accuracy of energy simulation. The comparison among different calculation strategies indicates that time-dependent infiltration rate could increase the accuracy of energy simulation with 3–11% reduction of CVRMSE and 2–11% reduction of NMBE. Furthermore, the time-dependent infiltration simulations do not require pre-existing knowledge on the building tightness level.

AIVC database is not fully able to model every aspect of wind pressure profiles. The infiltration rates from AIVC database are based on 1:1 aspect ratio and standard shelters around building. ASHRAE database is surface-averaged data, which is based on simple rectangular building geometries. However, in this case study, the building aspect ratio is 3:1, and the geometry profile is not rectangular either. Therefore, the limitation of the wind pressure profile database could increase the uncertainty in the calculation of infiltration rates, therefore, impacting the accuracy of building energy simulation. Time-dependent simulation of infiltration rates could increase the simulation accuracy because building geometries, weather profiles and surroundings could be fully considered by coupling CFD and airflow multi-zone modeling. CFD could become an important source of C_p data due to improvements in computer performance, price reduction, and the availability of commercial CFD software [6].

Since the methodology of coupling multi-zone and CFD models is proposed [31], there have been several studies applying the methodology in different research issues: natural ventilation [41] and contaminant dispersion calculation [42]. This study deployed a case study of time-dependent infiltration rates calculation method integrating CFD and airflow multi-zone model. It is supported by the result of this case study that time-dependent infiltration rates could relatively increase the accuracy of building energy simulation. With the improvement of computational speed, time-dependent infiltration rates should be considered in building energy simulations.

The objective of this study focused on comparing the accuracy of building energy simulation results associated with different calculation strategy of infiltration rates. Therefore, there are still several parts that could be improved in this study. Firstly, the accuracy of wind pressure profile could be improved. The current setting of turbulence model, boundary conditions, and grid discretization is limited by using CFD0. Yoshie et al. [43] shows different turbulence models have different performance in certain conditions. The turbulence model used in CFD0 is either simple zero-equation or standard k–ε model, which could be replaced by differential stress model (DSM) or large eddy simulation (LES) [44,45]. Secondly, this study only compares the time-dependent method with the infiltration rate calculations based on database sources, rather than wind tunnel experiments and full scale field measurements. Further work could compare the accuracy of difference energy simulations based on all of these methods. Furthermore, this study does not consider the amount of computational time required by different infiltration calculation methods.

7. Conclusions

This study discusses three different approaches of infiltration rate calculations in building energy simulations including coupled time-dependent infiltration calculations, AIVC database, and default calculations for leaky, medium and tight buildings. A framework of building energy simulations associated with time-dependent infiltration rates is used in the study, integrating computational fluid dynamics and airflow multi-zone modeling approach with energy simulations. The study examines results of the framework by deploying it to a case study for an office building. To compare energy simulation results and demonstrate the influence of different infiltration calculation strategies, this study also conducts building energy simulations associated with infiltration rates defaulted by the energy simulation program and calculations based on AIVC databases. The simulation-predicted data are compared with the actual utility data and evaluated according to ASHRAE guideline 14-2002.

The result shows that the energy consumption due to air infiltration takes approximately 12% of the total annual energy consumption (standard deviation: 3.3%). There are four scenarios in this study associated with four different infiltration rates calculation methodologies. Using default settings in the energy simulation program in scenario 1, the accuracy of the energy simulation result greatly depends on the estimation of the tightness level of building envelope. Although the accuracy of default setting simulations cannot meet the ASHARE guideline requirement, appropriate estimation of building envelope tightness could improve simulation accuracy by 9% of coefficient of variation of the root mean square error (CVRMSE) and normalized mean bias error (NMBE) at most. Multi-zone modeling approach is employed to calculate the infiltration rates in scenarios 2–4, which relatively increases the accuracy of energy simulations. However, various sources of wind pressure loads result in different simulation accuracy levels. In scenarios 3 and 4, coupling CFD0 in multi-zone modeling could provide the wind pressure load profile that takes building geometry, weather profiles, and surroundings into account. The reduction of the CVRMSE and NMBE indicates that coupling CFD0 improves energy simulation accuracy. Compared to the simulation results associated with default setting and database, the simulations using monthly and yearly inputted infiltration rates have more accurate results. In this case study, the ranges of CVRMSE and NMBE of energy simulation associated with different infiltration rates calculations are 3–11% and 2–11%, respectively. Accurate estimation and simulation of air infiltration rates is playing an important role in the accuracy of building energy simulation results. A coupled CFD-multi-zone methodology should be selected in energy simulations to estimate infiltration rates to account for the complexity of building configuration, weather profile, and surrounding terrain and sheltering effect.

References

[1] P.I. Sandberg, E. Sikander, Airtightness issues in the building process, in: Proceedings of the 7th Symposium on Building Physics in the Nordic Countries, 2005, pp. 420–427.
[2] M.W. Liddament, M. Orme, Energy and ventilation, Applied Thermal Engineering 18 (11) (1998) 1101–1109.
[3] M.H. Sherman, Air Infiltration in Buildings, 1980.
[4] S.J. Emmerich, A.K. Persily, Energy impacts of infiltration and ventilation in US office buildings using multizone airflow simulation, in: Proceedings of IAQ and Energy, Vol. 98, 1998, pp. 191–206.
[5] J. Jokisalo, J. Kurnitski, M. Korpi, T. Kalamees, J. Vinha, Building leakage, infiltration, and energy performance analyses for Finnish detached houses, Building and Environment 44 (February (2)) (2009) 377–387.
[6] D. Cóstola, B. Blocken, J.L.M. Hensen, Overview of pressure coefficient data in building energy simulation and airflow network programs, Building and Environment 44 (October (10)) (2009) 2027–2036.

[7] J.L. Weidt, Field air leakage of newly installed residential windows, in: Lawrence Berkeley National Laboratory: Lawrence Berkeley National Laboratory, LBNL Paper LBL-9937, July 2012.
[8] C. Thormark, A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential, Building and environment 37 (4) (2002) 429–435.
[9] J.L. Niu, L.Z. Zhang, H.G. Zuo, Energy savings potential of chilled-ceiling combined with desiccant cooling in hot and humid climates, Energy and Buildings 34 (June (5)) (2002) 487–495.
[10] J. Kurnitski, A. Saari, T. Kalamees, M. Vuolle, J. Niemelä, T. Tark, Cost optimal and nearly zero (nZEB) energy performance calculations for residential buildings with REHVA definition for nZEB national implementation, Energy and Buildings 43 (November (11)) (2011) 3279–3288.
[11] S. Hassid, M. Santamouris, N. Papanikolaou, A. Linardi, N. Klitsikas, C. Georgakis, D.N. Assimakopoulos, The effect of the Athens heat island on air conditioning load, Energy and Buildings 32 (July (2)) (2000) 131–141.
[12] L.C. Ng, A. Musser, A.K. Persily, S.J. Emmerich, Multizone airflow models for calculating infiltration rates in commercial reference buildings, Energy and Buildings 58 (2013) 11–18.
[13] K. Gowri, D.W. Winiarski, R.E. Jarnagin, Infiltration Modeling Guidelines for Commercial Building Energy Analysis, Pacific Northwest National Laboratory, USA, 2009.
[14] D. Cóstola, B. Blocken, M. Ohba, J.L.M. Hensen, Uncertainty in airflow rate calculations due to the use of surface-averaged pressure coefficients, Energy and Buildings 42 (6) (2010) 881–888.
[15] Ashrae, Guideline 14-2002, Measurement of Energy and Demand Savings, American Society of Heating, Ventilating, and Air Conditioning Engineers (ASHRAE), Atlanta, GA, 2002.
[16] C. Younes, C. Abi Shdid, A methodology for 3-D multiphysics CFD simulation of air leakage in building envelopes, Energy and Buildings 65 (2013) 146–158.
[17] M. Bernier, S. Hallé, A critical look at the air infiltration term in the Canadian energy rating procedure for windows, Energy and Buildings 37 (10) (2005) 997–1006.
[18] L.L. Wang, Z. Zhong, An approach to determine infiltration characteristics of building entrance equipped with air curtains, Energy and Buildings 75 (2014) 312–320.
[19] L. Du, R. Zmeureanu, T. Stathopoulos, An empirical model of air displacement by revolving doors, Energy and Buildings 70 (2014) 127–134.
[20] G.M. Richardson, A.P. Robertson, R.P. Hoxey, D. Surry, Full-scale and model investigations of pressures on an industrial/agricultural building, Journal of Wind Engineering and Industrial Aerodynamics 2 (1990) 1053–1062.
[21] Y. Tominaga, A. Mochida, R. Yoshie, H. Kataoka, T. Nozu, M. Yoshikawa, T. Shirasawa, AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings, Journal of Wind Engineering and Industrial Aerodynamics 11 (2008) 1749–1761.
[22] M. Grosso, Wind pressure distribution around buildings: a parametrical model, Energy and Buildings 18 (2) (1992) 101–131.
[23] C. Hirt, J. Cook, Calculating three-dimensional flows around structures and over rough terrain, Journal of Computational Physics 10 (October (2)) (1972) 324–340.
[24] S. Murakami, A. Mochida, K. Hibi, Three-dimensional numerical simulation of air flow around a cubic model by means of large eddy simulation, Journal of Wind Engineering and Industrial Aerodynamics 25 (3) (1987) 291–305.
[25] S. Murakami, A. Mochida, Three-dimensional numerical simulation of turbulent flow around buildings using the k–ε turbulence model, Building and Environment 24 (1) (1989) 51–64.
[26] P.J. Jones, G.E. Whittle, Computational fluid dynamics for building air flow prediction—current status and capabilities, Building and Environment 27 (July (3)) (1992) 321–338.
[27] A. Baskaran, T. Stathopoulos, Computational evaluation of wind effects on buildings, Building and Environment 24 (4) (1989) 325–333.
[28] K. Häggkvist, U. Svensson, R. Taesler, Numerical simulations of pressure fields around building, Building and Environment 24 (1) (1989) 65–72.
[29] H. Montazeri, B. Blocken, CFD simulation of wind-induced pressure coefficients on buildings with and without balconies: validation and sensitivity analysis, Building and Environment 60 (February) (2013) 137–149.
[30] W.S. Dols, NIST Multizone Modeling Website, NIST, Gaithersburg, MD, 2001.
[31] L. Wang, Q. Chen, Theoretical and numerical studies of coupling multizone and CFD models for building air distribution simulations, Indoor Air 17 (5) (2007) 348–361.
[32] G. Tan, L.R. Glicksman, Application of integrating multi-zone model with CFD simulation to natural ventilation prediction, Energy and Buildings 37 (October (10)) (2005) 1049–1057.
[33] M.W. Liddament, Air Infiltration Calculation Techniques: An Applications Guide, Air Infiltration and Ventilation Centre, 1986.
[34] A.H.-F. Ashrae, American society of heating, refrigerating and air-conditioning engineers, Inc. Atlanta (1997).
[35] Air Infiltration Centre, Wind Pressure Workshop: Brussels, Belgium, 21–22 March, 1984: Proceedings, Air Infiltration Centre, 1984.
[36] A.J. Bowen, A wind tunnel investigation using simple building models to obtain mean surface wind pressure coefficients for air infiltration estimates, in: Aero. Estab. Tech. Rep. LPR-LA-209, 1976.
[37] R.E. Akins, J.A. Peterka, J.E. Cermak, Averaged pressure coefficients for rectangular buildings, Wind Engineering 1 (1979) 369–380.
[38] G.N. Walton, AIRNET. A Computer Program for Building Airflow Network Modeling, National Institute of Standards and Technology, Gaithersburg, USA, 1989.
[39] DesignBuilder, DesignBuilder User's Manual, Version 3.0., 2013.
[40] A.K. Persily, Airtightness of Commercial and Institutional Buildings: Blowing Holes in the Myth of Tight Buildings, Building and Fire Research Laboratory, National Institute of Standards and Technology, 1998.
[41] L. Wang, N.H. Wong, Coupled simulations for naturally ventilated rooms between building simulation (BS) and computational fluid dynamics (CFD) for better prediction of indoor thermal environment, Building and Environment 44 (January (1)) (2009) 95–112.
[42] L. Wang, Q. Chen, Applications of a coupled multizone-CFD model to calculate airflow and contaminant dispersion in built environments for emergency management, HVAC&R Research 14 (6) (2008) 925–939.
[43] R. Yoshie, A. Mochida, Y. Tominaga, H. Kataoka, M. Yoshikawa, Cross comparison of CFD prediction for wind environment at pedestrian level around buildings, in: Part, Seoul, Korea, 2005, pp. 2648–2660.
[44] Y. Tominaga, A. Mochida, R. Yoshie, H. Kataoka, T. Nozu, M. Yoshikawa, T. Shirasawa, AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings, Journal of Wind Engineering and Industrial Aerodynamics 11 (October) (2008) 1749–1761.
[45] Y. Tominaga, A. Mochida, S. Murakami, S. Sawaki, Comparison of various revised k–ε models and LES applied to flow around a high-rise building model with 1:1:2 shape placed within the surface boundary layer, Journal of Wind Engineering and Industrial Aerodynamics 96 (April (4)) (2008) 389–411.