Comparing methods of modeling air infiltration through building entrances and their impact on building energy simulations

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ABSTRACT

Building entrance doors are a major source of air infiltration and energy loss in commercial buildings. Previous studies have calculated entrance doors air infiltration and energy saving potential of vestibules with the simplified method which is based on pressure factors. However, challenges are still faced in estimating the pressure difference and the resultant infiltration rates across doors as well as validating the used airflow coefficients under different flow conditions. In this paper, an experimental study is used to validate the airflow coefficient for a fully open single door under both infiltration and exfiltration conditions. The study presents four methods for modeling air infiltration across automatic single and vestibule doors for two reference building models: two methods use the pressure factors and the two others are based on airflow simulations. Energy simulations are then conducted using the air infiltration rates obtained from each method. The results revealed that the design methods overestimate the pressure difference across doors, the air infiltration rates as well as the vestibule savings potentials in comparison to the simulation methods. In conclusion, airflow simulations were found to provide more realistic estimates of pressure differences and infiltration rates across entrance doors when compared to the widely-used design methods.

KEYWORDS

Air infiltration, Entrance doors, Vestibules energy savings, Experimental validation, Airflow and energy simulations

NOMENCLATURES

A	Area
C	Automatic door coefficient (for specific door size)
C_A	Airflow coefficient
C_d	Discharge coefficient
$C_{D, \text{section}}$	Average discharge coefficient for each door operation section
C_{Dave}	Average flow coefficient for a full door operation cycle
CZ	Climate zone
H	Door height

P_h	People per hour (door usage)
Q	Volume flow rate
R_p	Pressure factor
S	Summer season
T_h	Usage per hour (doors)
W	Winter season
ΔP	Pressure difference
ρ	Air density

ABBREVIATIONS

ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineer
Design Method	Design infiltration rates calculation using the R_p factor at 16°C for the whole year
DB	Dry bulb temperature
Fully open door	Door open at 90°
LG	Large store (in the strip mall reference building model)
NIST	National Institute of Standard and Technology
RH	Relative Humidity
Seasonal CONTAM Method	Infiltration rates obtained using airflow simulation for the building with the design conditions of climate zones for two design conditions (summer & winter)
Seasonal Design Method	Design infiltration rates calculation using the R_p factor for two design conditions (summer & winter)
Single door	Double swing doors opening out (without vestibule)
SM	Small store (in the strip mall reference building model)
US. DOE (DOE)	United States Department of Energy
Vestibule door	Vestibule with double swing doors opening out (2 set of double swing doors)
Yearly CONTAM Method	Infiltration rates obtained using yearly whole building airflow simulations

1 INTRODUCTION

The building sector (residential, commercial and institutional) in the United States was reported to account for approximately 40% of primary energy usage nationwide [1]. A study on U.S. office buildings indicated that, in modern well-constructed and insulated buildings, air infiltration can be responsible for up to 25% of the building heating loads [2]. ASHRAE defines air infiltration as the uncontrolled inward leakage of outdoor air into building caused by the existence of a pressure deferential across the various building enclosure elements [3]. Entrance doors, which in commercial buildings are often automatic doors, are generally one of the major sources of air infiltration especially when they are used frequently [4], [5]. Based on the available studies [5], [6] regarding automatic doors, current building energy codes (such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers - ASHRAE Standard 90.1 – Energy Standard for Buildings Except Low-Rise Residential Buildings [3], as well as the International Energy Conservation Code) require entrances to be equipped with vestibules (vestibule doors) in most commercial buildings to reduce air infiltration.

The study conducted by Yuill in 1996 [5] on the impact of use of automatic doors and the infiltration reduction of vestibules is one of the most cited up to this day. Based on experiments and field observations, Yuill [5] developed an empirical model (Eq. 1) in the form of orifice equation to estimate the infiltration rates through single and vestibule doors. Yuill developed average discharge coefficients for the doors by dividing their opening cycle in four main sections (sections a to d in Eq. 1) which vary based on the door usage frequency [5], [7]. If the pressure difference across a door is known, these coefficients can then be used in the orifice equation to estimate air infiltration rates through building entrances. In this paper, we refer an entrance with vestibule to “a vestibule door”, and without vestibule to “a single door” [7].

$$Q = C_{Dave} A T_h \sqrt{\frac{2\Delta P}{\rho}} \quad (1)$$

Where C_{Dave} is the overall average discharge coefficient,

$$C_{Dave} = \frac{C_{D_a}a + C_{D_b}b + C_{D_c}c + C_{D_d}d}{a + b + c + d}$$

$C_{D, \text{section (a,b,c,d)}}$ is the average discharge coefficient for each door operation section,

a, b, c & d are the time period (in seconds) for each door operation section based on field observations

T_h is the door usage per hour (h/h),

A is the full door size (m^2),

ΔP is the pressure difference across the door (Pa), and

ρ is the air density (kg/m³).

Further simplifications (e.g. Eq. 2) were made by Yuill to the model [5], [7]. Charts were developed to directly obtain overall air coefficient, C_A , which depends on the door usage frequency and the door type, and simplified pressure charts for the pressure factor, R_p , were also suggested [7]. Based on a number of assumptions, the pressure factor, R_p , was suggested to be used as a design value for the pressure difference across the door [5]. These assumptions are, (1) steady winds of 6.7 m/s (15 mph) with no correction for terrain, (2) the location of the neutral pressure plane at the building's mid-height, and (3) that the draft coefficient to be 0.9 [5]. The value of R_p , which can also be obtained from the charts given, depends only on the height of the building and the outdoor temperature [4], [5].

$$Q = C_A A R_p \text{ or } Q = C_A A \sqrt{\Delta P} \quad (2)$$

Or for a known door size

$$Q = C R_p \text{ or } Q = C \sqrt{\Delta P}$$

Where C_A is the overall air coefficient (single door or vestibule door) or C is the overall door coefficient (m³/s Pa^{1/2}),

R_p is the pressure factor obtained from ASHRAE and based on the outdoor temperature and building height [8], and ΔP is the pressure difference across the door.

In the original study by Yuill [5] and in ASHRAE publication [8] where these design charts appear, it is stated that if the assumptions regarding the R_p do not hold, the calculation of the pressure difference across the door should be completed by considering the stack and wind pressures in more details. Yuill [5], [7] also suggested using of airflow network models for more realistic estimations of the pressure difference across the door. In these simulations, the door can experience flow in two directions, infiltration or exfiltration. Despite the wide use of door coefficients suggested by Yuill [5] in many studies [6], [9]–[14], none of these subsequent studies experimentally verified the coefficients proposed, especially for the exfiltration flow region.

Building energy simulation has become a common tool in measuring the impact of various envelope related characteristics on energy use. The U.S. Pacific Northwest National Laboratory (PNNL) published a report where they investigated the energy saving impact of vestibules in commercial reference buildings [4]. The reference building models of the national building stock, which were developed by a number of national laboratories in collaboration with the U.S. DOE, are used in the

development, assessment, and research of new technologies and codes (DOE and PNNL use these reference models for the development of new ASHRAE Standard 90.1 Versions) [15]. These reference models are available online as input files for the widely used energy simulation program EnergyPlus [16]. In their study [4], PNNL used EnergyPlus [16] to conduct simulations for 12 reference building models in 16 climate zone locations. The study [4] used the models proposed by Yuill [5], [8] to calculate the infiltration rates through single and vestibule doors in buildings that have building specific door usage and operation schedules. To quantify the pressure across the doors in their study, PNNL used the R_p factor charts in ASHRAE [8] while adding the assumption that, for all the buildings in all climate zone (which vary from arctic to very hot climate), the outdoor temperature is constant at 16 °C [4]. The PNNL study used the pressure coefficient (R_p) to consider pressure difference (ΔP) across the door and a sensitivity study was also conducted to see the impact of temperature variations on the results using the R_p factor charts of ASHRAE [8]. In addition, they completed the study assuming that the size of main entrance doors in all buildings types are 0.9 m $\times$ 2.1 m (W $\times$ H) [4]. The results of their study showed that vestibule doors can result in national weighted energy savings [15], [17] of a maximum of 5.61% in the strip mall building and a minimum of 0.03% in the outpatient healthcare building. The currently available ANSI/ASHRAE/IES Standard 90.1 Prototype Building Models, which are readily used by researchers [1], [4], [18]–[21], include the single vestibule infiltration rates calculated from the PNNL study (based on constant outdoor temperature of 16 °C in all climate zones) as a separate input, besides all the other modeled building leakages [4].

In a study by Mahajan et al. [11], an analytical method was proposed to calculate the pressure difference across automatic doors and to calculate their infiltration rates using the coefficients proposed by Yuill [5]. The process, which is validated by comparison to field data, was used to calculate the infiltration rates through the single and vestibule doors in the standalone restaurant reference building model for two design days [11]. It was concluded that building specific infiltration rates calculated can differ greatly from those proposed by the PNNL study [4] and while still indicating that vestibule doors can reduce air infiltration through the entrance door of the reference building studied [11]. However, no energy simulations were conducted for the building and it was indicated that this process was limited to only certain door configurations and hardly applicable for annual building simulations [11].

Recently, to better quantify infiltration through buildings, the U.S. National Institute of Standards and Technology (NIST) developed multi-zone airflow network models of all the DOE reference buildings [22], which makes it possible to calculate detailed annual whole building infiltration rates [13], [23]. Based on the NIST airflow simulation software CONTAM [24], these multi-zone airflow network models use transient weather data to calculate transient air infiltration (through openings

and leakages) at each time step simulated. This method thus provides more realistic estimations for air infiltration since they consider the outdoor weather, internal zonal/system interactions, stack effect etc. in the buildings [22]. The studies conducted by Wang et al. [12], [13], [25] and Goubran et al [9], which aimed to assess the energy savings realized by the use of air curtain doors (in comparison to vestibule doors), utilized the CONTAM reference building models [22] to calculate yearly air infiltration. Wang used a coupled CONTAM-TRNSYS model to calculate the yearly energy savings in heating and cooling generated by the air infiltration reductions (achieved from the use of the air curtain) in the medium office DOE reference building model in 8 climate zones [13] (the study does not use the ASHRAE 90.1 EnergyPlus model). The use of TRNSYS [26] in Wang's study was mainly justified by the availability of the data interface with CONTAM [13]. However, no studies have been found that utilized either coupled or uncoupled CONTAM-EnergyPlus simulations for the study of energy impact of building entrances.

To summarize the literature review, four different methods have been available for modeling building entrance infiltration for building energy simulation purposes:

1. *Design infiltration calculation method (hereafter, Design Method)* – Following the process proposed by ASHRAE [8] and used by the PNNL's study for the vestibule requirements of ASHARE 90.1 [4], the design pressure difference across the door is calculated for each building based on the R_p factor at 16 °C and used in Eq. 2. The data obtained using this method is used as the baseline for the study considering it is the method often used by PNNL [15].
2. *Seasonal design infiltration calculation method (hereafter, Seasonal Design Method)* – Similar to the Design Method method, the R_p factor is calculated and used. However, the climate specific winter and summer design temperatures are used to calculate the pressure differences across the doors of each climate zone location.
3. *Seasonal design infiltration simulation method (hereafter, Seasonal CONTAM Method)*: using the airflow building models [22] for the simulation software CONTAM [24], the seasonal door infiltration rates for each door type in both buildings is obtained by simulations using the design conditions. Only the door infiltration rates from the airflow simulations are used as input in the energy model to replace the existing door infiltrations
4. *Yearly infiltration simulation method (hereafter, Yearly CONTAM Method)*, similar to the Seasonal CONTAM Method, yearly transient airflow simulations are used. The hourly infiltration rates of the whole building in the different climate zones are exported and input in the energy model.

It is important to note that methods 1 and 2 focus only on the entrance door and are based on calculations while methods 3 and 4 use airflow simulations which consider all the building parameters and climate conditions. Although the four methods use Yuill's model for single and vestibule door infiltration (Eq. 2), the main difference between the presented methods lay in the calculation of pressure difference across the door: in methods 1 and 2 the pressure coefficient is used to calculate the pressure difference, and for methods 3 and 4 the pressure difference across the door is obtained by CONTAM simulations, which take into account various building and weather parameters [22]. The validity of the CONTAM simulations of the DOE reference buildings can be further found from the study by Ng et al. [22].

This paper compares four different methods for calculating building entrance air infiltration rates. It also investigates the corresponding impact of these methods on whole building annual energy performance using EnergyPlus simulations. Since Yuill's infiltration coefficients were developed using chamber depressurizations mostly for door infiltration conditions [5], for the airflow simulations in this study of both infiltration and exfiltration, the paper presents an experimental verification to confirm the single fully open (90°) door airflow coefficients suggested by Yuill [1] under negative infiltration (exfiltration) condition. In Yuill's study, he first measured steady-state flow discharge coefficients without considering door opening and people movement for different door opening angles, and then in the second step, he proposed a method to consider these effects using an idea of effective opening area during a full opening/closing cycle of door. For Yuill's model, the HVAC on/off effect, if any, will be reflected in the pressure difference during the calculation of infiltration/exfiltration rates. Therefore, in both Yuill's and this study's experiments, there is no need to consider them. In this study, we focus on his first step (without door movement and people) and try to verify his flow coefficients in the negative flow region (exfiltration). For this purpose, the door movement, people and HVAC are not required to be captured in the experimentation. Comparisons are made between the air infiltration rates and the end use energy consumption obtained through each method. The paper uses the ASHRAE 90.1-2013 strip mall and outpatient healthcare reference building models [27] and the corresponding airflow network models [22] to conduct energy and airflow simulations for the buildings with single and vestibule doors in three climate zone locations. In addition, the sensitivity of the results to different aspects such as the door usage frequency and door size are also presented.

2 METHODOLOGY

2.1 *Experimental validation*

This study uses an experimental chamber (the CUBE in Figure 1) of $2.44 \text{ m} \times 2.44 \text{ m} \times 1.30 \text{ m}$ ($L \times W \times H$) with a double swing door of $0.61 \text{ m} \times 0.71 \text{ m}$ ($W \times H$), which is the same size as that used by Yuill in his study [5] representing a 1/3 sub-

scale of a real building. The chamber is equipped with a duct fan [28] to pressurize or depressurize the enclosure. The pressure difference across the door, ΔP , is recorded based on the average pressure measurements at four points in the chamber's mid-depth plane (between the door and the fan) in comparison to a reference pressure outside of the enclosure. The air volumetric flow rates through the fan, which are equivalent to those through the door due to mass balance, were measured using the DG-700 model pressure transducer that was furnished with the fan [29]. The flow rates were recorded at different pressure difference conditions with the doors open at 90° . All the experimental data were recorded based on 10 seconds time averaged readings. In order to ensure the repeatability, all measurements were repeated at least once and averaged for the final readings. The experimental data measured is then directly compared to the theoretical curve obtained based on the findings of Yuill [5] for the same case. Based on the instrument error, the averaged pressure measurements had a random error range of $\pm 1.3\%$ or ± 0.21 Pa (whichever is larger). The volumetric flow rate had both random instrumental error as well as systematic errors due to the chamber leakages which, in total, were about $\pm 9\%$ or ± 0.02 m^3/s (whichever is larger).

Figure 1. The CUBE experimental chamber – picture of the laboratory setup (left, courtesy of MĚKANIC) and location of the pressure reading points/nodes within the chamber (right)

The experimental setup used was able to achieve a maximum pressure difference across the door of 1.3 Pa (with 0.38 m^3/s of flow through the door) and a minimum of -0.85 Pa (with -0.24 m^3/s of flow). A final total of 10 averaged data points for the air flow and pressure differences were reported by using 20 measurements acquired with two data points for each pressure condition. The paper focuses on validating the discharge coefficient suggested by Yuill [5].

2.2 Building models parameters

For this study, the ASHRAE 90.1-2013 strip mall and outpatient healthcare reference building models [15], [27] are used to investigate the impact of air infiltration calculation on energy consumption in three climate zone (CZ) locations. In order to have an array of different weather conditions, the study uses CZ 3A - Memphis, CZ 5A - Chicago and CZ 7 - Duluth.

The commercial reference building models, weather files and simulation software that are used in this study are as follows:

- for the building energy simulations, the ANSI/ASHRAE/IES Standard 90.1 Prototype Building Models that are compliant with ASHRAE 90.1-2013 are used [15]. Separate and unique models for each climate zone location are available as EnergyPlus input files.
- for the multi-zone airflow network models, the “New-Construction” versions of the NIST models of DOE Reference Commercial Buildings are used [22]
- TMY3 weather data files [30] for the 3 climate zone locations are used in the simulations. TMY3 files are compatible with EnergyPlus and the weather file creator tool [31] was used to convert them to compatible formats for CONTAM
- EnergyPlus [16] Version 8 & CONTAM [24] version 3.1 are used
- The buildings are simulated with their default north orientations in both software.

More details of the models and their inputs can be found in the appropriate literature sources [15], [22] and technical sources [27]. Some key information regarding the models and weather files that are relevant to this study are presented in Table 1 and Table 2. It is important to note that the outpatient healthcare building is a much more complex model which includes more than 110 zones with only one main entrance door. However, the strip mall building only consists of 8 small stores (SM) and two large stores (LG) which all have individual entrances.

Table 1. Strip mall and outpatient healthcare reference buildings models details [15], [22], [27]

	Strip Mall Building	Outpatient Healthcare Building
Height (m)	5.19	9.15
Gross floor area (m ²)	2070	3767.4
Footprint area (m ²)	2070	1255.8
Entrance zone (m ²)	345 (LG); 172 (SM)	1008.3
Number of zones	10	118
Number of entrance doors	10 (10 stores)	1 (Lobby Zone)

Entrance door (s) azimuth from north	180°	270°
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Table 2. Summer (S for July 21st) and winter (W for January 21st) design conditions based on the TMY3 weather files

Climate zone	City	Season	DB (°C)	RH (%)	P (Pa)	Wind speed (m/s)	Wind direction on design day (° from north)	Weighted average seasonal wind direction (° from north)
3 (A)	Memphis	W	-8.3	100	100356	4.1	0	188
		S	35.6	43.51	100356	3.8	240	179
5 (A)	Chicago	W	-20	100	98934	4.9	270	219
		S	33.3	45.06	98934	5.2	230	182
7	Duluth	W	-28.6	100	96230	4.6	310	240
		S	29.2	48.18	96230	5.2	220	197

In order to simplify the simulation process, the door usage schedules of the models were modified. A unified schedule for both buildings was used (Table 3). This simplification would allow the impact of the infiltration calculation methods to be comparable across the two buildings used in this study. In addition and in order to simplify the analysis, the calendar year has been divided into two “seasons”, namely summer and winter (Table 3).

Table 3. Door operation schedule and seasons details

Door usage	Strip Mall Building	Outpatient Healthcare Building
Time of the day	8:00 AM to 8 PM	
Schedule days	All Week - All Year	
Summer	March to August	
Winter	September - February	

2.3 Air infiltration calculation and modeling

As mentioned previously, four methods are used to calculate air infiltration through doors in this study. The detailed calculation/simulation process of each method is as follows (details seen in Table 4):

1. *Design Method* – Based on the assumptions described previous, the door infiltration rates in the two buildings are calculated using Eq. 2. Only one rate is calculated for each building at each door usage. The rates are used as input in

EnergyPlus as design flow rate zone infiltration replacing the existing door infiltration in the model. A schedule is then used to control the door operation.

2. *Seasonal Design Method* – A process similar to that used in the Design Method is followed while calculating two infiltration rates for each building at each door usage; one rate corresponding to the winter and the other to the summer season design conditions. A program within the energy model then selects different infiltration rates based on the season.
3. *Seasonal CONTAM Method* – Steady state airflow simulations for the two seasons’ design conditions are conducted for the buildings in each climate zone location. The infiltration rates obtained from simulation are then input to EnergyPlus and are used similar to the Seasonal Design Method. For this method, the design conditions presented in Table 2 are inputs in CONTAM (for each location and each season).
4. *Yearly CONTAM Method* – A whole year airflow simulation with hourly outputs is completed with doors in the airflow model following the same door operation schedule used in the energy simulation (Table 3). The results are exported from CONTAM using the “CONTAM Results Export Tool” developed by NIST [32], [33]. Since the infiltration exported from CONTAM contains all the building infiltration (not only that of doors), all the infiltration in energy models are replaced by the exported CONTAM infiltration data.

5. **Table 4.** Assumptions and modeling process for the 4 infiltration methods presented

Modeling Method	Assumptions	Modeling
<i>Design Method</i>	R_p used assuming constant temperature of 16°C all year in all locations.	Door air filtration rates for each building are calculated and input in EnergyPlus for all the year (wall leakage inputs are not changed).
<i>Seasonal Design Method</i>	R_p used while considering the summer and winter design conditions for each location.	Summer and winter door air filtration rates are calculated for each building in each location and input with a seasonal schedule in EnergyPlus (wall leakage inputs are not changed).
<i>Seasonal CONTAM Method</i>	Pressure difference is simulated (using CONTAM) not assumed. Summer and winter design conditions are used.	Summer and winter door air filtration rates obtained for each building in each location and input with a seasonal schedule in EnergyPlus (wall leakage inputs are not changed).
<i>Yearly CONTAM Method</i>	Pressure difference is simulated (using CONTAM) not assumed. Annual hourly air infiltration rates for the whole buildings are obtained.	Air infiltration rates obtained for each building zone are input in EnergyPlus replacing all original infiltration inputs in the model.

It is important to note that in each of the four methods, single and vestibule door cases are both simulated. In CONTAM, entrance doors are modeled using the one way flow - power law model, where the flow coefficient is the door coefficient [5], C , and the flow exponent is equal to 0.5 [9], [13], [25]. In EnergyPlus, when using methods 1, 2 and 3, door infiltration is modeled as design rate in Zone Infiltration category [4]. When using the Yearly CONTAM Method (method 4), a process of zone matching was required due to some differences between the airflow models and the energy models were found [22]. When using method 4, the infiltration rates obtained from CONTAM (hourly infiltration rates by zone) are modeled in EnergyPlus as design rate in Zone Infiltration category and replace the original infiltration inputs in the energy model. The changes made to the original CONTAM and EnergyPlus models are detailed in Table 5.

Table 5. Changes made to the original CONTAM [22]and EnergyPlus models [15]

Modeling Method	CONTAM	EnergyPlus
<i>Design Method</i>	NA	The original door infiltration rates and schedules are replaced by the calculated infiltration rates based on $2\text{ m} \times 2.4\text{ m}$ door. The door usage frequency is $100 P_h$ (except the sensitivity study when the usage is varied) and the doors are used from 8 AM to 8 PM. The infiltration is modeled as design rate in zone infiltration category.
<i>Seasonal Design Method</i>		
<i>Seasonal CONTAM Method</i>	Single and vestibule door models ($2\text{ m} \times 2.4\text{ m}$) are added to the CONTAM models and modeled using the power-law model based on Yuill's findings [5].	The original door infiltration rates and schedules are replaced by the infiltration rate obtained from CONTAM.
<i>Yearly CONTAM Method</i>	The door usage frequency is $100 P_h$ (except the sensitivity study when the usage is varied) and the doors are used from 8 AM to 8 PM.	The original door infiltration and wall leakage is removed. The hourly zone infiltration rates for the whole year is used in the energy models and is used as design rate input in zone infiltration category.

For this study, following PNNL's method [4], the single doors for each case are used as the baseline for the calculations of the air infiltration/energy reductions obtained from vestibule door (Eq. 3 and Eq. 4).

$$\text{Reduction} = \text{Single Door} - \text{Vestibule Door} \quad (3)$$

$$\% \text{ Reduction} = \frac{\text{Reduction}}{\text{Single Door}} \quad (4)$$

The overall door coefficients, C , used for all the methods in this paper, are based on the flow coefficient, C_a , obtained from Yuill [5] for single and vestibule doors (Eq. 2). The door coefficients depend on the door usage frequency as well as the door size. In this paper, $100 P_h$ door usage frequencies and $2\text{ m} \times 2.4\text{ m}$ door size are used as the baseline of comparison (Table 6 shows C for a $2\text{ m} \times 2.4\text{ m}$ door at different door usage values). The pressure differences, ΔP , across the doors presented in

Table 7 are calculated based on the R_p values obtained from ASHRAE [8]; where $\Delta P = R_p^2$. The pressure differences presented in Table 7 are only used in the Design and Seasonal Design Methods and they depend on the building height and outdoor temperature.

Table 6. Door coefficients, C , for the single and vestibule doors of $2 \text{ m} \times 2.4 \text{ m}$ at varying door usage frequencies, P_h , based on Yuill's study [5].

Ph	Single Door	Vestibule Door
0	0.000	0.000
10	0.058	0.034
50	0.274	0.163
100 (baseline)	0.538	0.326
200	1.018	0.643
400	1.766	1.166

Table 7. Pressure difference, ΔP , for different outdoor temperatures across the door for the two building models calculated based on R_p obtained from ASHRAE [8].

Outdoor Temperature (°C)	Entrance Pressure Difference (Pa)	
	Strip Mall Building	Outpatient Healthcare Building
38	18.92	17.81
27	19.45	19.10
16 (baseline)	20.16	20.52
4	20.79	22.09
-7	21.44	23.52
-18	22.18	25.30
-29	23.04	27.35
-40	24.01	29.16

In total, more than 100 EnergyPlus energy simulations and 50 CONTAM airflow simulations have been conducted for this study.

3 RESULTS AND DISCUSSION

3.1 Experimental validation

The comparison between the experimental and theoretical results [5] are presented in Figure 2. In the negative pressure difference range, the difference between the extrapolated Yuill's infiltration curve for the single door and the experimental results is 5.9% proving the accuracy for Yuill's model [5]. It is important to note however that, the average overall calculated difference between the experimental results and the infiltration curve obtained from Yuill's [5] model is 3.48%. This indicates that in the negative pressure region a higher difference can be observed. In addition, the average calculated flow coefficient, C_D , for the experimental results is 0.62, which is similar to that obtained by Yuill [5]. However the C_D in the positive pressure region was calculated to be 0.60 and in the negative pressure region range it was calculated to be 0.67. This indicated that the airflow in the chamber can experience slightly different resistance based on the direction of the flow through the door. The average error for the pressure difference measurements was calculated to be $\pm 1.3\%$ or ± 0.21 Pa. The average bias error for the air flow measurements (for all the experiments conducted) was calculated to be $\pm 9\%$ or ± 0.02 m³/s (based on tests conducted on the air tightness of the chamber and the error range of the equipment used). Finally based on the small differences calculated, the experimental data presented in Figure 2 provide a validation for the flow coefficients of the single door case reported in Yuill's study in the negative as well as the positive flow directions [5].

Figure 2. Volume flow rate and pressure difference measurements obtained at the chamber door in comparison to the theoretical infiltration curve calculated based on Yuill's model [5].

3.2 Airflow and energy simulations

As indicated, the Design Method adopted by the PNNL's study on the vestibule requirements for the ANSI/ASHRAE/IES Standard 90.1 [4] will be used as the baseline of comparison for this paper. The pressure difference across the entrance doors (single and vestibule doors) obtained by using the four proposed methods is presented and discussed followed by the comparison of infiltration rates obtained. The annual energy consumption of the two building models and the effect of the infiltration calculation method on the results are discussed. Finally, the effect of different parameters, such as the size of the door and the door usage frequency is presented.

3.2.1 Pressure difference across the entrance doors

As previously indicated, the pressure differences across the entrance doors are one of the major causes for the differences in the air infiltration calculation methods. When using the Seasonal Design Method, the pressure difference across the door varied from the baseline (Design Method) in the strip mall building by an average of 10.8% in winter and -4.8% in summer and in the outpatient healthcare building by an average of 26.9% in winter and -25.4% in summer (Figure 3). In their study, PNNL conducted the sensitivity study to calculate the impact of outdoor temperatures on air infiltration rates through door openings, they found variations of only up to 7% [4]. The seasonal difference observed in the strip mall building is close to PNNL's finding. The bigger difference observed in the outpatient healthcare building is mainly due to its larger building height. Since the Seasonal Design Method uses R_p , which depends only on the outdoor temperature and building height, the type of the door and its usage rate have no effect on the calculated pressure difference across the doors.

Figure 3. ΔP across door using the Seasonal Design Method for the strip mall building (left) and the outpatient healthcare building (right) at 100 P_h

When comparing the pressure differences across the entrance doors obtained using the Seasonal CONTAM Method to the baseline, significant differences can be observed (Figure 4). Differences exceeding 100% are observed in cases where negative pressure differences across the entrance doors exist especially during the summer season. When using the Seasonal and Yearly CONTAM Methods (which both use airflow simulations), the type of the door (single or vestibule door) and its usage affect the calculated pressure difference across the door. The vestibule door is seen to experience, on average, higher pressure differences in winter and lower pressure differences in summer in comparison to the single door. This higher pressure difference is due to the higher resistance vestibule having on airflow.

Figure 4. ΔP across door using the Seasonal CONTAM Method for the strip mall building (left) and the outpatient healthcare building (right) at 100 P_h.

When using the Yearly CONTAM Method, the pressure difference across the doors highly varies throughout the year (Figure 5 shows an example for the outpatient healthcare building in CZ-5A). It is important to note that the pressure difference across the door never reaches the baseline value calculated using the Design Method. The pressure difference seen throughout the year in Figure 5 indicates that the design conditions used in the Seasonal CONTAM Method (presented in Table 2) do not necessarily coincide with the maximum or minimum pressure differences obtained by the yearly airflow simulation. This is due to the fact that the airflow simulations depend on many factors such as the wind speed and direction as well as stack effect created by the difference in temperatures [22].

Figure 5. ΔP across the door using the Yearly CONTAM Method for the outpatient healthcare building at 100 P_h in CZ-5A

Figure 3, Figure 4 and Figure 5 illustrate that the pressure differences across the entrance door calculated based on the R_p exceed those achieved by the airflow simulations significantly for both buildings in all studied climate zones.

3.2.2 Infiltration Rates

When using the Seasonal Design Method to calculate the infiltration rates (Eq. 2), infiltration rates in summer are lower than the baseline calculated using the Design Method and infiltration rates in winter exceed the baseline. In the strip mall building, summer infiltration rates differed on average by -2.5% in summer and 5.2% in winter from the baseline case for both the single and vestibule doors (Figure 6). In the outpatient healthcare building, the calculated rates differed from the baseline by -5.2% and 11.5% in summer and winter respectively (Figure 6). For both buildings, the highest difference in the winter infiltration is seen in the coldest climate zone (CZ 7) and highest difference in the summer infiltration is seen in warmest climate (CZ 3A). The air infiltration reduction obtained from the Design and Seasonal Design Methods are similar in each building for each door usage frequency. The vestibule door reduced 38.7% of the single door infiltration in the two building at 100 P_h door usages. When varying the door usage frequency, the vestibule is seen to reduce 41.1% at 10 P_h and 33.9% at 400 P_h from the single door infiltration in both buildings (Figure 8).

Figure 6. Infiltration rate through the doors of the Seasonal Design Method for the strip mall building (left) and the outpatient healthcare building (right) at 100 P_h

As suggested by the pressure difference data presented in Figure 4 for the Seasonal CONTAM Method, the infiltration data obtained by (Figure 7) indicates negative airflow (exfiltration) through the doors in a number of climate zones during the summer design conditions. In the strip mall building, exfiltration is only seen in the warmest climate zone with the summer design conditions. In the outpatient healthcare building, exfiltration is seen in all the climate zones when simulated with the summer design conditions. In the strip mall building, summer infiltration rates differed on average by -101.6% and -75.6% in winter from the baseline (Design Method) for both the single and vestibule doors. In the outpatient healthcare building, average difference in summer was calculated to be -106.8% and -71.3% in winter (Figure 7).

Figure 7. Hourly average infiltration rate through the doors using of Seasonal CONTAM Method for the strip mall building (left) and the outpatient healthcare building (right) at 100 P_h

When compared to the Design and Seasonal Design Methods, the Seasonal CONTAM Method suggests that vestibules reduce much less infiltration across all the climate zone locations. Unlike the Design and Seasonal Design Methods, the Seasonal CONTAM Method shows that the air infiltration reduction achieved by vestibules depends on the climate conditions and building parameters. The results of the airflow simulations for the Seasonal CONTAM Method indicate that the ability of vestibules to reduce air infiltration decreases in colder climate zones (Table 8). In the strip mall building, a maximum average reduction of 11.5% is achieved in winter in CZ 5A while the lowest air infiltration reduction of -1.95% is achieved in summer in CZ 7 for a 100 P_h door usage. The simulation results for the strip mall building suggests that, under specific building and climate conditions, vestibule doors can increase the exfiltration in summer. In the outpatient healthcare, the maximum reduction was 12.24% in CZ 5A during winter and a minimum reduction was 3.57% in CZ 7 in summer for a 100 P_h door usage. These reductions are much lower than those calculated using the Design or Seasonal Design Method.

Table 8. Infiltration rate reduction achieved by the vestibules in comparison to single doors at 100 P_h using the Seasonal CONTAM Method (in comparison the Design Method - baseline)

	Strip Mall Building			Outpatient Healthcare Building		
	Seasonal CONTAM Method		Design Method (baseline)	Seasonal CONTAM Method		Design Method (baseline)
	S	W		S	W	
3A - Memphis	9.41%	11.02%	38.74%	12.24%	10.45%	38.74%
5A- Chicago	5.88%	11.50%		8.60%	12.24%	
7 - Duluth	-1.95%	11.37%		3.57%	11.82%	

When comparing the air infiltration reduction of vestibule doors with different door usage rates, the Seasonal CONTAM Method suggests a very strong decline in the reductions with increasing door usage in both buildings (Figure 8 shows an example for CZ-5A). When using the Seasonal CONTAM Method, vestibule infiltration reductions in the two buildings decrease by almost 90% between 10 P_h to 400 P_h . In the strip mall building, the average difference between the infiltration rates calculated using the Seasonal CONTAM Method and the Design Method at 10 P_h is 67.4% and 95.4% at 400 P_h . While in the outpatient healthcare building, the difference was 78.1% at 10 P_h and 96.3% at 400 P_h .

Figure 8. Vestibule air infiltration reduction obtained using the Seasonal CONTAM Method in the strip mall building (left) and in the outpatient healthcare building (right) in CZ-5A with different door usage rates.

The data presented in Table 6 and Figure 8 indicates that the Design and Seasonal Design Methods overestimate the ability of vestibule doors to reduce air infiltration in buildings when compared to the Seasonal and Yearly CONTAM Methods.

3.2.3 Energy Simulations

Generally, the annual whole building energy use of the strip mall building is more affected by door infiltration when compared to the outpatient healthcare building. This is mainly due to the fact that all the strip mall's 10 zones have entrance doors while in the outpatient healthcare building only 1 zone out of 118 has an entrance door. This is also why the energy saving from vestibules compared to single doors was found to be the most for the strip mall and the least for the outpatient healthcare among all the building types in the PNNL's study [4]. The energy simulations conducted (Figure 9 and Figure 10) for the two buildings using the 4 different infiltration methods suggest that using R_p values (the Design and the Seasonal Design Methods) can lead to significant overestimations in the end-use energy consumption of the energy models as well as in the whole building energy reductions achieved by vestibule doors (in comparison to single doors). Using the Seasonal Design Method led to the highest end-use energy consumption in both buildings as well as the highest vestibule energy reductions. In the strip mall building, the maximum end-use energy consumption was found, when simulated with the Design Method in CZ 7 with single door, to be 4680.7 MJ/m^2 as opposed to 1453.2 MJ/m^2 when simulated with the Seasonal CONTAM Method (68% difference). In the outpatient healthcare building, the maximum end-use energy consumption was obtained when simulated with the Design Method in CZ 7 with single door at 3176.9 MJ/m^2 as opposed to 1368.5 MJ/m^2 when simulated with the Seasonal CONTAM Method (56% difference). The maximum whole building energy reduction

achieved by vestibules was achieved for both buildings in CZ 7 when simulated with Seasonal Design Method; the vestibule doors reduced 32.3% of the energy in the strip mall and 8.97% in the outpatient healthcare building when compared to single doors. It is hereby noted that the energy reduction from using vestibules is found significantly higher in this study than that by the previous PNNL vestibule study [4] as shown in Figs. 9 and 10. The difference can be explained by several reasons: this study modeled a $2\text{ m} \times 2.4\text{ m}$ (4.8 m^2) door, which is about 2.5 times bigger and thus more resultant infiltration than that in the PNNL study (we need to use 4.8 m^2 door to be consistent with another companion project); the 2010's PNNL study was based on EnergyPlus v3.1 and associated prototype buildings compared to v8.0 used in this study so many changes of the software and code requirements may affect the results; a longer door operation schedule was used (8 AM – 9 AM) and thus more frequent use of doors in this study than the PNNL's. Another note here is that the main focus of this paper is not to try to replicate a previous study of PNNL but to compare the impact of different methods on modeling infiltration and their energy implications so it may serve the purpose of drawing attentions on modeling building infiltration, which is often overlooked/underrated otherwise, for building energy modeling community.

It is also observed that using the Seasonal CONTAM Method resulted to the lowest end-use energy consumption due to lowest infiltration and energy use in the buildings. Based on the results presented, it is concluded that the airflow simulations, especially the Yearly CONTAM Method, can provide more conservative estimates of the vestibule end-use energy reductions.

Figure 9. End-use energy consumption (left) and vestibule energy reduction (right) in the strip mall building at 100 P_h using the 4 methods of infiltration modeling.

Figure 10. End-use energy consumption (left) and vestibule energy reduction (right) in the outpatient healthcare building at 100 P_h using the 4 methods of infiltration modeling.

The impact of infiltration on the whole building end-use energy consumption is shown by Table 9 and Table 10. When using the design and seasonal design methods, infiltration is calculated to be responsible for approximately 80% of the strip mall building's annual energy use and approximately 18% in the outpatient healthcare building (for the single door cases). When using the Yearly or seasonal CONTAM methods, infiltration is calculated to be responsible for approximately 40% of the strip mall building's annual energy use and approximately 8% in the outpatient healthcare building (for the single door cases). Thus, the impact of infiltration obtained by simulation is approximately half that of infiltration obtained through calculation. The higher impact of infiltration in the strip mall building is due to the existence of doors in each of the 10 zones while in the outpatient healthcare building only 1 zone has an entrance door. The infiltration impact calculated for the Seasonal and Yearly CONTAM methods is much conservative and falls within the ranges reported in previous studies [2], [34] while the infiltration impact calculated by the Design and Seasonal Design methods exceeds these ranges.

Table 9. Infiltration impact on building end-use energy as percentage in the strip mall building with 100 P_h door usage

City		Single Door				Vestibule			
		Design	Seasonal Design	Seasonal CONTAM	Yearly CONTAM	Design	Seasonal Design	Seasonal CONTAM	Yearly CONTAM
3(A)	Memphis	72.89%	73.36%	23.90%	26.27%	62.43%	62.98%	21.65%	25.14%
5(A)	Chicago	81.77%	82.27%	44.91%	48.13%	73.59%	74.24%	41.84%	46.05%
7	Duluth	84.88%	85.43%	51.31%	54.72%	77.73%	78.48%	48.29%	53.00%

Table 10. Infiltration impact on building end-use energy as percentage in the strip mall building with 100 P_h door usage

City		Single Door				Vestibule			
		Design	Seasonal Design	Seasonal CONTAM	Yearly CONTAM	Design	Seasonal Design	Seasonal CONTAM	Yearly CONTAM
3(A)	Memphis	13.15%	13.75%	4.40%	7.95%	9.06%	9.48%	4.18%	7.79%
5(A)	Chicago	16.29%	17.72%	1.97%	11.41%	9.56%	10.64%	1.38%	10.91%
7	Duluth	22.68%	24.17%	5.50%	16.58%	15.26%	16.70%	4.80%	16.07%

When simulating the buildings with different door usage frequencies, this study found that again, using the R_p (Design and Seasonal Design Methods) suggests that vestibule doors can maintain high energy reductions even up to 400 P_h (Figure 11). This conclusion is unrealistic because the energy reduction performance from vestibules will certainly decrease with higher frequency of door usages. In comparison, using the airflow simulations (Seasonal CONTAM and Yearly CONTAM Methods) indeed illustrates a decreasing reduction trend with increased door usages in both buildings. Considering the continuous entrance door operation at door usages of 400 P_h , the limited ability of vestibules in reducing whole building energy usage obtained from the Seasonal and Yearly Methods CONTAM are considered more realistic.

Figure 11. Vestibule end-use energy reduction reduction in the strip mall building (left) and in the outpatient healthcare building (right) at CZ 5A for different door usage rates

3.2.4 Effect of Door Size

Finally, energy simulations were conducted for the strip mall building considering different door sizes (Figure 12) in CZ-5A using the Design Method and Yearly CONTAM Method. The Design Method yields higher reductions from vestibules with larger doors and higher door usage rates. The Yearly CONTAM Method however, indicates that a maximum saving can be

achieved for each door size at different usage rates. For the largest door size used ($2.4 \text{ m} \times 4 \text{ m}$), the Design Method vestibules yielded energy reductions of more than 30% with door usage of $400 P_h$, while only 0.11% energy reduction is calculated with Yearly CONTAM Method (more than 99% difference in the results of both methods). It is worthy to mention that when simulating the strip mall building with conditions similar to that in PNNL study [4] (with the smallest door - $2 \text{ m} \times 1 \text{ m}$ - at the lowest door usage and using the Design Method - seen on the far left of Figure 12), the vestibule door reduced 6.14% of the annual whole building energy when compared to the single door (which, considering the different model version used in this study, agrees well with the 6.86% reported by PNNL in the same climate zone for the same building).

Figure 12. Vestibule end-use energy reduction in the strip mall building with different door size in CZ-5A.

In summary, the Yearly CONTAM Method is considered to provide the most realistic estimates for the infiltration rates and the energy impacts for building entrances of different sizes. This is due to the more sophisticated calculations used in the airflow simulations (i.e. based on weather conditions, building conditions and internal building/system interactions) considered in the Yearly CONTAM Method.

4 CONCLUSION

Air infiltration through entrance doors is one of the leading causes of energy loss in commercial buildings. A good estimate of the pressure difference across the doors still remains one of the main challenges to realistically estimate air infiltration in buildings. An experimental study by Yuill [5] proposed using the pressure factor, R_p , to estimate pressure differences across doors and airflow coefficients, which were developed in the study, in the orifice equation to estimate the infiltration through

automatic single and vestibule doors. Based on this study suggestions, the current reference building energy models [15] include door infiltration rates calculated based on R_p and airflow coefficients while assuming of steady temperature through all climate zones. However, other studies [11] have indicated that using R_p can lead to large errors due the assumptions used for its development. More recent studies [13], [14], [22] used multi-zone airflow models and weather files to estimate the pressure differences across doors which lead to air infiltration. These studies indicate that airflow simulations can provide more realistic estimates of infiltration since they consider weather, building and internal interaction parameters.

Using a chamber similar to the one used by Yuill [5], an experimental validation for the discharge coefficient of a fully open single door was conducted within a pressure range of -0.85 Pa to 1.2 Pa. Yuill's study focused on the infiltration (positive pressure difference range) while the testing conducted in this study focused on both infiltration and exfiltration conditions. The experimental results validated the coefficients reported by Yuill [5] in the negative flow direction (exfiltration). A 5.9% average difference between the measurements and the theoretical infiltration curve in the negative pressure range was calculated and an overall difference of 3.48% for the entire test points (in both the positive and negative range).

The study then investigated the impact of infiltration calculation methods on the reductions in infiltration and whole building annual end-use energy consumption. The study used the ASHRAE 90.1-2013 strip mall and outpatient healthcare reference building energy models [27] and the corresponding airflow models for the building [22] to conduct EnergyPlus energy and CONTAM airflow simulations respectively. The study proposed four different infiltration calculation methods:

1. The Design Method (baseline): which follows the same assumptions and methods used by the developers of current reference building energy models [4]
2. The Seasonal Design Method: where the value of the R_p is calculated based on the summer and winter design conditions
3. The Seasonal CONTAM Method: which uses simulation on the multi-zone airflow models of the building to calculate the air infiltration through the doors at the seasonal design conditions of each climate location
4. The Yearly CONTAM Method: which uses yearly airflow simulations for the building to calculate the zone specific air infiltration rates of all the building

Analysis the pressure differences obtained across the entrance doors, the Seasonal Design Method showed differences of more than 25% in winter and -25% in summer when compared to the baseline. When airflow simulations are used (Seasonal and Yearly CONTAM Methods), higher pressure differences were observed across the vestibule door (in comparison with

the single door), suggesting that the pressure difference across the door is affected by the type of door. This effect is neglected when the R_p factor is used. When using the Seasonal CONTAM Method, negative pressure differences across the doors led to differences from the baseline exceeding 100%. Finally, The Yearly CONTAM Method showed highly variant pressure difference across the door through the year which suggests a more realistic estimation that is building and hourly weather conditions.

The infiltration rates calculated using the Design and Seasonal Design Methods suggest that vestibule doors can reduce single door air infiltration by more than 30% at door usage of 400 P_h and more than 40% at 10 P_h . The Seasonal CONTAM Method showed maximum reductions of up to 25% at 10 P_h with a decline of more than 90% in reduction with higher door usage. The results obtained by airflow simulation suggest a significant decline in the vestibule's effectiveness in reducing air infiltration at higher door usage rates; is more realistic considering the high traffic condition of the doors.

The energy simulations conducted for the building showed that the Design and Seasonal Design method result in very high end-use energy consumption in both buildings when compared to the methods that use airflow simulations (Seasonal and Yearly CONTAM Methods). In addition, the vestibule end-use energy reduction calculated using the Design Method exceeds 30% in some cases where the Yearly CONTAM Method showed reductions below 10%. The results of the energy simulations suggested that the infiltration modeling methods that use R_p to calculate pressure difference (Design and Seasonal Design Methods) can result in exaggerated vestibule energy reductions. Based on the analysis of the data, it was observed that the Yearly CONTAM Method, considering its sophistication, provided more realistic vestibule reductions for both buildings. In addition, when looking at the infiltration impact on energy consumption, the impact calculated by CONTAM methods falls within the ranges found in literature [2], [34] while the impact calculated by the Design methods generally exceeds these ranges.

Finally, energy simulations conducted for the strip mall building with different door sizes indicated that the Design Method shows growing vestibule energy reductions with higher door usage and large doors. In contrast, the Yearly CONTAM Method showed that vestibules are much less effective in frequently used large doors than in smaller ones. In addition, a coherence in the reported values was evident when comparing the results of cases similar to existing studies [4].

The comparison between the infiltration rates and energy simulation results presented in this study suggest that the simplified methods based on pressure factors, R_p , which were used for the development of the vestibule requirements in the current building standards/codes, may overestimate vestibule energy performance, and users should use their results with caution. In

comparison, using airflow simulation models, e.g. based on an airflow network program, CONTAM, can provide more realistic estimates that consider local weather as well as building specific parameters.

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REFERENCES

- [1] W. Jiang, K. Gowri, M. Lane, B. Thornton, and B. Liu, “Technical Support Document: 50% Energy Savings Design Technology Packages for Highway Lodging Buildings,” *Pacific Northwest Natl. Lab.*, no. September, 2009.
- [2] S. J. Emmerich and A. K. Persily, “Energy Impacts of Infiltration and Ventilation in U.S. Office Buildings Using Multizone Airflow Simulation,” in *IAQ and Energy 98 Conference*, 1998, pp. 191–203.
- [3] ASHRAE, *ASHRAE standard 90.1-2010: Energy Standard for Buildings Except Low-Rise Residential Buildings*. 2010.
- [4] H. Cho, B. Liu, and K. Gowri, “Energy Saving Impact of ASHRAE 90.1 Vestibule Requirements: Modeling of Air Infiltration through Door Openings,” *Pacific Northwest Natl. Lab.*, no. November, 2010.
- [5] G. K. Yuill, “Impact of High Use Automatic Doors on Infiltration,” Pennsylvania, 1996.
- [6] Nicklas Karlsson, “Air Infiltration through Building Entrances,” Chalmers University of Technology, 2013.
- [7] G. K. Yuill, R. Upham, and C. Hui, “Air leakage through automatic doors,” *ASHRAE Trans.*, vol. 106, no. 2, pp. 145–160, 2000.
- [8] ASHRAE, *ASHRAE Handbook–Fundamentals*. Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., 2009.
- [9] S. Goubran, D. Qi, and L. (Leon) Wang, “Annual Energy Saving Impact of Air Curtains in Commercial Reference Buildings,” in *ISHVAC-COBEE*, 2015, p. 8.

- [10] G. Verhaeghe and M. Van Belleghem, "Study of air curtains used to restrict infiltration into refrigerated rooms," in *7th International conference on Heat Transfer, Fluid Mechanics and Thermodynamics (HEFAT 2010)*, 2010, p. 8.
- [11] G. Mahajan, H. Cho, K. Shanley, and D. Kang, "Comprehensive modeling of airflow rate through automatic doors for low-rise buildings," *Build. Environ.*, vol. 87, pp. 72–81, 2015.
- [12] L. (Leon) Wang and Z. Zhong, "An approach to determine infiltration characteristics of building entrance equipped with air curtains," *Energy Build.*, vol. 75, pp. 312–320, Jun. 2014.
- [13] L. (Leon) Wang, "Investigation of the Impact of Building Entrance Air Curtain on Whole Building Energy Use," 2013.
- [14] D. Qi, S. Goubran, R. Zmeureanu, and L. L. Wang, "Effect of People on Infiltration of Building Entrance with Air Curtains," in *ISHVAC-COBEE*, 2015, p. 9.
- [15] M. Deru, K. Field, D. Studer, and K. Benne, "US Department of Energy commercial reference building models of the national building stock," *Natl. Lab. U.S. Dep. Energy*, no. February 2011, 2011.
- [16] US DOE, "EnergyPlus Engineering Reference," *Ref. to EnergyPlus Calc.*, 2010.
- [17] R. Jarnagin and G. Bandyopadhyay, "Weighting Factors for the Commercial Building Prototypes Used in the Development of ANSI/ASHRAE/IESNA Standard 90.1," *Pacific Northwest Natl. Lab.*, no. January, 2010.
- [18] B. Thornton, W. Wang, Y. Xie, H. Cho, B. Liu, and J. Zhang, "Achieving the 30% Goal : Energy and Cost Savings Analysis of ASHRAE Standard 90.1-2010," *Pacific Northwest Natl. Lab.*, p. 370, 2011.
- [19] K. Gowri, D. Winiarski, and R. Jarnagin, "Infiltration Modeling Guidelines for Commercial Building Energy Analysis," *Contract*, no. September, p. 21, 2009.
- [20] J. Zhang, R. Athalye, R. Hart, M. Rosenberg, and Y. Xie, "Energy and Energy Cost Savings Analysis of the IECC for Commercial Buildings," *Pacific Northwest Natl. Lab.*, no. August, 2013.
- [21] B. Thornton, W. Wang, Y. Huang, M. Lane, and B. Liu, "Technical Support Document: 50% Energy Savings for Small Office Buildings," *Pacific Northwest Natl. Lab.*, no. April, 2010.
- [22] L. C. Ng, A. Musser, A. K. Persily, and S. J. Emmerich, "Airflow and indoor air quality models of DOE reference commercial buildings," 2012.
- [23] L. C. Ng, S. J. Emmerich, and A. K. Persily, "An Improved Method of Modeling Infiltration in Commercial Building Energy Models," in *2014 ASHRAE/IBPSA Building Simulation Conference*, 2014, pp. 308–315.
- [24] "CONTAM User Manual." [Online]. Available: <http://www.bfrl.nist.gov/IAQanalysis/CONTAM/userguide.htm>.

[Accessed: 01-Dec-2015].

- [25] L. (Leon) Wang and Z. Zhong, “Whole Building Annual Energy Analysis of Air Curtain Performance in Commercial Building,” in *eSim Building Performance Simulation Conference*, 2014.
- [26] “TRNSYS.” [Online]. Available: <http://sel.me.wisc.edu/trnsys/features/>. [Accessed: 01-Dec-2015].
- [27] “Commercial Prototype Building Models | Building Energy Codes Program,” *U.S. Department of Energy*. [Online]. Available: <https://www.energycodes.gov/commercial-prototype-building-models>. [Accessed: 01-Dec-2015].
- [28] “Minneapolis Duct Blaster® System - The Energy Conservatory.” [Online]. Available: <http://products.energyconservatory.com/minneapolis-duct-blaster-system/>. [Accessed: 04-Dec-2015].
- [29] “DG-700 Pressure and Flow Gauge - The Energy Conservatory.” [Online]. Available: <http://products.energyconservatory.com/dg-700-pressure-and-flow-gauge/>. [Accessed: 04-Dec-2015].
- [30] D. Crawley, “Which weather data should you use for energy simulations of commercial buildings?,” *Am. Soc. Heat. Refrig. Air-conditioning*, pp. 1–18, 1998.
- [31] “CONTAM Weather File Creator.” [Online]. Available: <http://www.bfrl.nist.gov/IAQanalysis/software/WEATHERprogram.htm>. [Accessed: 04-Dec-2015].
- [32] National Institute of Standards and Technology, “CONTAM Results Export Tool Description,” *National Institute of Standards and Technology*, 2014. [Online]. Available: http://www.bfrl.nist.gov/IAQanalysis/webapps/contam_results_exporter/desc.htm. [Accessed: 23-Mar-2015].
- [33] B. Polidoro, L. C. Ng, W. S. Dols, and S. J. Emmerich, “NIST Technical Note 1873: CONTAM To EnergyPlus Infiltration Features of the CONTAM Results Export Tool,” Gaithersburg, 2015.
- [34] J. Jokisalo, J. Kurnitski, M. Korpi, T. Kalamees, and J. Vinha, “Building leakage, infiltration, and energy performance analyses for Finnish detached houses,” *Build. Environ.*, vol. 44, no. 2, pp. 377–387, 2009.

FIGURE CAPTIONS

Figure 1. The CUBE experimental chamber – picture of the laboratory setup (left, courtesy of MĚKANIC) and location of the pressure reading points/nodes within the chamber (right)

Figure 2. Volume flow rate and pressure difference measurements obtained at the chamber door in comparison to the theoretical infiltration curve calculated based on Yuill's model [1].

Figure 3. ΔP across door using the Seasonal Design Method for the strip mall building (left) and the outpatient healthcare building (right) at 100 Ph

Figure 4. ΔP across door using the Seasonal CONTAM Method for the strip mall building (left) and the outpatient healthcare building (right) at 100 Ph

Figure 5. ΔP across the door using the Yearly CONTAM Method for the outpatient healthcare building at 100 Ph in CZ-5A

Figure 6. Infiltration rate through the doors of the Seasonal Design Method for the strip mall building (left) and the outpatient healthcare building (right) at 100 Ph

Figure 7. Infiltration rate through the doors using of Seasonal CONTAM Method for the strip mall building (left) and the outpatient healthcare building (right) at 100 Ph

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Figure 11. Vestibule end-use energy reduction reduction in the strip mall building (left) and in the outpatient healthcare building (right) at CZ 5A for different door usage rates

Figure 12. Vestibule end-use energy reduction in the strip mall building with different door size in CZ-5A.