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A Characterization of time-dependent air infiltration rates in retail stores using calibrated multi-zone model

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The main goal of this article is to quantify the time-dependent air infiltration rates for two retail stores using a calibrated multi-zone model. The calibration focused on the automatic entrance doors as the flow element with significant infiltration rates. This study examined the application of a modified leakage airflow element for automatic entrance doors to predict physical conditions, including differential pressures and airflow rates across the doors. The results show that the simulation of differential pressures across the entrance doors was consistent with the measured data after the model used the corrected flow coefficient (C) based on an hourly rate of people passing through the doors. The airflow rates through the automatic entrance doors represented 75%–80% of the total air infiltration and accounted for 12%–19% of the total ventilation rates. Furthermore, installing a door vestibule decreased the infiltration airflow rates through the automatic entrance doors by approximately 23%. Overall, the present study proposes and validates a method based on the calibrated multi-zone model to quantify the time-dependent infiltration rates in retail buildings.

Introduction

Unlike other commercial buildings, retail buildings are assumed to have airtight building envelopes. However, air infiltration rates for retail buildings were approximately two to four times higher than the rates observed in schools and office buildings due to the frequently used entrance doors (Shaw 1981; Zaataria et al. 2014). Retail buildings have a small number of critical openings, including the automatic entrance doors that represent main paths for air infiltration. Many studies found that the use of automatic doors brought large amounts of air infiltration, and the infiltration rates significantly increased as the frequency with which the doors were used increased (Simpson 1936; Min and Ala 1958; Kohri 2001; Yuill et al. 2000). Kohri (2001) calculated the airflow rates through the automatic entrance doors in an office building based on the observations that the door opening area increased as the number of people using the automatic entrance doors increased. The infiltration rates ranged from 2100 to 4280 L/s (4450–9070 cfm) through the entrance doors with the door opening area ranging from 2.5 to 3.7 m^2 (27–40 ft^2) and a traffic passage of 40 to 370 people per hour. Several studies provided methods for estimating infiltration rates through automatic doors based on the door opening area, number of people using the door, and pressure differences across the doors (Simpson 1936; Min and Ala 1958; Yuill et al. 2000). For commercial buildings, the measured infiltration rates through the operating entrance doors with an area of 3.2 m^2 (ft^2) varied from 65 to1590 L/s (140–3370 cfm; (Simpson, 1936), and the infiltration rate measured through a single door was up to 12,270 L/s (26,000 cfm; Min and Ala, 1958). Table 1 summarizes the air infiltration rates through automatic entrance doors measured in the existing commercial buildings.Yuill et al. (2000) also provided the airflow coefficient (C_a) for the orifice equation to estimate airflow rates through several automatic doors with and without a vestibule found in typical retail buildings and healthcare facilities. The entrance vestibule is the passage area located between entrance and interior doors before entering to the building. Figure 1 presents the characteristic of entrance door with a vestibule and without a vestibule. Calculating infiltration rates using the airflow coefficient requires the time-dependent number of people using a door and the differential pressure across that door.

To save energy consumed due to the air infiltration through the entrance doors, ASHRAE 90.1-2010 required a vestibule for building entrances (ASHRAE 2010). Previous studies showed that installing a door vestibule could potentially save energy demand ranging from 1% to 9% for the whole building (Cho et al. 2010; National Renewable Energy Laboratory [NREL] 2012). Installing the door vestibule reduced amount of air infiltration through the entrance doors by 18% to 25% (Simpson 1936). This range is lower than the values of 50% to 60%, observed by Min and Ala (1958), and 30% to 40%, observed by Yuill et al. (2000). The difference in these observations could be explained by the pressure differential at

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Table 1. Air infiltration rates through automatic entrance doors measured in commercial buildings.

Study	Door type	Airflow rate, L/s (cfm)	Airflow rate per door area, L/s.m^2 (cfm/ ft^2)	ACH, h^{-1}
Simpson (1936)	Without vestibule	86–1590 (180–3370)	27–497 (5.3–98)	n/a
	With vestibule	65–1304 (140–2760)	20–408 (3.9–80)	n/a
Kohri (2001)	Without vestibule	1070–4640 (2270–9830)	290–1250 (57–250)	0.30–1.30[a]
	With vestibule	720–4280 (1530–9070)	190–1160 (37–230)	0.20–1.20[a]
Cho et al. (2010)	Without vestibule	200–1420 (420–3010)	102–710 (20–140)	0.05–0.36
	With vestibule	120–940 (250–1190)	62–469 (12–92)	0.03–0.23
Bennett et al. (2012)	n/a	n/a	n/a	0.30–4.80

[a] Based on the entrance hall volume.

the entrance doors and the number of people passing through the doors. For example, Cho et al. (2010) calculated infiltration rates through the automatic entrance doors during the peak and off-peak hours using the orifice equation with the flow coefficient developed by Yuill et al. (2000). The calculated infiltration rates through the doors without a vestibule were 33% higher than the infiltration rates through the doors with a vestibule. Previous studies also found that the operation of entrance doors made a significant contribution to the air exchange rates of entire buildings (Vatistas et al. 2007; Bennett et al. 2012). The investigation in an experimental room showed that air infiltration through an operating door accounted for 47% of the total outdoor airflow rate (Vatistas et al. 2007). Another study showed that the commercial buildings in which the doors were kept open most of the time had air exchange rates 1.5 to 2 times greater than the rates observed for the buildings in which the doors were kept closed (Bennett et al. 2012). Overall, for the infiltration rates in commercial buildings, the previous studies have shown that the entrance door operation conditions, including the pressure differential and number of people passing through the doors, are as important as the door type, including the presence and absence of the vestibule.

A multi-zone model, CONTAMW, has been successfully used to calculate airflow rates and contaminant dispersion influenced by the wind, buoyancy effect, mechanical ventilation, and/or building operation schedules (Walton and Dols 2005). However, the multi-zone model result accuracy depends on the accuracy of the model inputs (Persily and Ivy 2001). Therefore, several studies have proposed a calibrated multi-zone modeling approach for ventilation analyses as applied to case studies of institutional, residential, and office buildings (Musser et al. 2001; Firrantello et al. 2007; Saekow 2010; Snyder 2011). For the air infiltration analysis, Musser et al. (2001) adjusted the envelope leakage in the model using the measured data from the fan pressurization tests. Most studies calibrated the airflow direction through the interior doors by adjusting the airflow rates using the air distribution system and opening the interior doors (Firrantello 2007; Saekow 2010; Snyder 2011). The leakage characteristics of building envelopes and exterior doors in these existing models were derived from building-specific measurements (Persily and Ivy 2001; ASHRAE 2009). Another study adjusted only the number of leakage paths in the building envelope to correct the total ventilation rates (Townsend et al. 2009). According to the previous studies, the airflow rates at the supply/return diffusers and the number/size of leakage pathways are considered for the calibration of multi-zone models. However, existing studies did not examine the model calibration to accurately account for air infiltration through the automatic entrance doors, even though this pathway represents a major source of air infiltration.

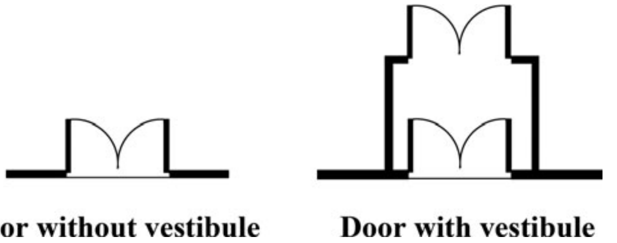


Fig. 1. Characteristics of the automatic entrance doors with vestibule and without vestibule.

According to the existing literature, accurate quantification of infiltration rates in commercial buildings is possible, but it requires a calibration of a multi-zone model that is building type specific. Specifically, the studies on the calibration of the multi-zone models were performed in institutional, residential, and office buildings where structural characteristics differ from retail buildings. Consequently, the existing calibration methods and adjusted parameters might not be appropriate to assess the infiltration rates for retail buildings. Therefore, to understand air infiltration characteristics that are influenced by retail building airflow pathways and operation schedules, the present study developed and validated a calibrated multi-zone model to calculate realistic time-dependent air infiltration rates through automatic entrance doors and building envelopes in two retail buildings. The implementation of this calibrated multi-zone model can be further used to investigate the impact of air infiltration through the automatic entrance doors on indoor air pollutant associated with outdoor contaminant as well as building energy consumption in different types of retail stores.

Methodology

The multi-zone model, CONTAMW (Walton and Dols 2005),was used to calculatethe hourly differential pressures and airflow rates across automatic entrance doors. The buildings studied during this research included a big-box general merchandise store (Building A) located in Pennsylvania (zone 5A) and one-story small grocery store (Building B) located in Texas (zone 2A) (Jareemit 2014). Table 2 presents additional details for the two retail building case studies. The multi-zone model used actual meteorological year (AMY) measured data for the calibration and a separate dataset for the model validation. These weather datasets were collected on April 10, 2012, for Building A and on August 3, 2012, for Building B. The data are provided in the final project report (Siegel et al. 2013).

The calibration procedure for the air infiltration model during store operating hours involved the following two steps:

1. Update the airflow coefficient for the automatic entrance doors based on the hourly number of people passing through the doors and
2. Adjust the diffuser airflow rates based on the measured supply airflow rates.

In the first step, the initial airflow rates used the measured airflow rates from the ventilation system. The supply airflow rate at each of the rooftop units was measured using TrueFlow metering plates installed at the filter location. The flow measurement accuracy of this device is ±7% of the reading. The total supply airflow rate measured in Building A was 28,000 ± 1960 L/s (59,330 ± 4150 cfm), and the measured supply airflow rate for Building B was 3400 ± 238 L/s (7200 ± 500 cfm). As the return airflow rates were not measured during the data collection period, it was assumed that the return airflow fraction (R) was approximately 0.9 of the supply airflow rate. The return airflow fraction is defined as follows:

$$R = \frac{return\ airflowrate}{supply\ airflowrate} \tag{1}$$

The outdoor air fraction was calculated from a mass balance for CO_2 concentration using the following equation:

$$OA(\%) = \frac{(CO_{2RTU} - CO_{2Indoor})}{(CO_{2Amb} - CO_{2Indoor})} \times 100\%, \tag{2}$$

where OA is the outdoor air fraction (in%), CO_{2RTU} is the CO_2 concentration at the supply air stream in the rooftop unit (RTU) (in ppm), $CO_{2Indoor}$ is the average CO_2 concentration in the retail area (in ppm), and CO_{2Amb} is the outdoor CO_2 concentration (in ppm).

All CO_2 sensors with the measurement accuracy of ±50 ppm or approximately 5% of the reading were calibrated with a CO_2 sensor with the measurement accuracy of ±0.5% of the reading. Five CO_2 sensors were used to measure the indoor CO_2 concentration, and one sensor was used to measure the ambient CO_2 concentration. In Building B, CO_2 sensors were installed at the supply airflow stream in all rooftop units to continuously collect the data every 5 min for 5 days. In Building A, it was impossible to install the CO_2 sensors in all 23 rooftop units due to insufficient number of CO_2 sensors. Consequently, in Building A, only one handheld CO_2 sensor was used for a short time interval measurement of CO_2 concentrations in each rooftop unit approximately for 3 to 5 min.

In addition to the measurement of airflow rates in the rooftop units, this study used a multi-zone model, CONTAMW, to calculate airflow rates through leakage areas and closed openings. The leakage area for exterior walls and roof was 6.9 cm^2/m^2 (0.1 in^2/ft^2) and in loading doors was 0.45 cm^2/m^2 (0.007 in^2/ft^2), obtained from Appendixes C2 and C3 in Persily and Ivy (2001). The total envelope leakage area for Building A was approximately 4.9 m^2 (53 ft^2) and Building B was 1.2 m^2 (13 ft^2), which was relatively lower than the door area of 8 m^2 (82 ft^2) for Building A and 4 m^2 (43 ft^2) for Building B. The investigation of airflow through automatic entrance doors used a calibrated multi-zone model. In the simulation model, the setting of leakage characteristics for the automatic entrance door uses the orifice equation, also known as the power law model, as follows:

$$Q = C\Delta P^n \tag{3}$$

where Q is the airflow through the opening (in L/s [cfm]), C is the flow coefficient (in L/s.m^2.Pa$^{0.5}$ [cfm]), ΔP is the pressure difference (in Pa [in. H_2O]), and n is the flow exponent (dimensionless). This airflow model allowed the flow coefficient and the flow exponent to be adjusted. The modified flow coefficient in Equation 3 was developed from the following equation:

$$Q = C_a A \Delta P^n \tag{4}$$

where the measured door area A for Building A was 7.6 m^2 (82 ft^2) and for Building B was 4 m^2 (43 ft^2). According to a relevant study, flow coefficient n obtained from the laboratory test was 0.5 (Yuill et al. 2000). Furthermore, the calculation of the airflow coefficientC_a (in m/s.Pa$^{0.5}$ [cfm/(ft^2.in.$H_2O^{0.5}$)]), accounts for the number of people using the door per hour, N (h^{-1}). Figure 2 shows the correlations between the airflow coefficient and the number of people passing through the doors hourly with and without a vestibule. These two correlations were obtained from the experimental data available in the literature (Yuill et al. 2000). Therefore, airflow coefficient C_a for the swinging door without a vestibulein Building B used the following equation:

$$C_a = -0.0024N^2 + 4N \tag{5}$$

The set of swinging door with a vestibule, present in Building A, used the following equation:

$$C_a = -0.0014N^2 + 3N \tag{6}$$

Differential pressure ΔP and the number of people passing through the automatic entrance doors N in Equation 3 were obtained from field measurements. A pressure sensor with an accuracy of 1% in its readings connected to a hobo logger

Table 2. Comparison of case studies of buildings that differ in size.

Scale		Building A	Building B
Store type		Big-box general merchandise store	Small grocery store
Climate zone		Moderate-to-cold (Zone 5A)	Hot and humid (Zone 2A)
Total floor area		11,330 m^2 (121,960 ft^2)	1180 m^2 (12,700 ft^2)
Retail area fraction		83%	69%
Total volume		66,600 m^3 (2,352,000 ft^3)	5,390 m^3 (190,300 ft^3)
Number of floors		1	1
HVAC system	Number of rooftop unit	23 RTUs	2 RTUs
	Operation system	Constant air volume	Constant air volume
Operating hours		8:00–22:00	7:00–23:00
Air change rate (h^{-1})		0.69	0.63

was installed at the entrance to measure differential pressures across the automatic entrance doors. The sensor was connected to one side of a rubber tube. The other side of the tube was run to the outside of the retail store entrance doors. The differential pressure across the automatic entrance doors was collected every 5 min for 5 days. To observe the hourly rate of people passing through automatic entrance doors, N, in Building A, a field technician installed a thermal imaging people-counter sensor at the ceiling over the exit door only. It was assumed that the number of people passing through the exit door would be approximately equal to the number of people passing through the entrance door within an hour. The people-counter data were compared to the transaction rates recorded at the store check-out counters. The average hourly rate of people passing through the automatic entrance doors was approximately 1.3 times greater than the average rate observed at the store check-out counters. Nevertheless, Building B did not have a people counter, so the hourly rate of people passing through the doors was estimated from the hourly transaction rates recorded at the check-out counters using a multiplication factor of 1.3. Figure 3 shows the hourly transaction rate obtained at the check-out counter and the adjusted number of people passing through the automatic entrance doors in Buildings A and B.

Figure 4 shows the calculation of the flow coefficient, C, in relation to the hourly rate of people passing through the automatic entrance doors. In Building A, flow coefficient C ranged from 0.4 to 1.6 $m^3/s/Pa^{0.5}$ (1240–4970 cfm/ in.$H_2O^{0.5}$), whereas the flow coefficient calculated for Building B ranged from 0.03 to 0.38 $m^3/s/Pa^{0.5}$ (90–1180 cfm/in.$H_2O^{0.5}$).

Flow coefficient C, calculated from Equations 5 and 6, was then updated in Equation 3, representing the leakage chracteristics for the automatic entrance doors in the simulation model. The calculated differential pressure obtained from the simulation model was compared with the results from the field experiment and then deployed in the calculations of the airflow rates across the entrance doors.

In the second step, the model was further calibrated by adjusting the diffuser airflow rates to perfect the amplitude of the differential pressure across the automatic entrance doors. Specifically, the return airflow fraction was adjusted to 85% ($R = 0.85$) and 95% ($R = 0.95$) of the supply airflow rate from the initial setting of 90% ($R = 0.90$) in the base case model. The

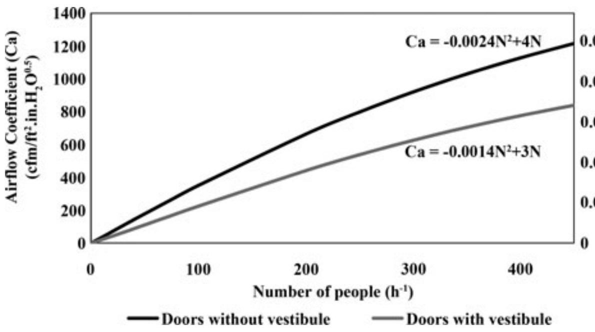


Fig. 2. Experimental correlations for the airflow coefficient and number of people passing through the door per hour for automatic swinging doors with and without a vestibule (data from Yuill et al. 2000).

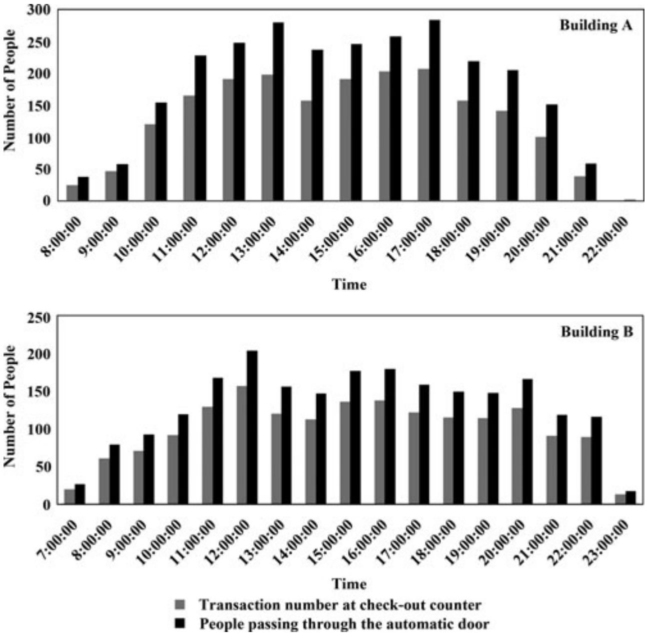


Fig. 3. Comparison of the hourly transaction rates at the check-out counters and the adjusted number of people passing through the automatic entrance doors for Buildings A and B.

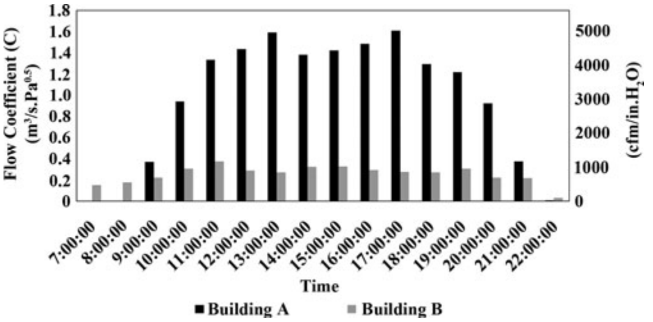


Fig. 4. Calculated values of hourly flow coefficient *C* for automatic swinging doors with a vestibule.

study compared the impact of the changes in the return airflow fractions on the differential pressures and airflow rates across the automatic entrance doors. The quality of the simulation results were evaluated with six statistical models, including the correlation coefficient, the regression intercept regression slope, normalized mean square error, the index of bias, and the fractional variance, provided in Standard ASTM D5157 (ASTM 2008).

Calibration results for differential pressures across automatic entrance doors

Figure 5 presents the model calibration results for the differential pressures across the automatic entrance doors for Buildings A and B. After airflow coefficient *C* for the leakage airflow element was corrected based on the hourly rate of people passing through the automatic entrance doors, the model provided realistic results pertaining to the door pressure differences and airflow rates. The simulated differential pressures across the automatic entrance doors agreed well with the values observed from the field measurements. However, even when Building B was pressurized, air infiltration was found at the automatic entrance doors, represented by the negative differential pressures in Figure 5b. These specific conditions occurred during the hours when the entrance doors experienced direct wind flow, resulting in external air pressures being higher than the internal air pressures due to the mechanical system airflows.

This present study calculated correlation coefficients to investigate a relationship between the wind direction/speed and the number of people passing through the automatic entrance doors per hour, associated with the differential pressures across the automatic entrance doors. The hourly rate of people passing through the automatic doors had a high correlation with the differential pressures across the automatic entrance doors for both buildings, specifically, the correlation coefficient $r = 0.75$ for Building A and $r = 0.78$ for Building B. The wind direction had a higher correlation with the differential pressures for Building B ($r = 0.\ 79$) than for Building A ($r = 0.59$) because the entrance door in Building B was located on the windward side of the building. The wind speed had no correlation with the differential pressures for both buildings ($r = 0.22$ for Buildings A and B). Therefore, in the interest of potentially reducing the infiltration rates into retail buildings, it is important to understand that the local wind rose to identify dominant wind directions.

The study evaluated the calibrated multi-zone model performance using six statistical models provided in Standard ASTM D 5157 (ASTM 2008), as shown in Table 3. The calculations of the correlation coefficient, regression intercept, regression slope, normalized mean square error, index of bias (FB), and fractional variance (FS) for both buildings were within the required ranges by Standard ASTM D5157. Therefore, the proposed calibration method using the new airflow element based on the hourly rate of people passing through the automatic entrance doors can provide realistic transient pressure differentials across the automatic entrance doors.

Calculation of airflow rates through automatic entrance doors

The calibrated differential pressures represent an accurate driving force for the calculation of airflow rates through the automatic entrance doors. Therefore, the calibrated multi-zone model was further used to calculate transient airflow rates through the automatic entrance doors. Figure 6 shows the

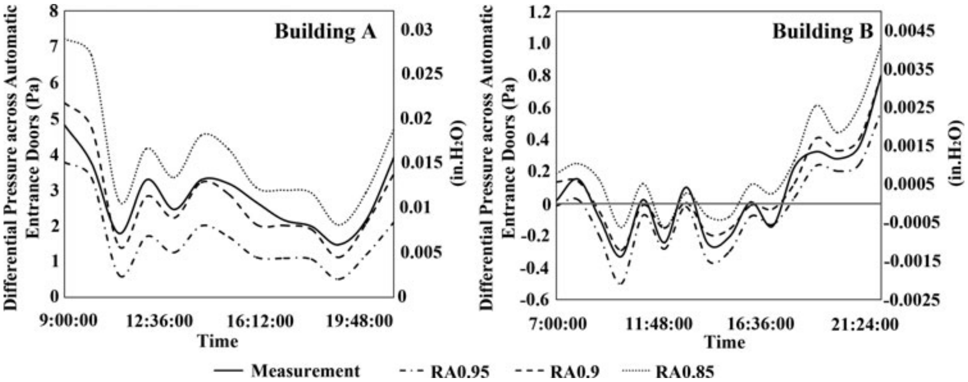


Fig. 5. Calibration results for differential pressures across automatic entrance doors during store operating hours. a. For swinging doors with a vestibule in Building A. b. For swinging doors without a vestibule in Building B.

Table 3. Assessment of model performance based on Standard ASTM D5157 (data from the calibrated multi-zone model with the return airflow rate at 90% of the supply airflow rate).

Cases	Correlation coefficient (>0.9)	Regression slope (0.75 to 1.25)	Regression intercept (25% or less average measured concentration)	NMSE (<0.25)	FB (<0.25)	FS (<0.5)
Building A	0.99	0.96	0.03	0.04	−0.001	−0.33
Building B	0.95	1.1	−1.05	0.01	−0.03	−0.21

NMSE = normalized mean square error.

calculations of transient airflow rates through the automatic entrance doors for Buildings A and B when the buildings operated with the 90% return airflow fraction of supply airflow ($R = 0.90$). The results showed that adding a vestibule reduced the airflow through the automatic entrance doors by approximately 23%. The values of the airflow rates through the automatic entrance doors in Building A were larger than those in Building B, mostly due to the relatively high values of differential pressure across the automatic entrance doors.

Besides the model validation with the measured data, the present study compared the calculated airflow rates normalized by the entrance door area with the rates obtained in three existing studies, as shown in Figure 7 (Simpson 1936; Khori 2001; Cho et al. 2010). The calculated airflow rates through the area of the automatic entrance doors were within the range of values obtained by the existing studies.

The study also compared calculated air infiltration rates through the automatic entrance doors for the current and three existing studies, as shown in Figure 8. The calculated air exchange rates for Building A were not compared because this building had no infiltration through the automatic entrance doors. The calculated exfiltration rate at the entrance door of this building ranged from 0.05 to 0.13 h^{-1}.The air infiltration rates through the automatic entrance doors in Building B accounted for approximately 0.2 h^{-1}. This value was within the range from 0.03 to 0.36 h^{-1} established by Cho et al. (2010). However, it is lower than the values observed in an office building by Khori (2001) and the air exchange rates investigated by Bennett et al. (2012). These results indicate that both Building A and Building B have well-controlled HVAC systems that successfully minimized infiltration rates.

Airflow fraction through building envelopes and entrance doors

To investigate an effect of air infiltration rates on a building's total ventilation rates, the present study compared airflow fractions through air distribution systems and building envelopes, including automatic entrance doors. Figure 9 presents a comparison of the airflow rates calculated with the calibrated multi-zone model when the buildings were operated with the return airflow fractions, R, of 0.85 and 0.90. Overall, when the buildings were operated at a slightly positive pressure with the return airflow fraction of 90% ($R = 0.90$), the total air infiltration rates accounted for 12% to 19% of the total ventilation rates for Buildings B and A, respectively. For Building B, the air infiltration rates through the automatic entrance doors represented 84% to 87% of the total air infiltration rate beings approximately 0.2 h^{-1}. The calculated air infiltration rate per the entrance door area was ranging from 75–100 $L/s.m^2$, which was relatively high when compared to the air infiltration through the leakage area on the building envelope being approximately 23 $L/s.m^2$. In Building A, the infiltration originated from the walls located on the windward building side, and no air infiltration was found at the automatic entrance doors. The air infiltration rates through the envelopes represented 19% of the total ventilation rate being approximately

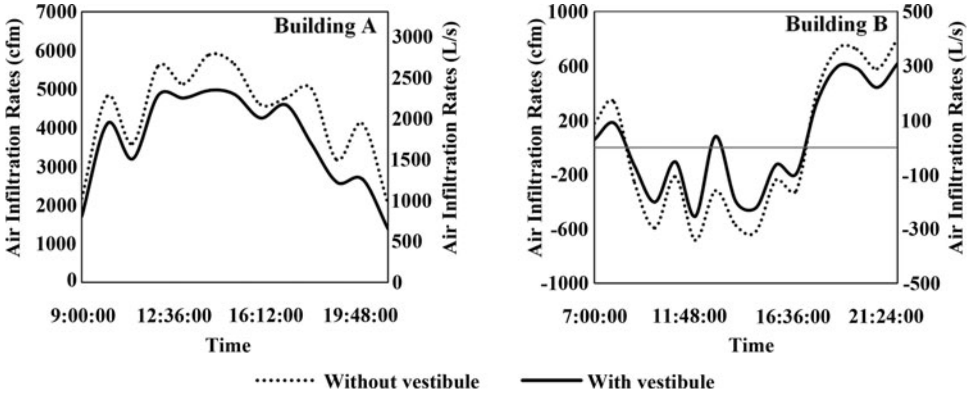


Fig. 6. Calculations of transient airflow rates through the automatic entrance doors with and without vestibule when the buildings operated with the 90% return airflow fraction of supply airflow ($R = 0.90$).

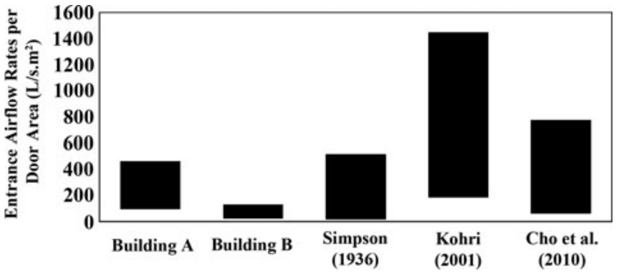
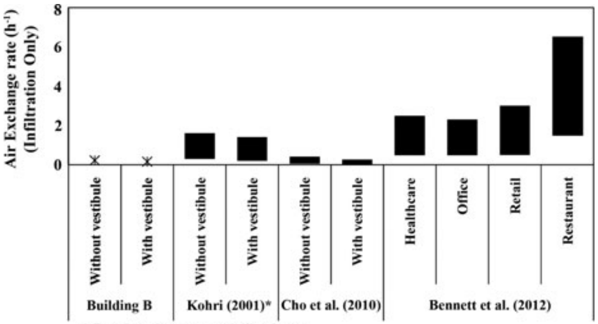


Fig. 7. Comparison of calculated air infiltration rates normalized by the entrance door area for the current and three existing studies.



* Based on the entrance hall volume

Fig. 8. Comparison of calculated total air infiltration rates for the current and three existing studies.

0.06 h^{-1}. The automatic entrance doors were the main path of air exiting the building, which accounted for 75% of the total air exfiltration. For Building A, the airflow rates from the retail zone through the office, storage, and kitchen zones were only 1% to 2% compared to the airflow rates through meachnical ventilation and building envelopes, which can be considered negligible.

The study further investigated an impact of the air distribution system operation mode on the airflow through building envelopes. It was found that changes in the return airflow fraction of ±5% significantly impacted the airflow through the automatic entrance doors. For Building B, when the building was operated at return air fraction $R = 0.85$, the air infiltration rate through the automatic entrance door was reduced by approximately 22%. The air infiltration rate through walls differed by approximately ±7%. For Building A, where the air infiltration was found at the walls only, reducing the return air fraction of $R = 0.85$ decreased the air infiltration rate through the walls by roughly 16%. The air exfiltration rate through the automatic entrance doors deviated by approximately 27%, and the air exfiltration rate through walls changed by roughly 12%. The results indicate that the automatic entrance doors are a major path of air infiltration and that the air infiltration rates through the automatic entrance doors are very sensitive to the changes in the internal pressure due to the operation of the air distribution system. Consequently, an appropriately operated air distribution system can significantly reduce the air infiltration rates through the automatic entrance doors.

Discussion

Although the simulated pressure differentials across automatic entrance doors corresponded with the measured data, there is

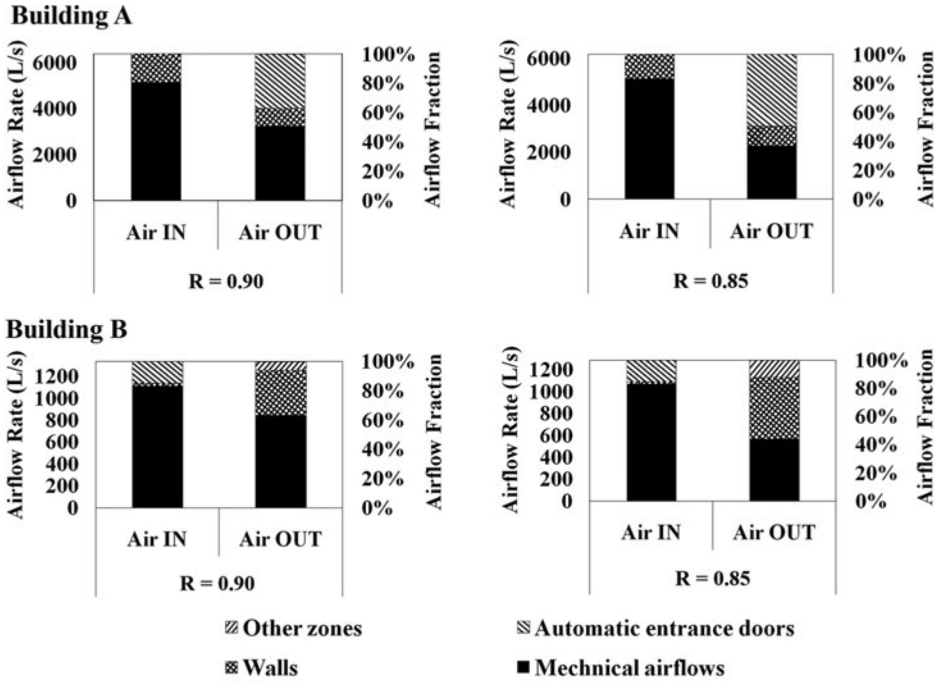


Fig. 9. Comparison of airflow rates through the building envelopes modulated by the air distribution system with airflow fractions R of 0.85 and 0.90 in Buildings A and B, respectively.

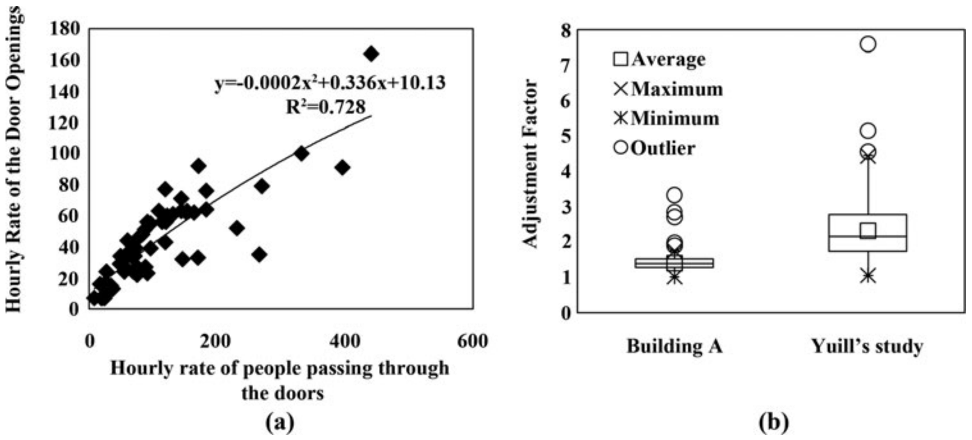


Fig. 10. a. Correlation for the hourly rate of people passing through the automatic entrance doors and the hourly rate of the door openings (data source: Yuill et al. 2000). b. Boxplots of calculated adjustment factors from the present investigation in Building A and previous investigation results.

a potential source of error in the calculation of flow coefficient (*C*) due to the accuracy of number of people passing through the automatic entrance doors. In this present study, the hourly rate of people passing through the automatic entrance door for Building B was adjusted by multiplying the hourly transaction rates with an adjustment factor of 1.3. The hourly transaction rate represents a number of people at check-out counters, obtained from the store computer system. This study found 1.3 to be the ratio of the hourly rate of people passing through automatic entrance doors to the hourly transaction rate. This factor was obtained from the investigation in Building A. Unfortunately, there is no study directly calculating a correlation between these two parameters. Similarly, a previous study measured the hourly rates of people passing through the automatic entrance doors as well as the number of door openings, which was further used to establish airflow coefficient (C_a; Yuill et al. 2000). Based on the data from the previous study, Figure 10a presents the correlation of these two hourly rates. Based on the data in Figure 10a, the door openings value is assumed to be approximately equal to the hourly transaction rate. Consequently, the average ratio of people passing through the automatic entrance doors to the hourly transaction rate is 2.2 ($SD = 0.9$), as shown in Figure 10b. The adjustment factor of 2.2 calculated from the previous study is higher than the factor of 1.3 calculated in the present study. A large difference for the adjustment factor is probably due to the several different types of public buildings being investigated by the previous study. Lessons learned from this study suggest that estimating the hourly rate of people passing through the automatic doors from the hourly transaction rate carries a high uncertainty. Therefore, people counters installed at the entrance doors are needed for accurate assessments of air infiltration rates in retail stores.

Besides requiring the accurate hourly rate of people passing through the automatic entrance doors, another challenging aspect of assessing the air infiltration rates through automatic entrance doors is monitoring the airflow rates in the rooftop units. Instead of time-consuming on-site measurements, using real-time data recorded from a ventilation control system might provide reliable airflow rates and reduce the effort in data collection.

In addition to investigating airflow rates through the automatic entrance doors, future studies should further investigate the airflow rates through other types of operating doors, such as loading docks and lumber doors, as long as their frequency of use is significant. The operation of loading docks and lumber doors with plastic sheets has different characteristics from the automatic entrance doors. These additional door types are another probably a significant path of air infiltration when the products are loaded in a retail building, but their frequency of use is typically sporadic when compared to the frequency of use for the entrance doors. It would be interesting to investigate airflow characteristic and establish leakage airflow elements for these door types, but such an investigation is out of the scope of the present study.

Conclusions

The goal of this research study is to quantify air infiltration rates through the frequently used automatic entrance doors with a calibrated multi-zone model. Leakage airflow elements, typically used in such multi-zone programs as CONTAMW, do not account for a frequently used automatic entrance door. In this study, the calibrated model provides realistic results for the door pressure differentials and associated air infiltration rates through the automatic entrance doors. The automatic entrance doors represent the major path of air infiltration for retail buildings. Overall, the amount of airflow through automatic entrance doors is approximately 75% to 80% of the total air infiltration rate, which accounts for 12% to 19% of the total ventilation rates. Adding a door vestibule reduces the airflow through the automatic entrance doors by 22% to 24%. In addition to installing the door vestibule, operation of air distribution system and design location of entrance doors could potentially reduce air infiltration rates through the automatic entrance doors.

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