A Field Investigation of Air Infiltration Rates through Automatic Entrance Doors in Retail Buildings

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Abstract

This paper presents field investigations of air infiltration rates in twelve big-box retail stores and two small grocery stores located in two different climate zones: hot and humid (zone 2a) and moderate to cold (zone 5a) climates. The investigations of the entrance door characteristics, differential pressures across the automatic entrance doors, and number of people using the doors per hour were used to calculate transient air infiltration rates through various types of automatic entrance doors. It was found that the calculated air infiltration rates for retail stores and supermarkets ranged from 40 L/s to 5,800 L/s. Normalized by the door area, the range of air infiltration rates through the automatic entrance door for a supermarket was from 100 L/s.m^2 to 3,000 L/s.m^2, which was greater than the range previously observed in retail stores from 100 L/s.m^2 to 1,100 L/s.m^2. In terms of air exchange rates, the air infiltration rates through the automatic entrance doors for small stores, especially in supermarkets and grocery stores, had a larger impact than those rates found in the big-box retail stores due to the size of building volume.

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1. Introduction

The required ventilation rates defined in ASHRAE Standard 62.1 (2010) for retail buildings were determined based on the field investigations in office buildings. With an assumption that retail stores had different functions and operating schedules from those found in office buildings, the ventilation rate requirements for office buildings may not be appropriate for retail buildings. There were several studies of ventilation rates in retail stores (Chao & Chan, 2001; Wargocki, Fanger, Krupicz & Szczecinski, 2004; Hotchi, Hodgson & Fisk, 2006; Wu, Apte, Maddalena & Bennett, 2011; Bennett et al., 2012; Chan, Sidheswaran, Sulivan, Cohn & Fisk, 2012) and few of them investigated air infiltration through the automatic entrance doors which significantly affected building energy consumption (Bennett et al., 2012; Chan et al., 2012). However, with these limited number of ventilation studies, the field investigation results were insufficient to develop the ventilation database for further determining the ventilation standard for retail building stock. To establish the ventilation database, ASHRAE RP-1596 investigated ventilation rates including air infiltration through the automatic entrance doors in 14 retail stores, including supermarkets, with a total of 33 experiments.

Retail buildings typically have airtight envelopes, and the automatic entrance doors are considered to be a main path of air infiltration. Such air infiltration significantly influences building energy consumption (American Society of Heating, Refrigeration and Air Conditioning Engineering [ASHRAE], 2010a; Cho, Gowri & Liu, 2010; National Renewable Energy Laboratory [NREL], n.d.). A multi-zone airflow model has been widely used to analyze airflow characteristics through building leakage components, including openings and doors. The model provided information about air leakage in order to build a database for different types of wall constructions, windows, and closed doors, but this database does not cover the leakage information or air infiltration for the automatic entrance door (Persily & Ivy, 2001). At present, there are a few studies investigating air infiltration through the automatic entrance doors which found that the range of air infiltrations rate for each entrance door area was approximately 50-1,250 L/s.m^2 (Yuill, Upham & Hui, 2000; Kohri, 2001; Cho, Gowri & Liu, 2010; Bennett et al., 2012; Srisuwan & Varodompun, 2013, pp. 5-20).

Yuill et al. (1996; 2000) developed the method to investigate air infiltration rates through the automatic entrance doors based on the field observations in various public buildings, including retail stores. The study did not provide the range of air infiltration rate through the automatic entrance doors. However, they provided the airflow model for the calculation of airflow rates based on differential pressures across the automatic entrance doors and the hourly rate of people walking through the doors. Kohri (2001) observed the automatic entrance door operation in relation to number of people using the doors for an entrance hall in an office building. The study used an airflow circuit network model to calculate the air infiltration rates. The air infiltration rates through the entrance doors ranged from 190-1,250L/s.m^2. Cho et al. (2010) later used the model provided by Yuill et al. (1996; 2000) to calculate air infiltration rates through the automatic entrance doors in various types of commercial buildings, including retail stores. For retail stores, the air infiltration rates they calculated per entrance door area ranged from 80-1000 L/s.m^2. The study also calculated air infiltration rates through the entrance door with and without a vestibule for the estimation of the building energy consumption of these 2 scenarios. It was found that the air infiltration rate through the automatic entrance doors without a vestibule was greater than the rate through the doors with a vestibule by approximately 1.5. Bennett et al. (2012) found that the air infiltration through the doors significantly influenced the total air exchange rate. The opened entrance door increased the air exchange rate by approximately 2 times greater than the rate observed when the entrance doors were closed. From the literature, the air infiltration rate through the automatic entrance doors was extremely high and considered to be a significant parameter for the field investigations in the ASHRAE RP-1596 project.

This paper focuses on the field investigations of air infiltration through the automatic entrance doors observed in the ASHRAE RP-1596 project. The measurements of total ventilation rate in retail stores are provided in the ASHRAE RP-1596 project report (Siegel et al., 2013). The results of this investigation provide a typical air infiltration rate through various types of automatic entranced doors in different types of retail stores.

2. Building Description

This study investigated air infiltration rates through the automatic entrance doors in twelve big-box retail stores and two grocery stores located in Central Pennsylvania (moderate-to-cold climate, Zone 5a) and Texas (hot and humid climate, Zone 2a). According to Table 1, the first

Site	Test IDs	Type	Floor Area (m^2)	Volume (m^3)	Door type	Door area (m^2)
HaP	1 2	Home improvement	11,700	93,400	SLWV	7.2
HaT	1	Home improvement	12,400	91,800	SLWV, SWWV	11.1
MbP	1 2 3 4	General merchandise	16,600	99,500	SLWV	14.2
MbT	1 2 3 4	General merchandise	8,740	61,200	SWWV	14.1
MiP	1[a]	General merchandise	11,300	66,800	SWWV	7.2
MiT	1[a]	General merchandise	12,100	55,200	SLWV	14.1
EgP	1 2	Electronics	2,700	20,300	SLWV	8.5
OhT	1	Office supply	2,280	20,700	SWWV	4.6
FfP	1	Furniture	1,970	8,170	RVV	2.2
FfT	1 2	Furniture	3,250	19,800	SWWOV, SWWV	7.2
GeP	1	Grocery (mid-size)	3,100	25,300	SLWV	3.8
GeT	1 2	Grocery (mid-size)	3,250	14,900	SLWV	7.7
ScP	1	Grocery (small)	836	3,340	SLWV	3.52
SdT	1	Grocery (small)	1,180	5,390	SWWOV	6.4

a Intervention sites
SLWV- Sliding door with a vestibule
SWWV- Swinging door with a vestibule
SWWOV- Swinging door without a vestibule
RVV- Revolving door.

Table 1. Summary information of the building case studies and entrance door characteristics.

two letters of the site code represents store types and brands for example home improvement (Ha), merchandise retailer (Mb and Mi), electrical store (Eg), furniture store (Ff), small grocery (Ge), and supermarket (Sd). The last letter of the code represents the store's locations (Pennsylvania (P) or Texas (T)) and the test ID represents the repeated measurements in the same store. Site MiP and MiT were tested for two consecutive weeks, called intervention site. During the first week, the ventilation rate operated at full condition while the operated ventilation rate in the second week followed a typical schedule. The measured ventilation rate in the first week was not accounted for in this study. The total volume for retail stores ranged from 8,200 m^3 to 99,500 m^3 and 830 m^3 to 3,200 m^3 for grocery stores. Several types of entrance doors, such as double swinging doors, sliding doors, and revolving doors were found in these retail stores. The door area ranged from 2 m^2 to 14 m^2. The average entrance door area for retail was 9.2 m^2 and 5.7 m^2 for supermarkets. Typically, the automatic entrance door observed in retail stores were sliding and swinging doors with a vestibule since there is the vestibule requirement for the entrance door for commercial buildings which have floor area greater than 280 m^2. This is to prevent air infiltration through the entrance door influenced by wind driven pressure and stack effect (ASHRAE 90.1, 2010b). However, some of entrance doors in one furniture store (FfT) and a small supermarket (SdT), whose areas were greater than the above requirement, had no the entrance vestibule.

3. Methodology

The air infiltration rates through the automatic entrance doors presented in this paper were investigated when the tracer gas measurement was performed, typically taken in 4-hour period for each test. The calculation of air infiltration through the automatic entrance doors based on the airflow model as shown in Equation (1) required information about the entrance door characteristics including door type and availability of a door vestibule, pressure

$$Q=C_A A_d \sqrt{\Delta P} \quad (1)$$

where A_d is the door opening area [m^2]. ΔP is the pressure difference across the automatic entrance doors [Pa]. The pressure differences across the automatic entrance doors were measured during the 4-hour test period when the building ventilation rate was measured. The differential pressure sensors were installed inside the building near the entrance door to measure the air pressure difference between the inside and outside of each retail building. A rubber tube was used to connect one sensor inlet and another side of the tube was located outside the building. The reading of positive pressure showed that the building was pressurized, and negative pressure meant a depressurized building. C_A is the airflow coefficient [L/s. m^2. $Pa^{0.5}$], which depends on the door types and number of people using the door per hour, N [h^{-1}]. The calculation of the airflow coefficient used Equation (2). The number of people using the door per hour, N, for all tested sites was estimated from the hourly transaction rate recorded at check-out counter. However, it was considered that this number might not represent the actual hourly rate of people using the door since some people did not purchase goods and just walked directly to the entrance door. Consequently, to obtain a more accurate number of people using the entrance door, the study installed a thermal image people counter sensor (1% of reading) to measure the hourly rate of people at the entrance doors in Site MiP.

$$C_A=aN^2+bN \quad (2)$$

In Table 2, the coefficient a and b were generated from the fitting curves based on the data provided in Table 4-1 in ASHRAE RP-763 report (Yuill, 1996).

To calculate the air infiltration rate through a revolving door, the study used Equation (3), which was developed in ASHRAE RP-1236 (McGowan, 2006).

$$Q=1.6\Delta P^{0.66} \quad (3)$$

4. Uncertainty of air infiltration rate

The uncertainty of air infiltration through the automatic entrance doors originates from three factors: 1) the differential pressure across the automatic entrance doors 2) the number of people using the door per hour, and 3) the door opening area. The study used a general error propagation rule as shown in Equation (4) to calculate the uncertainty of the air infiltration rate for the swinging and sliding doors. The first term, $(A_d \Delta P^{0.5})^2 \delta_{CA}^2$, is associated with the airflow coefficient measurement. A_d is the measured entrance door area [m^2]. ΔP is the measured differential pressure across the automatic entrance doors [Pa]. δ_{CA} is the accuracy of the airflow coefficient [L/s. m^2. $Pa^{0.5}$], which can be calculated from Equation (5). N is the average hourly rate of people using the door [people] during the test period. The coefficients a and b [dimensionless] were from Table 2 [dimensionless].δ_N is the standard deviation of the average hourly rate of people passing through the entrance doors [people]. $(C_A \Delta P^{0.5})^2 \delta_{Ad}^2$ is the uncertainty associated with the door opening area. δ_{Ad} is the uncertainty of the measured door area [m]. C_A is the airflow coefficient [L/s. m^2. $Pa^{0.5}$]. The calculation of δ_{Ad} was found using Equation (6). H and W is the door height and width [m].δ_H and δ_W is the uncertainty of the measurement of the entrance door [m]. $\left(\frac{C_A A_d}{2\Delta P^{0.5}}\right)^2 \delta_P^2$ is associated with the pressure differential measurement and δ_P is the standard deviation of the pressure differential calibration [Pa] whereas the uncertainty calculations of air infiltration through revolving doors used Equation (7).

Table 2. Values of curve-fitting coefficients a and b.

	Door Type	a	b
1	Sliding doors without vestibule	-0.0021	3.5
2	Swinging doors without vestibule	-0.0024	4.0
3	Swinging door with vestibule	-0.0014	3.0
4	Sliding door with vestibule	-0.0013	2.5

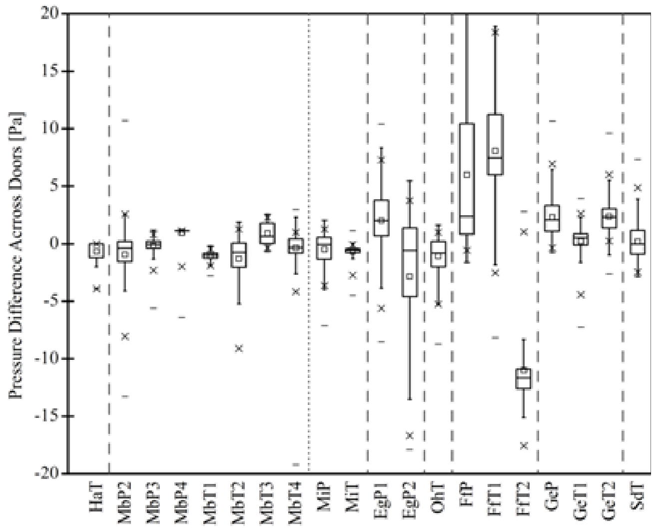
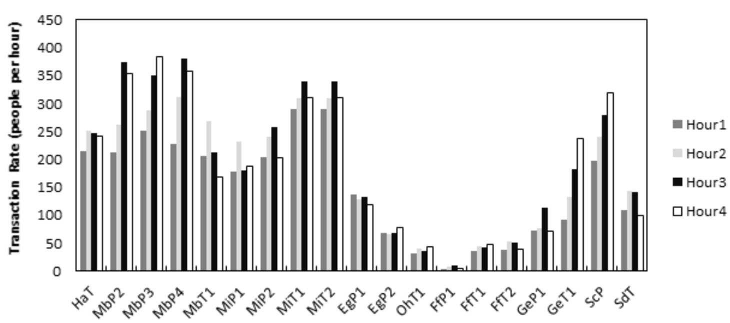


Figure 1. The boxplots present the measurement results of differential pressure across the automatic entrance doors.

Figure 2. Hourly transaction rates counted at check-out counter during the test period (4 hours).



$$\delta_Q^2=(A_d\Delta P^{0.5})^2\delta_{CA}^2+(C_A\Delta P^{0.5})^2\delta_{Ad}^2+\left(\frac{C_A A_d}{2\Delta P^{0.5}}\right)^2\delta_P^2 \quad (4)$$

$$\delta_{CA}=(b-aN)^2\delta_N^2 \quad (5)$$

$$\delta_A^2=\left(\frac{\delta_H}{H}\right)^2+\left(\frac{\delta_W}{W}\right)^2 \quad (6)$$

$$\delta_Q^2=(1.04\Delta P^{-0.35})^2\,\delta_P^2 \quad (7)$$

5. Results

Figure 1 presents the box plots of measured differential pressures across the automatic entrance doors. The vertical dashed line between the columns separates type of retail stores, while the dotted line separated the store by brand. From the figure, 85% of the tested numbers had the differential pressures across the automatic entrance doors ranging from -5 Pa to 5 Pa. Negative values represent that the building was depressurized, and positive values represent a pressurized building. The measured differential pressures across the automatic entrance doors for electronic (Sites EgP1 and EgP2) and furniture (Sites FfT1 and FfT2) stores had a relatively wide range, between -15 Pa to 15 Pa, since these buildings operated flush ventilation during the morning, when the test was performed, in order to dilute contaminant concentration during night time.

Instead of the differential pressures, another parameter required for the calculation of air infiltration through the automatic entrance doors is the hourly rate of people using the entrance door. Figure 2 presents the hourly transaction rates counted at check-out counter. During the test period, the rate of transactions at the check-out counter ranged from 4-383 people per hour. The transaction rates observed in office supplies, electrical, and furniture stores were typically lower than the rate observed in merchandise stores and supermarkets. For Site MiP, the study additionally counted the hourly rate of people using the automatic entrance doors and compared the results with the transaction rate. It was found that the hourly rate of people passing through the automatic entrance doors was approximately 1.3 times greater than the transaction rate. The hourly transaction rate was then multiplied with the adjustment factor of 1.3 and further used to calculate airflow rates through the automatic entrance doors.

In order to check the reliability of the measurement method of differential pressure across the automatic entrance doors, the study repeated the measurements when the HVAC operation was controlled at the same condition in Sites MiP and MiT. Such pressure data was used to calculate air infiltration through the automatic entrance doors as presented in Figure 3. The calculated airflow through the automatic entrance

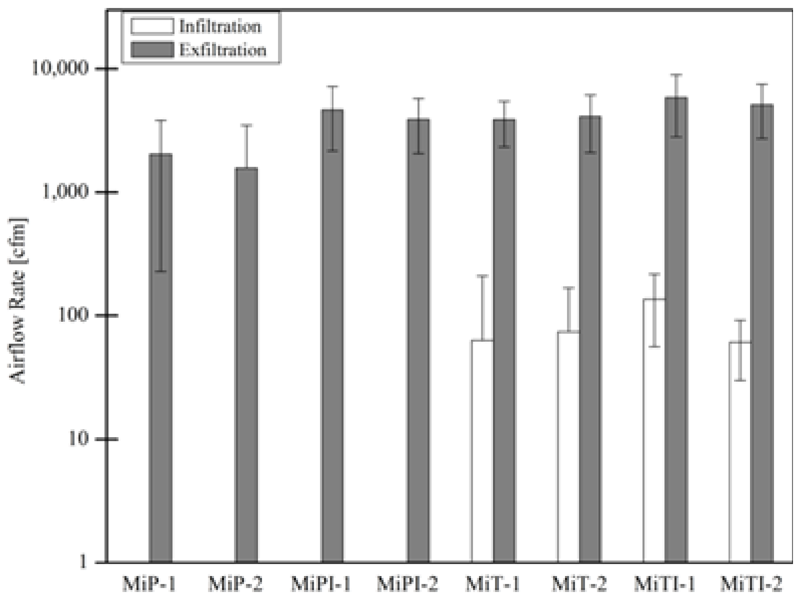


Figure 3. The repeatability of airflow rates calculated at intervention sites.

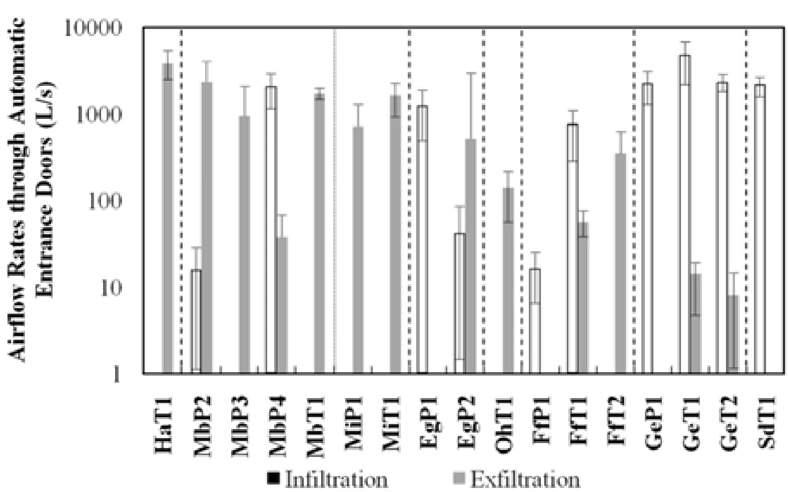


Figure 4. Calculated air infiltration and air exfiltration rates through the automatic entrance doors.

doors provided that the measurement method had a good reproducibility. The calculation results of air infiltration and air exfiltration through the automatic entrance doors in each store were presented in Figure 4.

From the figure, the airflow rate through the automatic entrance doors had a relatively wide range, from 300 L/s to 5,800 L/s. The range of the air infiltration rate through automatic entrance doors observed in retail stores was lower than that observed in the supermarket and grocery stores. Supermarket (Sd) and grocery (Ge) stores had a high range of air infiltration rates of 2,200-3,800 L/s. The air infiltration rates through the automatic entrance doors for merchandise stores (Mb) ranged from 620 L/s to 2,560 L/s. The range of air infiltration rates for electronics (Eg) and furniture stores (Ff) was 770-1,420 L/s. The air infiltration rates for Site FfP1 was relatively low when compared to other stores, since the entrance door of this building was a revolving door. The calculated airflow rate through the automatic entrance doors for Sites MbT2, MbT3, MbT4, and ScP due to unavailable measured data of either pressure difference or hourly transaction rate. It was found that 47% of the tests (15 out of 33 tests) observed air infiltration through the automatic entrance doors. Air infiltration and exfiltration could be found at the same period, especially in Sites MbP2, MbP4, EgP2, FfT1 and GeT1, since the operation of mechanical ventilation and wind driven pressure difference across the building influenced that the air entered the entrance door and escaped using another entrance door. After being normalized by the entrance door areas, the airflow rates ranged from 37 L/s.m^2 to 2,700 L/s.m^2, as shown in Figure 5. Figure 6 compares the air infiltration rates per the entrance door areas calculated from the current studies with the rates observed from three existing studies (Simpson, 1936; Kohri, 2001; Cho et al., 2010). It was found that the range of air infiltration rates investigated in retail stores was 100-1,100 L/s.m^2, which more than 75% of the tested numbers were within the range of the rates investigated by Simpson (1936) and Cho et al. (2010). However, the range of air infiltration rates per the door area for supermarkets of 100-3,000 L/s.m^2 was slightly higher than the rates investigated from the three existing studies (Simpson, 1936; Kohri, 2001; Cho et al., 2010).

The comparison of air infiltration rates normalized by the entrance door area in Figure 6 shows that the air infiltration rates for retail stores had similar ranges as found in supermarket and grocery stores. However, when the air infiltration rate was normalized by the building volume, the range of air exchange rate caused by air infiltration for supermarket and grocery stores was greater than the range found in retail stores, as shown in Figure 7. The average air exchange rate of air infiltration for supermarkets was approximately 1 h^{-1}, and for retail stores was 0.09 h^{-1}.Compared to the existing studies, the air exchange rates observed in retail stores was the same range found in Cho et al.'s investigation (2010), but this range was significantly lower than the range observed in Bennett et al.'s studies (2012), which most of retail stores investigated in their studies were small buildings.

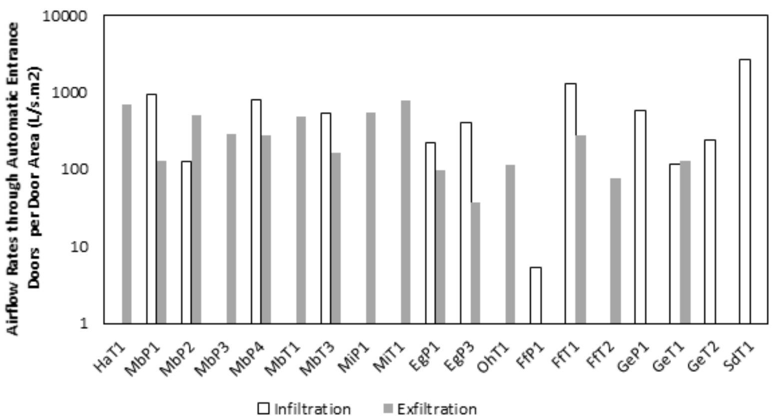


Figure 5. Calculated air infiltration and air exfiltration rates through the automatic entrance doors normalized by the door area.

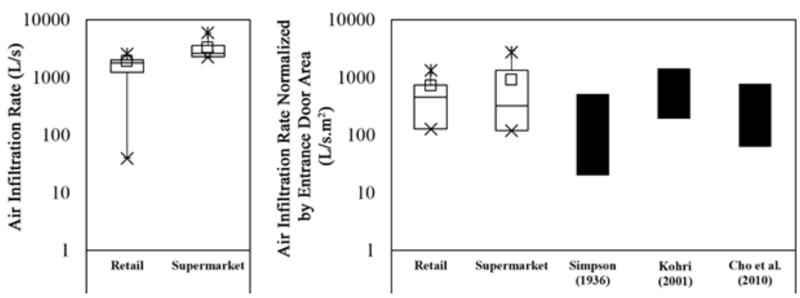


Figure 6. Box plots compare the range of air infiltration rate through the automatic entrance doors for the current and three existing studies.

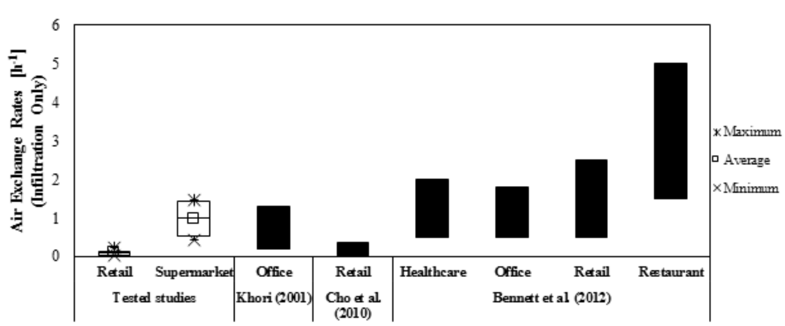


Figure 7. Calculated air exchange rates of air infiltration in retails and supermarkets compared to three existing studies.

When considered the air infiltration rates through several types of automatic entrance doors, the average air infiltration rates through the sliding door with a vestibule was 5,000 L/s, which was the highest value when compared to the infiltration rates through other door types, as shown in Figure 8. The average air infiltration rate through the door without a vestibule was 1,000 L/s, which was lower than the infiltration rates through the doors with a vestibule. It was probably due to the opening area of the entrance door. The average area of the door without a vestibule was 5 m^2, which was lower than the average area of 9 m^2 for the door with a vestibule. The air infiltration rates through the revolving door was approximately 20 L/s.

6. Study Limitations

The infiltration and exfiltration airflow rates were calculated based on the measurement of room pressure differentials and hourly rates of people passing through the automatic entrance doors. Although the calculation results provided that the air infiltration rates through the automatic entrance doors was within the range of the rates investigated by the existing studies, the possible errors from the calculated air infiltration rates are due to 1) the measurement of occupancy rates and 2) the limited number of pressure sensors. In this project, it is assumed that the hourly transaction rate counted at a check-out counter can represent the actual rate of people using the door per hour. After the comparison of this data set with the rate counted at the check-out counter, it is found that this data set is not sufficient to represent the hourly rate of people using the automatic entranced doors since the transaction rate is approximately 1.3 times lower than the rate counted at the automatic entrance door. However, the comparison of these two data sets was done only in one site. Consequently, the adjustment factor of 1.3 is certainly not applied for all tested numbers. The future studies should directly count the actual number of people using the door per hour via using an accurate people counter sensor. About the measurement of differential pressure across the automatic entrance doors, due to the limited number of pressure sensor, it is not possible to measure differential pressures in all automatic entrance doors. Consequently, it is assumed that the automatic entrance doors which have the same characteristics and locate in the same side of the building should have the same operating conditions. This assumption might provide the error in the calculated air infiltration rates. To reduce the uncertainty from this assumption, the future studies should measure differential pressures and investigate the door operating condition in all entrance doors.

7. Conclusions

This paper presents the field investigations of air infiltration rates through the automatic entrance doors in 14 retail stores, including supermarkets. It was found that the calculated air infiltration rates through automatic entrance doors had a wide range, from 40 L/s to 5,800 L/s. The range of air infiltration rates normalized by entrance door area in supermarket, 100-3,000 L/s.m^2, was greater than the rate observed in retail stores, which ranged from 100L/s.m^2 to 1,100 L/s.m^2. The amount of air infiltrates through automatic entrance doors had a relatively small impact on building ventilation, except for buildings of small volumes, such as supermarkets and grocery stores. The average air exchange rate caused by air infiltration through the automatic entrance doors for supermarkets was 1 h^{-1}, while the average air exchange rate of air infiltration rate observed in retail stores was 0.1 h^{-1}. Overall, future studies aiming to reduce the uncertainty for calculated air infiltration rates, require measurements of the differential pressures in all entrance doors and the investigation of number of people passing through the automatic entrance doors.

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