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Field study to characterize customer flow and ventilation rates in retail buildings in Shenzhen, China

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Keywords: Customer flow, Dwell time, Occupant density, Ventilation rate, Retail

ABSTRACT

Reduction of the customers’ exposure risk of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in the retail buildings, i.e., supermarkets and small shops where residents purchase daily necessities is of prime importance during pandemic. In this study, the main influencing factors of the exposure risk of SARS-CoV-2, namely the occupant density, dwell time, and fresh air volume per person, were on-sited measured in 5 supermarkets and 21 small shops in Shenzhen, China. The small shops with an occupant area per person of 4.7 m²/per presented a more crowded environment than the supermarkets with an occupant area per person of 18.8 m²/per. The average dwell time of customers in the supermarkets linearly increased with the floor area and its probability distribution was fitted well by the Gamma distribution with a shape parameter of 3.0. The average dwell time of customers in the small shops was relatively longer than the combination of five types of small shops. In addition, the measured average outdoor air change rate of the small shops by natural ventilation was 10.7 h⁻¹, while that of the supermarkets by mechanical ventilation was only 0.7 h⁻¹. Correspondingly, the CO₂ concentration in the small shops was 100-150 ppm lower than the supermarkets. The small shops provided an average fresh air volume per person of 216 m³/(h-per), far exceeding the supermarkets with a value of 95 m³/(h-per).

1. Introduction

The outbreak of Coronavirus disease 2019 (COVID-19) imposes serious public health and financial burdens to the entire world [1]. Up until now, the full impact remained to be unpredictable. Yet it is necessary to restart the economy and resume economic and social activities. Investigations were carried out to assess the infection risk of SARS-CoV-2 in ten of activities. Investigations were carried out to assess the infection risk of SARS-CoV-2 in ten of activities.

Transmission routes through droplets, aerosols and fomites have been well-recognized as the main spreading routes of COVID-19 [4–6]. Droplets and aerosols are both respiratory particles, mostly from the sneezing, coughing, talking and exhaling of the infected persons [7]. Related investigations cover the fields of sources and mechanisms of droplets/aerosols generation [8], their characteristics and transmission phenomena [9], infection risk assessment [41,42], as well as the safeguards measurements [1,10]. With regards to the virus emission, Zhou et al. [11] demonstrated that SARS-CoV-2 can be detected from the air in hospitals. Significant cautions should be taken to cope with the transmission of COVID-19 through air. The Wells-Riley equation is a classic model for evaluating the infection risk of respiratory disease, where the quantum generation rate is a critical parameter [12,13]. Dai and Zhao [14] estimated the quantum generation rate of COVID-19 (i.e., 14–48 h⁻¹) for the Wells-Riley equation using a reproductive number-based fitting approach. Meanwhile, Buonanno et al. [15] revealed that vocalization during light activity (i.e., walking slowly) can lead to...
quantum emission rate larger than 100 h$^{-1}$. With regards to the transmission distance, the droplets with an aerodynamic diameter larger than 100 μm fall to the floor within a horizontal distance of 2.0 m from the source due to gravity [16]. As a result, social distancing of 2.0 m is widely adopted for the prevention of infection through droplet transmission. Other studies have proven that a cloud of pathogen-bearing droplets of different sizes can travel up to 7–8 m from the point of source when an infected person of a respiratory illness coughs or sneezes [17,18]. Considering the shopping activities, these distances are within the scope of customer interaction in retail buildings.

According to the virus emission and transmission distance of the SARS-CoV-2, the exposure risk in the retail buildings is mainly affected by the ventilation rate, occupant density and dwell time [19,20]. Good ventilation could dilute the virus concentration and mitigate exposure risk in retail stores [21]. Dai and Zhao [14] proposed that a ventilation rate of 30–90 m$^3$/h per) was required to ensure an infection probability of less than 1% for 0.25 h of exposure, under circumstance of only one infector in a confined space and all occupants wearing surgical masks. The suggested 90 m$^3$/h per) fresh air volume in retail buildings exceeds the Chinese Standard GB 50736-2012 with a minimum people outdoor air rate of 19 m$^3$/h (per) [22] and ASHRAE Standard 62.1–2019 with a threshold of 27 m$^3$/h (per) [23]. Air curtain was brought forward to reduce the possibility of aerosol transmission [43]. However, the field study on the ventilation rates in the retail buildings is seldom in references. COVID-19 transmission in the retail buildings is highly related to the occupant flow. The occupant density reflects the average distance between individuals and the dwell time reflects the exposure duration. Previous studies investigated the occupant density and the dwell time mainly for fire safety design of the means of egress in buildings [24], energy consumption [25], building design optimization [44] and ventilation demand analysis [26]. The occupant density is highly influenced by the individual’s choice and the necessity of a person to visit the store, resulting in a high variability of the occupant density in time. According to the long-term data of customer frequencies, the mean occupant density in the supermarkets was 12 m$^3$/per) and the mean dwell time of occupants in the supermarkets ranged 15–30 min which was highly related with the floor area. However, the on-site measured occupant density and dwell time in the small shops on the street are still absent to our knowledge. The relation between the mean dwell time and the floor area of the supermarket is ambiguous.

In this study, concerning the main transmission routes of droplets and aerosols, the influencing factors of exposure risk of SARS-CoV-2, including occupant density, dwell time, fresh air volume per person, were on-site measured in 5 supermarkets and 21 small shops in Shenzhen, China. The time varying influencing factors in the retail buildings were monitored hourly on a weekday and a weekend. The survey results provided first-hand data for evaluation of exposure risks in retail buildings. Furthermore, the present methodology can be applied to other high population density buildings to better control the spread of infectious diseases.

The rest of present paper is organized as following: the methodology including building information of both supermarkets and small shops are introduced in Part 2. The survey results are presented in Part 3, including the customer flow and personal density, dwell time distribution and ventilation rates. The main findings and limitations are discussed in Part 4, with main conclusions given in Part 5.

2. Methodology

2.1. Building information

In this study, the characteristics of customer flow and ventilation rates in 5 supermarkets and 21 small shops in Shenzhen, China were on-site measured in June and July 2020. During the survey, it was still mandatory to wear surgical masks in commercial buildings.

The goods offering in the surveyed supermarkets is diverse, ranging from food, commodity to clothes, which could meet various requirements of daily life. The floor plans of the 5 surveyed supermarkets are depicted in Fig. 1. The dimensions of the supermarkets are described in Table 1. Most of the supermarkets (except the 4th one) located underground of shopping malls. The 4th supermarket was a two-storey building and located above-ground. The public areas of the supermarkets ranged from 1450 m$^2$ to 8456 m$^2$. Approximately 40% of the areas were occupied by goods shelves, and these areas were excluded in the calculation of personal density. The height of the supermarkets ranged 4.6–5.9 m. All the supermarkets are equipped with central air-conditioning systems to maintain suitable indoor air temperature and humidity. The air-conditioning systems are the main source of fresh air, as infiltration of the underground shopping zones was very limited. The air-conditioning system operated continuously during the business hour, i.e., 8:00–22:00.

Five types of small shops were surveyed synchronously, i.e., convenience stores, vegetable and meat shops, bakeries, fruit shops, as well as grain, oil and fast food shops. They were all located on the street in the residential communities where nearby residents purchased daily necessities. Building information of the 21 small shops under survey are depicted in Table 2.

The floor areas of the small shops varied in the range of 21.3–46.8 m$^2$, with an average area of 33.4 m$^2$. The heights of the small shops ranged from 2.4 to 3.4 m, with an average height of 2.9 m. The external views of the representative small shops are shown in Fig. 2. The ratios of the occupied area by goods shelves to the floor area varied in the range of 40–70%, larger than that of the supermarkets. In front of each small shop, there was one door for entry and exit, which was kept open during the business hour to attract customers. The open doors were beneficial for natural ventilation and reduced the possibility of fomite transmission of infectious disease through the door knob. The areas of the open door ranged from 2.6 to 13.5 m$^2$ with an average area of 5.8 m$^2$, and the average ratio of the open door area to the floor area was 17%. During the survey, the split air-conditioners in the small shops continuously operated throughout the business hour to maintain indoor thermal comfort.

2.2. Customer flow survey

Customer flow survey was carried out on a weekday and a weekend in the retail buildings. The occupant density is calculated as the ratio of the net floor area (not including the area covered by goods shelves) to the total occupant number (i.e., sum of the customers and staff). The numbers of customers and staff in the retail buildings were counted hourly during business hour.

All of the supermarkets were equipped with surveillance cameras at every entry and exit. From the surveillance videos, the inlet customer flow of the supermarkets was counted. The dwell time of customer in the supermarkets is the time interval between his/her entry and exit. The total number of the visiting customers was further calculated according to the counted inlet customer flow. In the surveillance video of the entry of the supermarkets, approximately 5% customers (i.e., 1373 customers) were selected by interval sampling according to the visiting customer sequence. The exact entry and exit time of each selected customer was obtained from the surveillance videos. Examples of the screenshots for dwell time calculation are shown in Fig. 3. From the perspective of customers’ privacy, the images were processed with mosaics.

Among the selected 1373 customers, there were 825 female customers, which was about 1.5 times of the male customers. The dwell time of customers in the shopping zone is a stochastic value that is influenced by the personal choice, product variety, shopping zone area and so on. The Gamma distribution [27] was introduced in the present study to fit the probability distribution of the customer dwell time in the supermarkets. The Gamma distribution was expressed as:
\[ p(\Delta T) = \frac{\beta}{\Gamma(\alpha)} \Delta T^{\alpha-1}e^{-\beta T} \quad \text{where} \quad \Gamma(\alpha) = \int_0^{\infty} x^{\alpha-1}e^{-x}dx \quad (1) \]

Where \( p(\Delta T) \) is the probability density function of dwell time of the customer; \( \Gamma(\alpha) \) is the Gamma function. \( \alpha \) and \( \beta \) are the shape parameter and inverse scale parameter of the Gamma distribution. \( \alpha \) and \( \beta \) were calculated by the maximum likelihood estimation according to the data of dwell time. The average dwell time of the customers is equal to \( \alpha/\beta \).

Due to lack of surveillance videos of the small shops, we randomly

Table 1
Building information of the surveyed supermarkets.

| No. | 1    | 2    | 3    | 4(1F) | 4(2F) | 5    |
|-----|------|------|------|-------|-------|------|
| Area (m²) | 1450 | 2324 | 4944 | 2296  | 6160  | 7765 |
| Height (m) | 5.2  | 4.7  | 5.9  | 5.2   | 4.6   | 4.8  |
| Floor    | B1   | B1   | B1   | 1F    | 2F    | B1   |

Table 2
Building information of surveyed small shops.

| Shop No. | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   |
|----------|------|------|------|------|------|------|------|------|------|------|------|
| Type     | Convenience store | Vegetable and meat | Bakery | Fruit shop | Grain, oil & fast food |
| Area (m²) | 38.4  | 33.1  | 28.5 | 46.5 | 38.4  | 30.1 | 38.4 | 21.3 | 31.7 | 26.5 |
| Height (m) | 2.6   | 3.0   | 2.6  | 2.7  | 2.6   | 2.8  | 2.6  | 2.7  | 2.8  | 3.3  | 3.3  |
| Door area (m²) | 9.2   | 7.2   | 9.2  | 2.7  | 9.2   | 3.7  | 9.2  | 2.7  | 3.8  | 2.7  | 2.7  |

Fig. 1. Floor plans of the surveyed supermarkets: (a) 1st; (b) 2nd; (c) 3rd; (d) 4th (1F); (e) 4th (2F); and (f) 5th.

Fig. 2. Exterior views of small shops: (a) convenience store; (b) vegetable and meat shop; (c) bakery; (d) fruit shop; and (e) grain, oil and fast food shop.
selected 10 min per hour to count the time varying inlet customer flow. Meanwhile, we on-site measured the dwell time of customers.

### 2.3. Measurement of ventilation rate

Both indoor and outdoor CO$_2$ concentrations were measured hourly during the survey. For every supermarket, 5 measuring points were positioned uniformly at a height of 1.5 m. As for the small shops, 2 measuring points were positioned. The CO$_2$ concentration was measured with TelAire (GE7001) for 12 h (8:30–20:30) on a weekday and a weekend. The measuring range of the apparatus was 0–2500 ppm and the accuracy was 50 ppm.

Carbon dioxide emitted from the occupants was the only CO$_2$ source taken into consideration. With the assumptions of a well-mixed single zone and constant air change rate, the variation of the indoor CO$_2$ can be described as Eq. (2). Consequently, the outdoor air change rate can be calculated based on measured data.

\[
\frac{dC_{in}}{dt} = a(C_{out} - C_{in}) + kVN \tag{2}
\]

Where $C_{in}$ (ppm) and $C_{out}$ (ppm) are the indoor and outdoor CO$_2$ concentration, respectively. $a$ (h$^{-1}$) is the outdoor air change rate. The fresh air of the supermarkets was mainly from the mechanical ventilation system and that of the small shops was all from the outdoor air infiltration. $V$ (m$^3$) is the volume of the confined zone. $N$ (–) is the occupant number in the zone. The time varying indoor CO$_2$ resulted from the change of the occupant number. $k$ (m$^3$/h) is the CO$_2$ emission rate of each occupant, which is influenced by multiple factors, e.g., gender, age, and metabolic rate. The value of $k$ can be calculated with Eq. (3) [28].

\[
k = \varepsilon RQ \frac{0.00056028H^{0.725}W^{0.425}M^{0.006}}{0.23RQ + 0.77} \tag{3}
\]

Where, $\varepsilon$ is an empirical factor for the CO$_2$ emission calculation, and is 1.0 for male and 0.75 for female customers; $RQ$ is the respiratory quotient (molar ratio of CO$_2$ exhaled to O$_2$ inhaled); $H$ and $W$ are the height (m) and weight (kg) of a typical Chinese human; $M$ is the metabolic rate of people in relaxation, which is assumed to be 58.5 W/m$^2$ in the calculation. The averaged value of $k = 0.018$ m$^3$/h for male and female customers is used in the calculation.

The air change rate was calculated by the least square method according to Eq. (2). Average CO$_2$ concentrations at evenly distributed

![Fig. 3. Screenshots of surveillance videos for the customer dwell time calculation in the supermarket (with the yellow arrows pointing at the target customers). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)](image)
measuring points (5 points for each supermarket and 2 points for each small shops) were utilized as $C_{in}$ in Eq. (2). Meanwhile, the outdoor concentration $C_{out}$ was measured at an ambient location near the building and far away from the traffic. Taking the 2nd supermarket as an example, the fitted air change rate was $0.605 \text{ h}^{-1}$. Based on this fitted air change rate, the simulated $\text{CO}_2$ concentration was compared with the on-site measured values in Fig. 4. The root mean square error between the simulated and measured values was 29.8 ppm. The results demonstrated the feasibility of air change rate estimation from the $\text{CO}_2$ concentration and occupant number.

3. Results

3.1. Customer flow and occupant density

Fig. 5 shows the time varying inlet customer flow on a weekday in the supermarkets (a) and the small shops (b). As shown in Fig. 5(a), the inlet customer flow in the supermarkets presented bimodal distribution characteristics. The customers preferred shopping in the supermarkets in the morning (9:00–11:00) and evening (18:00–20:00). In Fig. 5(b), the nodes represent the average inlet customer flow of each type of small shops according to the classification in Table 2. The customers preferred shopping in the neighboring small shops in the evening (17:00–20:00), as demonstrated in Fig. 5(b). Fig. 5(c) shows the total number of visiting customers of each small shop on a weekday. The small shops of the identical type had a variation in the number of visiting customers.

According to the counted occupant numbers, the hourly occupant density was calculated. Fig. 6 shows the quartile graph of the distribution of the occupant density in the supermarkets (a) and the small shops (b). Each box represents the occupant density on a weekday (or weekend) in a supermarket (or small shop), with the central red mark indicating the average value. And the bottom and top edges of the box indicating the 25th (quartile 1: $Q1$) and 75th (quartile 3: $Q3$) percentiles, respectively. The whiskers extend to the most extreme data points, with the outliers (identified as the values falling outside the range from $Q1 - 1.5 \times IQ$ and $Q3 + 1.5 \times IQ$ where IQ = $Q3 - Q1$ is the inter-quartile distance) excluded. The outliers are plotted individually using the red or blue dots.

As shown in Fig. 6, the occupant area per person of the supermarkets ranged 10–30 m$^2$/per, while that of the small shops ranged 3–8 m$^2$/per. The average occupant area per person of the 5 supermarkets was 19.7 m$^2$/per on the weekday and 18.0 m$^2$/per on the weekend. As for the small shops, the average occupant area per person was 4.7 m$^2$/per on the weekday and 4.8 m$^2$/per on the weekend. That is to say, the occupant area per person of the supermarkets was approximately 3 times larger than the small shops, which revealed a more crowded environment in the small shops. Meanwhile, the differences among the surveyed 5 supermarkets were quite remarkable, which was also the truth for different types of small shops. For example, the fruit shops had the smallest occupant area per person (average value) of 3.5 m$^2$/per, whereas the grain, oil & fast food shops presented the largest occupant area per person (average value) of 6.0 m$^2$/per. For each supermarket, the difference of the occupant densities between weekday and weekend was small. This pattern also suited the occupant densities of small shops.

Fig. 7 shows the time varying occupant density on a weekday. As shown in Fig. 7(a), the occupant area per person in the surveyed supermarkets remained stable during the business hour. There was an exception in the 5th supermarket, where extremely large occupant area person (over 65 m$^2$/per) was observed in the early morning. This was due to the relatively large area of this supermarket and the small customer flow in the morning. As for the small shops, larger fluctuation can be observed in Fig. 7(b). The reason lies in the small occupant numbers and floor areas of the shops.

3.2. Dwell time distribution

Fig. 8(a) shows the average dwell time of the customers in the 5 supermarkets (with the number below the points representing the supermarket number) on a weekday, which are plotted as a function of the floor areas of the supermarkets. The average dwell time deviates a lot among the 5 surveyed supermarkets. According to Fig. 8(a), the average dwell time of the customers increased approximately linearly with the floor area of the supermarkets. Their relationship can be described as follows:

$$\Delta T_{ave} = 0.0028 \times A + 9.39, \quad R^2 = 0.9954$$

Where $\Delta T_{ave}$ (min) is the average dwell time of customers in the supermarket; $A$ (m$^2$) is the floor area of the supermarket. The linear correlation fits well with the surveyed results with $R^2 = 0.9954$.

To compare the dwell time of the customers between the weekday and weekend, Fig. 8(b) illustrates the cumulative probability distribution of the dwell time in the 2nd supermarket on the weekday and weekend. Their distributions (curves formed by the orange and black color circles) were quite close. The Gamma distribution was utilized to fit the probability distribution of the surveyed dwell time. For the 2nd supermarket, the shape parameter ($\alpha$) and inverse scale parameter ($\beta$) of the fitted Gamma distribution of the weekday were 1.7739 and 0.1136, respectively. As for the weekend, the shape parameter ($\alpha$) and inverse scale parameter ($\beta$) values were 1.7774 and 0.1157, which are quite close to that of weekday. The average surveyed dwell time of the customers in the 2nd supermarket on the weekday and weekend were also similar, which were 15.6 min and 15.4 min, respectively.

Furthermore, the customers’ dwell time in the other supermarkets are also fitted with Gamma distribution based on the sampled dwell time on weekday. The cumulative probability distribution of the surveyed dwell time of customers in the five supermarkets on the weekday and the fitted Gamma distributions (by the maximum likelihood estimation) are depicted in Fig. 8(c), with good agreement. The calculated shape parameters and the inverse scale parameters are listed in Table 3. The shape parameters of fitting Gamma distribution ($\alpha$) ranged 1.8–4.1, with a mean value of 3.0.

Considering the different scales of the 5 surveyed supermarkets and the consequent influence on customers’ dwell time, non-dimensional dwell time ($\Delta T/\Delta T_{ave}$) is introduced in the present study. The cumulative probability distributions of $\Delta T/\Delta T_{ave}$ of the 5 supermarkets are plotted in Fig. 8(d). The black curve demonstrates the fitted Gamma distributions with $\alpha = \beta = 3.0$, and suits the cumulative probability distributions with small deviations. That is to say, the probability distribution of the customers dwell time distribution in a random supermarket (with similar service functions, in mega-cities like Shenzhen) could be calculated approximately. Therefore, the customer...
behavior can be well predicted in aspects of average dwell time ($\Delta T_{\text{ave}}$) calculated with Eq. (3) and the cumulative probability distributions described by a Gamma distribution with a shape parameter of $\alpha = 3.0$ and an inverse scale parameter of $\beta = 3/\Delta T_{\text{ave}}$.

The average dwell time of male and female customers spending in customers was compared in Table 4. Except the fifth supermarket, the dwell time of the male customers was a little shorter than that of the female customers. Two independent sample $t$-test on the dwell time was carried out. The results shows that gender was no significant difference between the dwell time of the male and female customers ($P = 0.35$).
As for the small shops, the customers’ dwell time was investigated by sampling survey. Due to the smaller area and fewer goods, the dwell time in the small shops was much shorter than the supermarkets. Fig. 9 shows the average dwell time in the small shops on the weekday and weekend. The customers’ dwell time in the small shops was close on the weekday and weekend. The customers’ dwell time of the small shops was close on the weekday and weekend. Fig. 9 shows the average dwell time in the small shops on the weekday and weekend. The customers’ dwell time of the small shops was close on the weekday and weekend. Fig. 9 shows the average dwell time in the small shops on the weekday and weekend. The customers’ dwell time of the small shops was close on the weekday and weekend. Fig. 9 shows the average dwell time in the small shops on the weekday and weekend. The customers’ dwell time of the small shops was close on the weekday and weekend. Fig. 9 shows the average dwell time in the small shops on the weekday and weekend. The customers’ dwell time of the small shops was close on the weekday and weekend. Fig. 9 shows the average dwell time in the small shops on the weekday and weekend. The customers’ dwell time of the small shops was close on the weekday and weekend. Fig. 9 shows the average dwell time in the small shops on the weekday and weekend. The customers’ dwell time of the small shops was close on the weekday and weekend. Fig. 9 shows the average dwell time in the small shops on the weekday and weekend. The customers’ dwell time of the small shops was close on the weekday and weekend. Fig. 9 shows the average dwell time in the small shops on the weekday and weekend. The customers’ dwell time of the small shops was close on the weekday and weekend. Fig. 9 shows the average dwell time in the small shops on the weekday and weekend. The customers’ dwell time of the small shops was close on the weekday and weekend. Fig. 9 shows the average dwell time in the small shops on the weekday and weekend. The customers’ dwell time of the small shops was close on the weekday and weekend. Fig. 9 shows the average dwell time in the small shops on the weekday and weekend. The customers’ dwell time of the small shops was close on the weekday and weekend. Fig. 9 shows the average dwell time in the small shops on the weekday and weekend. The customers’ dwell time of the small shops was close on the weekday and weekend. Fig. 9 shows the average dwell time in the small shops on the weekday and weekend. The customers’ dwell time of the small shops was close on the weekday and weekend. Fig. 9 shows the average dwell time in the small shops on the weekday and weekend. The customers’ dwell time of the small shops was close on the weekday and weekend. Fig. 9 shows the average dwell time in the small shops on the weekday and weekend. The customers’ dwell time of the small shops was close on the weekday and weekend. Fig. 9 shows the average dwell time in the small shops on the weekday and weekend. The customers’ dwell time of the small shops was close on the weekday and weekend.

Table 3
Regression parameters of dwell time fitted with the maximum likelihood estimation.

| Supermarket No. | 1   | 2   | 3   | 4   | 5   |
|----------------|-----|-----|-----|-----|-----|
| $\alpha$      | 2.5868 | 1.7739 | 3.3853 | 3.0566 | 4.1362 |
| $\beta$       | 0.1946 | 0.1136 | 0.1390 | 0.0933 | 0.1312 |
| $\alpha/\beta$| 13.3 | 15.6 | 24.4 | 32.8 | 31.5 |

As for the small shops, the customers’ dwell time was investigated by sampling survey. Due to the smaller area and fewer goods, the dwell time in the small shops was much shorter than the supermarkets. Fig. 9 shows the average dwell time in the small shops on the weekday and weekend. The customers’ dwell time of the small shops was close on the weekday and weekend.

Table 4
Average dwell time of occupants in the five supermarkets on a weekday.

| Supermarket No. | 1 | 2 | 3 | 4 | 5 |
|----------------|---|---|---|---|---|
| Dwell time (min) average | 13.3 | 15.6 | 24.4 | 32.8 | 31.5 |
| male | 12.9 | 14.2 | 21.6 | 32.6 | 32.2 |
| female | 13.6 | 16.2 | 26.7 | 32.9 | 31.0 |
weekday and weekend, with an average deviation less than 0.5 min. Two-way ANOVA was carried out to analyze the relation of the dwell time with the small shops and the weekday (or weekend). The results showed that there was no significant difference in the dwell time between the weekday and the weekend ($P = 0.82$). Besides, there was significant difference in the dwell time of different small shops ($P < 0.001$). Due to the difference in the commodity types and floor areas, the dwell time in the small shops varied in the range of 1.5–4.5 min. Overall speaking, the customers’ dwell time in the convenience stores was the shortest, i.e., 1.5–2.5 min, whereas the customers’ dwell time in the other small shops mainly ranged 3.5–4.5 min.

### 3.3. Indoor CO$_2$ level and ventilation rates

The indoor CO$_2$ concentration of the retail buildings were measured hourly on the weekday and weekend. Fig. 10 shows the time varying CO$_2$ concentration on the weekday. In the supermarkets, the peak of the CO$_2$ concentration appeared in the evening, i.e., 19:00–21:00. As in Fig. 7(a), the occupant areas per person in the supermarkets were at the lowest level in the evening. Fig. 10(b) illustrates the time varying CO$_2$ concentrations in the 5 types of the small shops, which were quite stable.

Fig. 11 is the quartile graph of the daily CO$_2$ concentration distribution on the weekday and weekend in the 5 supermarkets (a) and the 21 small shops (b). During the investigation, the outdoor CO$_2$ concentration ranged 420–440 ppm. With respect to the supermarkets, the average indoor CO$_2$ concentration varied in the range of 570–740 ppm on the weekday and in the range of 520–840 ppm on the weekend (see Fig. 11(a)). Due to the larger occupant number on the weekend, the indoor CO$_2$ concentration on the weekend was approximately 70 ppm higher than that on the weekday. According to two-way ANOVA, there was significant difference in the CO$_2$ concentration in the supermarkets between on the weekday and the weekend ($P < 0.001$). Besides, there was significant difference in the CO$_2$ concentration level among the supermarkets ($P < 0.001$). Moreover, the CO$_2$ concentration varied a lot among the 5 supermarkets. On the contrary, as shown in Fig. 11(b), the average indoor CO$_2$ concentrations in the small shops were close on the weekday and weekend, which ranged 530–610 ppm on the weekday and 520–560 ppm on the weekend. Two-way ANOVA also showed that there was no significant difference in the CO$_2$ concentration in the small shops between on the weekday and weekend ($P = 0.66$). Overall, the indoor CO$_2$ concentration in the supermarkets was approximately 100–150 ppm higher than that of the small shops.

According to the time varying indoor and outdoor CO$_2$ concentration difference and the occupant number, the air change rate of the supermarkets and the small shops were estimated by Eq. (2) through the least square method, with results demonstrated in Fig. 12. In Fig. 12, the differences of air change rates on the weekday and weekend were small for both supermarkets and small shops. Except the 4th supermarket, the surveyed supermarkets all located underground and utilized the mechanical ventilation systems to supply fresh air. The air infiltration could be neglected in these supermarkets. As a result, the air change rates on the weekday and weekend were identical for the same supermarket. As shown in Fig. 12(a), the average relative deviation of the measured air change rates on the weekday from that on the weekend was 12.6%. The small deviation validates the accuracy of the measurement of the air change rates in this study. Besides, according to two-way ANOVA, there was no significant difference in the air change rates between on the weekday and the weekend both for the supermarkets ($P = 0.40$) and the small shops ($P = 0.26$). There was a significant difference in the air change rates for the various supermarkets ($P = 0.005$) and for the various small shops ($P < 0.001$). The t-test analysis revealed that the air change rates in the small shops were larger than the supermarkets ($P < 0.001$). The air change rates of the supermarkets mainly ranged 0.5–1.0 h$^{-1}$, with an average value of 0.7 h$^{-1}$. The air change rates of the small shops ranged 5–15 h$^{-1}$, with an average value of 10.7 h$^{-1}$, which was 15 times larger than the supermarkets. The huge difference was mainly caused by the different ventilation modes. The supermarkets were mechanically ventilated with air-conditioning system, with very limited access to the ambient environment. Whereas in the small shops, the indoor and outdoor air exchange was largely enhanced from both natural ventilation and mechanical ventilation. As mentioned in Part 2.1, the doors of the small shops were constantly kept

### Fig. 9. Average dwell time of customers in the small shops on a weekday and a weekend.

### Fig. 10. Temporal variation of the indoor CO$_2$ concentration on a weekday: (a) in the supermarkets; and (b) in the small shops.
open in order to attract more customers. This largely facilitated the introduction of fresh air inward, considering the small shops were all located outdoor facing the pavement. Moreover, the split AC units in the small shops were always kept on during business hours. Therefore, the indoor air temperatures were much lower than ambient environment. This further promoted ventilation. Among the small shops, large discrepancy of air exchange rates was observed, which was caused by the different conditions within the small shops, including the ratio of the opened door area to the floor area, the setting of the shelves, the location of the AC vents, the facing direction of the entrance, and so on.

As mechanical ventilation is commonly acknowledged as efficient ventilation method, as the air change rate can be (or should be) maintained at an acceptable (or safe) level, the study of Bennett [29] and Ng [30] revealed a poor indoor air quality in retail buildings with...
mechanical ventilation. Though the air change rates were not mentioned in the papers, the insufficient fresh air supplement coincides with the present investigation. Considering that natural ventilation is not a choice for some of the large-scale retail buildings. The window-to-floor ratio can not be promised, let alone there is no window for the underground floors. As a result, the findings of present survey underlie the importance of proper design and functioning of HVAC system in retail buildings, especially the large-scale ones or the ones with underground floors.

Furthermore, the fresh air volume per person was calculated for the retail buildings by the surveyed occupant number, and the results are demonstrated in Fig. 13. The fresh air per person varied in the range of 50–100 m$^3$/(h-per) in the supermarkets and 100–300 m$^3$/(h-per) in the small shops. The fresh air volume per person in the small shops was over 2 times larger than that of the supermarkets.

4. Discussion

4.1. Exposure risk of SARS-CoV-2

The exposure risk of SARS-CoV-2 by the transmission route of spray droplets and aerosols was compared within supermarkets and small shops in mega-city Shenzhen. The exposure risk by droplet transmission would increase with decreasing social distance and rising exposure duration. With the premise of hexagonal close packing (i.e., the close packing in a two-dimensional Euclidean plane), a minimum occupant area per person of $2\sqrt{3} \approx 3.5 m^2$/per was required to meet the social distance of 2.0 m. Meanwhile, the exposure risk of aerosol increases with the virus concentration and the exposure duration. The virus concentration is influenced by the fresh air volume per person of the enclosed space. The influencing factors of the exposure risks are summarized and presented in Fig. 14.

4.1.1. Exposure duration

Since the product variety and customer service of the supermarket is far richer than the small shops, it is not reasonable to compare the dwell time of the supermarkets and small shops directly. As the combination of 5 types of the small shops basically meets the daily purchasing needs, the sum of the dwell time in 5 types of the small shops was considered comparable with the supermarkets. As shown in Fig. 14(a), the average dwell time in the supermarkets was relatively longer (23.5 min) compared with the combination of dwell time in 5 types small shops (17.3 min). Therefore, with respect of the exposure duration, the exposure risk of SARS-CoV-2 for the customers in the supermarket is higher than that in the small shops.

4.1.2. Occupant density and fresh air volume per person

In Fig. 14(b), the fresh air volume per person is plotted as a function of the occupant density in the retail buildings. For each scattered point, the horizontal-axis value represents the occupant area per person, and the vertical-axis value represents the fresh air volume per person. The slope of the line connecting a scattered point with the original point equals to the ratio of the room height to the air change rate. As illustrated, this slope value was higher for small shops comparing with the supermarkets. This represents a smaller occupant area and a higher fresh air volume per customer in the small shops. Using the occupant area per person of 3.46 m$^2$/per (the minimum area to guarantee the 2.0 m distancing between individuals) as a threshold, the compliance rates of the supermarkets and the small shops were 100% and 56%, respectively. However, it should be noted that there were circumstances of customers clustering in certain areas of the supermarkets. As a result, the 2.0 m distancing cannot be guaranteed. On the other hand, the minimum fresh air volumes per person in the surveyed supermarkets was 28.8 m$^3$/per and the minimum value in the small shops was 35.0 m$^3$/per. The minimum fresh air volumes per person in the surveyed supermarkets and small shops were both above the threshold of the Chinese Standard GB 50736-2012 with a minimum people outdoor air rate of 19 m$^3$/per [22] and ASHRAE Standard 62.1-2019 with a threshold of 27 m$^3$/per [23]. Thus, the compliance rates of the Chinese standard and ASHRAE standard were both 100%. Using the fresh air volume per person of 90 m$^3$/per as a threshold [14], the compliance rates of the supermarkets and the small shops were 42% and 88%, respectively.

4.1.3. Infection risk assessment

The infection risk of COVID-19 in the retail buildings for the customers was evaluated by the Wells-Riley equation. In this field study, all of the occupants in the retail buildings were required to wear surgical masks. Owing to the filtration effect of the mask, the modified Wells-Riley equation is as follows:

$$P = 1 - e^{-\frac{Iqpt(h-\eta)}{Q}}$$

Where $P$ is the infection risk; $I$ is the number of infectors. According to the serological evidence of human infection with SARS-CoV-2, the seroprevalence of general population in the Western Pacific region is 1.7% (95% CI 0.0–5.0%) [31]; Considering the treatment and recovery of infectors, the proportion of the infectors in population is assumed as 1% in this study; $q$ (h$^{-1}$) is the quantum generation rate by produced

![Fig. 14](image-url) Exposure risk comparison of SARS-CoV-2 between the supermarkets and small shops: (a) dwell time; and (b) fresh air volume per person plotted as a function of occupant density.
by one infector. According to Dai and Zhao’s study, the quantum generation rate of SARS-CoV-2 ranges 14–48 h⁻¹ [14]. In this study, the quantum generation rate is set as the upper limit, i.e., 48 h⁻¹ for the sake of safety; \( p (\text{m}^3/\text{h}) \) is the pulmonary ventilation rate of each occupant; \( p = 0.3 \text{m}^3/\text{h} \) when people are participating in light activity indoors [32]; \( t (\text{h}) \) is the exposure time; the exposure time is set as the average dwell time of the customers in the retail building. \( \eta_1 (\cdot) \) and \( \eta_3 (\cdot) \) are the exhalation filtration efficiency and respiration filtration efficiency. The filtration efficiency of surgical masks on virus-laden aerosols is approximately 60% [33]. In this study, \( \eta_1 = \eta_3 = 50\% \) considering the influence of air leakage. \( Q (\text{m}^3/\text{h}) \) is the room ventilation rate which is on-site measured.

Fig. 15 shows the infection risks of COVID-19 for the customers in the supermarkets (a) and in the small shops (b). The results show that the average infection risks in the supermarkets and small shops were 1.96 × 10⁻⁴ and 1.25 × 10⁻⁵, respectively, when the proportion of infectors is 1% and all of the occupants wear surgical masks in the retail buildings. The \( t \)-test analysis revealed that the infection risk in the supermarkets was larger than that in the small shops (\( P < 0.001 \)). The main reasons were that the fresh air volume per person in the supermarkets was less than the small shops and the dwell time of the customers in the supermarkets was longer than the small shops. The infection risks of the customers were at a relatively low level both in the supermarkets and small shops when everyone wears surgical mask in the retail building.

The supermarkets and small shops should take different measures to reduce the customers’ exposure risk of SARS-CoV-2. The supermarkets are suggested to raise the fresh air volume of the mechanical ventilation system or utilize high-efficiency return air filter to remove aerosol pathogen. Whereas the small shops should control the customer flow to ensure the individuals’ distancing in the shopping process. The customers are encouraged to avoid rush hours and to wear surgical masks during shopping.

4.2. Limitations

This study analyzed the exposure risk of droplet and aerosol transmissions of SARS-CoV-2 by qualitative research. The Wells-Riley model was utilized to assess the droplet and aerosol transmission risk [34]. Meanwhile, the fomite transmission is also a possible transmission route of COVID-19 [45]. It was suggested that the fomite transmission may exist in the retail buildings that sell frozen food [35]. Whilst, this transmission route was considered to be exaggerated, with very small chance of transmission through inanimate surfaces [36]. Up to date, there is no evidence that food is a likely transmission route of SARS-CoV-2 according to the work of Han [37]. Accordingly, the fomite transmission was not investigated in this study due to the complexity and incomprehension.

A lumped parameter, i.e., the occupant area per person, was introduced in the present investigation to represent the average distance between adjacent individuals during the shopping process. Considering the customers were randomly scattered in the supermarkets/small shops, this simplification would influence the accuracy of exposure risk evaluation. A possible improvement is to utilize real-time surveillance cameras and computer graphics algorithm. In this way, the exact location and motion track of each customer can be ascertained and exact distance between customers can be acquired.

It should be noted that the interactions among customers and cashiers were important factors pertaining the infectious disease transmission, which was omitted in the original manuscript. According to on-site observation, the customers seldom talk to each other, unless to their companions in both supermarkets and small shops (in which case, the transmission was more likely to occur outside of the shopping spaces). In respective of the payment process, the usage of Mobile Payment largely reduced the hand-to-hand contact between customers and cashiers. The utilization of automatic checkout machine in supermarkets further decreased the interaction. The most frequently observed interaction occurred between customers and sales promoters of different brands in the supermarkets, which would increase the infection risks. As for the small shops, the shop owners seldom introduced the goods. The customers were usually from neighborhood and purchased the same goods frequently. Above were the observations during on-site survey, which deserve further quantitative investigation.

The air change rates in the supermarkets and the small shops were calculated based on the measured indoor and outdoor CO₂ concentration differences with the least square method fitting. Due to the limitation of the field and facilities, only five CO₂ sensors were distributed in each supermarket to monitor the indoor CO₂ concentration. More CO₂ sensors could provide information with higher representativeness. As there were neither doors nor windows connecting the shopping area with ambient environment, the indoor air was actually well-mixed due to the primary return air ventilation system. The air-conditioning outlets were evenly distributed in all the supermarkets, which were responsible for the homogeneous mixing of indoor CO₂. The estimated air change rates in the supermarkets could be verified with the air flow measurement of the outdoor air system in the future study. Furthermore, the spatial distribution of the CO₂ concentration in the supermarkets (i.e., large spaces) was not uniform. The characteristics of the spatial distribution of the CO₂ concentration instead of the average value need to be investigated in the future study to better evaluate the customers’ exposure risk at different locations. With regards to the small shops, the
CO₂ concentration decay method using a CO₂ generator could provide a more accurate estimation of the air change rate [38].

5. Conclusions
A field study was conducted on the customer flow (i.e., dwell time and occupant density) and ventilation rates in retail buildings, including 5 supermarkets and 21 small shops in Shenzhen, China. The surveyed small shops in the residential community can be classified into 5 types, meeting the daily necessities. The customer flow and hourly occupants’ number were counted on both weekday and weekend. The dwell time of the randomly sampled 1373 customers was obtained through surveillance cameras at the entries and exits of the supermarkets. The air change rates were estimated by the least square method with the indoor/outdoor CO₂ concentrations and the occupant number. This study provided the first-hand data of the main influencing factors of the SARS-CoV-2 exposure risk in retail buildings. The main conclusions are summarized as follows:

(1) The average occupant area per person in the supermarkets and small shops was 18.8 m²/per and 4.7 m²/per, respectively, revealing a more crowded environment in the small shops.

(2) The average dwell time of customers in the supermarkets (23.5 min) was longer than the combination of the 5 types of small shops (17.3 min). Furthermore, the average dwell time of a supermarket approximately linearly increased with the floor area. The Gamma distribution with a shape parameter of 3.0 fitted well with the probability distribution of the dwell time in supermarkets.

(3) The average indoor CO₂ concentration in the supermarkets (utilizing mechanical ventilation with an average air change rate of 0.7 h⁻¹) was 100–150 ppm higher than the small shops (utilizing natural ventilation with an average air change rate of 10.7 h⁻¹). The small shops provided an average fresh air volume per person of 216 m³/h-per, far exceeding the supermarkets with a value of 95 m³/h-per.

Declaration of competing interest
We declare that we have no financial and personal relationships with other people or organizations that could inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled “Field study to characterize customer flow and ventilation rates in retail buildings in Shenzhen, China”.

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Nomenclature

\[ A \] Floor area (m²)  
\[ \alpha \] Shape parameter of Gamma distribution  
\[ \beta \] Inverse scale parameter of Gamma distribution  
\[ \Gamma \] Gamma function

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Greek symbols

\( \alpha \) Shape parameter of Gamma distribution  
\( \beta \) Inverse scale parameter of Gamma distribution  
\( \Gamma \) Gamma function
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