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Computational fluid dynamics simulation of SARS-CoV-2 aerosol dispersion inside a grocery store

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A B S T R A C T

Grocery stores provide essential services to communities all over the world. The COVID-19 pandemic has necessitated better understanding of the transport and dynamics of aerosolized viruses, particularly for the assessment of infection transmission risk within grocery stores and for other providers of essential services. In this study, a 3D computational fluid dynamics model was developed for a medium-sized grocery store in the United States using Ansys Fluent software. Different cases were simulated of a single infected person releasing viral aerosols with and without wearing a face mask. Results showed characteristic airflow and temperature distribution patterns inside the store that can drive the indoor dispersal of viral aerosols. Unsteady spatial distribution of mean age of air was used as a metric to indirectly quantify areas of higher risk of infection. Several factors affected the localization of suspended viral aerosols. Major recirculation patterns in certain locations of the store caused by persistent eddies were primarily attributed to increased mean age of air. The maximum mean age of air in the grocery store was found to be less than 30 min. Simulation results indicate that, without wearing a face mask, the aerosol particles released from a coughing infected person can be spread throughout nearly one-quarter of the grocery store in less than 6 min. The source-control strategy with a face mask showed significant reduction of viral aerosols being dispersed indoors.

1. Introduction

COVID-19, which is caused by the SARS-CoV-2 virus, was recognized as a global pandemic in March 2020 by the World Health Organization. More than 131 million cases were reported worldwide as of April 2021, including more than 30 million active cases and more than 550,000 deaths in the United States [1]. Since the COVID-19 outbreak starting at the end of 2019, several studies focused on the airborne transmission of SARS-CoV-2 virus, including a widely reported study in a poorly ventilated restaurant in China where customers were infected by the virus through airborne transmission [2,3]. Airborne transmission of the SARS-CoV-2 virus has been confirmed as the dominant route to spread the virus compared with contact transmission [4], and increasing outdoor air ventilation of enclosed spaces has been recommended to reduce the airborne transmission of SARS-CoV-2 [5]. Because the weight of the data indicates that the role of heating, ventilation, and air-conditioning (HVAC) systems have a pivotal role to control the airborne transmission, many investigations have been dedicated to understanding the impact of HVAC systems on airborne transmission route, and to control and reduce the spread of the SARS-CoV-2 aerosols in the enclosed spaces. Some studies have focused on capturing and eliminating the viruses using air filters and heated air disinfection systems [6] or ultraviolet air disinfection [7]. One study showed that besides high temperature and ultraviolet irradiation, the SARS-CoV-2 survival rate is also negatively impacted by ozone and low humidity [8]. Along with investigations on HVAC systems to minimize and control the spread, the proper use of face coverings (i.e., N-95 masks and surgical masks) has also been shown to be vital for fighting against viral infection transmission in other pandemics. For instance, studies conducted on influenza and coronavirus pandemics have shown that wide and effective use of face masks could make an important contribution to reducing the spread and, consequently, delaying the pandemic [9–11]. Similarly, the community-wide use of masks along with social distancing has been shown to effectively reduce community transmission of the SARS-CoV-2 virus [12,13].

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Although strict policies and strategies have been implemented to control the pandemic worldwide in addition to mandatory face coverings—such as social distancing, travel restrictions, population-wide screening and testing, isolation, and quarantine—some businesses are deemed necessary for sustaining life during the pandemic, such as grocery stores, which provide essential needs and supplies to everyone. However, because of the high occupancy circulation rate, grocery store employees and customers may be at a high risk of being exposed to the SARS-CoV-2 virus. For example, 20% of the 104 grocery workers tested at a store in Boston in May 2020 had COVID-positive results from nasal swab tests [14].

The requirement of continuous operation of the grocery stores during the pandemic is obvious. A comprehensive study of the airborne transmission of SARS-CoV-2 in grocery stores would be helpful to understand the virus spread and develop mitigation methods to lower the infection risks in grocery stores. Recently, Cui et al. [15] reported a numerical study of virus-laden particles in a supermarket, in which the particles are released from a fixed location in the supermarket. They found attachment on surfaces reduces the transport of particles significantly within the supermarket. In this paper, we investigated the SARS-CoV-2 aerosol dispersion in a grocery store setting in the United States using a 3D computational fluid dynamics (CFD) model. Since the infected person is moving, the particles are released along the trajectory of the person in the grocery store. The numerical methodology of the CFD modeling has been validated with a set of experimental data. We did not model any close-contact (large droplet transmission route, i.e., >100 μm) or fomite (i.e., surface-contact) transmission mechanisms of viruses and only modeled the aerosol (small droplets ≤3 μm) transmission route. The results from the present work show how the SARS-CoV-2 aerosols transmit in a grocery store and identifies some high-risk locations in the store.

Fig. 1. Layout of the grocery store and its air distribution system: (a) a 3D rendering, and (b) a top-down view.
2. Methods

A 3D CFD model was developed using a commercial code Ansys Fluent (Version 17.2) [16] to simulate the indoor airflow, temperature distribution, and dispersion of the virus-carrying particles. Ansys Fluent is installed in a workstation with an Intel Xeon E5-2630 v3 processor and 64 GB memory. The CFD modeling approach was initially validated with data from another study that simulated similar viral particle dispersion inside a single-patient ward [17]. The validated CFD model was then used to simulate the airflow and temperature distribution inside the grocery store under steady-state conditions. The air quality at various locations within the grocery store was also assessed using mean age of height and width of the shelves are 2 m and 1.32 m respectively. Two freezers are 1 m and 1.6 m.

The layout of the shelves and freezers is based on a typical medium-sized store. The height and width of the shelves are 2 m and 1 m, respectively, as shown in Fig. 1 (b). Most of the air goes back to the AHUs and supplied to the grocery store through four sets of diffusers.

2.1. Simulation domain

Fig. 1 shows the simulation domain of a grocery store, in which the layout of the shelves and freezers is based on a typical medium-sized grocery store in the United States. The length and width of the grocery store are 62.9 and 40.7 m, respectively, with 4.9 m roof height. The height and width of the shelves are 2.3 m and 1 m, respectively. Two kinds of freezers are deployed. The height and width of the freezers against wall are 2 m and 1 m, while height and width of the other freezers are 1 m and 1.6 m.

The two air handling units (AHUs) are suspended at a height of 4.0 m above the floor. Return air (8,500 cfm) and outdoor air (500 cfm) are mixed at each AHU. In total, 18,000 cfm of mixed air is cooled by the AHUs and supplied to the grocery store through four sets of diffusers. The flow rates of each set of the diffusers are 0.236 m³/s (550 cfm), 0.31 m³/s (650 cfm), 0.38 m³/s (800 cfm), and 0.40 m³/s (850 cfm), respectively, as shown in Fig. 1 (b). Most of the air goes back to the AHUs through two return air grilles, and the rest escapes from the grocery store through an exhaust hood at the northeast corner of the grocery store.

2.2. Governing equations and boundary conditions

The airflow in the grocery store was modeled with the following continuity and momentum equations:

\[ \frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0 \, , \tag{1} \]

\[ \frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] - \rho u_i u_j + F_i \, , \tag{2} \]

where \( u_i, \rho, p, \) and \( \mu \) are air velocity vector, density, pressure, and dynamic viscosity, respectively. \( F \) is the gravitational body force, which is described by a Boussinesq approximation. Because the airflow is turbulent in the grocery store, a basic renormalization-group (RNG) \( k-\epsilon \) model was adopted in the CFD model, based on the examples of previous studies on indoor airflows [18–20]. The Reynolds stress term is

\[ -\rho u_i u_j = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + \frac{2}{3} \left[ (\rho k + \mu) \frac{\partial u_i}{\partial x_j} \right] \delta_{ij} \, , \tag{3} \]

where \( \mu_t \) is the turbulence dynamic viscosity and calculated by introducing turbulence kinetic energy \( k \) and turbulence dissipation rate \( \epsilon \) as

\[ \mu_t = \rho C_f \frac{\epsilon^2}{\epsilon} \, . \tag{4} \]

The air temperatures at the interior surface of the roof and freezers are assumed to be 39.85°C and 16.85°C, respectively. The interior wall and shelves are assumed to be isothermal with room temperature, so heat does not transfer between these structures and the room air. The thermal mass of the goods/products on the shelves is assumed to be ignored.

Because the envelope of the grocery store is thermally insulated, the adiabatic boundary conditions are applied to all the exterior walls and floor.

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\[ \mu_t = \rho C_f \frac{\epsilon^2}{\epsilon} \, . \tag{4} \]
6. In the DPM, the particles are assumed to be reflected by the roof. For the other walls, including the floor, side walls, and shelves/freezers, the particles will be trapped (i.e., staying at the surface and not going back to the air).

7. All particles are assumed to return to the AHU and be trapped at the filter (e.g., using a HEPA filter with 99.97% theoretical filtration efficiency) [21] and thus will not recirculate into the space.

8. Because the infected person is moving, the airflow on the person’s body has a velocity equal to the moving speed of the person. The person’s body releases 76 W [22] heating to the grocery store. All particles that fell on the person’s body will stay with the person and will not be released to the space.

The CFD results were converged because the residual errors of continuity, velocities in x, y, and z directions, k, and ε were all less than $10^{-3}$ and the residual error of energy was less than $10^{-6}$. In addition, the room average temperature also reached a steady state, which indicates the result was converged. The criteria are enough to obtain the final solution.

2.3. Mesh generation

To conduct the simulation, 2.5 million cells of polyhedral mesh were generated in the grocery store model. The maximum size of the mesh is 0.3 m in the whole domain, except at sidewalls of the store and inlets/outlets of the air distribution system, where the mesh was reduced to 0.2 m and 0.1 m, respectively. At the cuboid representing the infected person’s body, the mesh was refined to 0.1 m vertically, and 0.05 m horizontally. At the mouth of the infected person, the mesh size was 5 mm. Fig. 2 (a) depicts the mesh of at the infected person’s body. The sensitivity of the mesh size has been tested by comparing simulation results using the described mesh and that using a finer mesh, which doubles the number of cells. The grid-convergence index (GCI) [23], calculated with Eq. (14), is used to estimate the error in velocity magnitude and temperature calculated with the described grid.

$$GCI = F_s \left( \frac{\rho^{\text{ref}} \delta}{1 - \rho^{\text{ref}}} \right),$$

where, $r = 2^{1/3}$ is the linear grid refinement factor, $\text{acc} = 2$ is the formal order of accuracy (second-order), $F_s = 1.25$ is the safety factor as suggested by Refs. [23, 24], and $\delta$ is the difference of the variables between the described mesh and a refined mesh. Here the variables are velocity magnitude and temperature. Fig. 2 (b) and (c) shows the comparison of velocity magnitude and temperature with GCI along the central vertical line of the grocery store between two meshes, which indicates the currently used mesh can achieve almost identical results to that using a finer mesh but requires only half of the computation time.

Fig. 2. (a) Mesh on the surface of the simulated infected person and the immediate vicinity of the 3-dimensional flow domain (Note that the actual flow domain is 3-dimensional, the full-scale illustration of which can provide limited useful information). Graphical depiction of the variation of the airflow velocity magnitude (b) and temperature (c) with GCI along a central vertical line in the grocery store to show grid-independence of the flow field characteristics.
2.4. Particle characteristics

The SARS-CoV-2 virus is usually carried by droplet particles blowing out to a space through human behaviors, such as breathing and coughing. The aerosol-specific parameters presented in a previous study [25] were adopted in this study to resemble the physical properties of airborne SARS-CoV-2 aerosols. About 44 particles are released during each breath, and the person breathes 15 times per minute [25]. Most particle diameters range from 0.3 to 3 μm [26], so the size distribution of the particles is considered in the model by defining a series of particle size parameters, including the minimum diameter, maximum diameter, mean diameter, and spread parameter in DPM. The particles are assumed to be released from the mouth of the person (opening size 16 cm²) during normal breathing with a speed of 0.3 m/s in a cone shape with a total angle of 25° [25]. For simplification, the temporal variations in the generation rates and velocities of the exhaled virus-laden aerosols have not been simulated. Although omitting this temporal variation will not perfectly reflect the actual airflow conditions, the authors believe that the current setup of the simulation case can provide an overall large-scale picture of the aerosol dispersion characteristics in the flow domain. Simulating the small factors such as temporal variation of the release rates, small drafts and air density gradients would otherwise introduce additional modeling complexity yet provide the same large-scale HVAC system-driven flow characteristics that we have simulated with a simplified CFD model. The particles density is assumed to be 1 g/mL, as the exhaled respiratory aerosols comprise mostly of saliva which largely resemble the physical properties of water [27]. When a person coughs without wearing a face mask, approximately 13,000 particles are released into the atmosphere with every cough [26]. The particle size distribution and releasing cone are assumed to be the same as that for breathing, but the release speed is 11.2 m/s for coughing according to an experimental measurement of a previous study [28].

2.5. Model validation

To validate the numerical methodology employed in the CFD model for modeling the airflow, temperature distribution, and particle transmission, a CFD model for a single-patient ward shown in Fig. 3 was built following the description detailed by Yin et al. [17]. The CFD model’s prediction of airflow, temperature distribution, and particle concentration were compared against the measured data in the patient ward. Fig. 4 shows the comparisons between the simulation results and the measured data of air velocity, nondimensional temperature, and nondimensional particle concentration at three locations in the ward.

The nondimensional temperature \( \theta \) was calculated with Eq. (15), and the nondimensional concentration \( \varepsilon \) was calculated with Eq. (16):

\[
\theta = \frac{(T - T_s)(T - T_s)}{(T_C - T_C)},
\]

\[
\varepsilon = \frac{(C - C_s)(C - C_s)}{(C_C - C_C)}.
\]

Where \( C \) is the particle concentration, subscript \( e \) is the average value, and subscript \( s \) is the value at the ventilation supply vent. Fig. 4 shows a very good agreement between the CFD model’s prediction and the measured data, indicating that the algorithms employed in the CFD model can accurately predict the indoor air velocity, temperature distribution, and particle concentration.

2.6. Simulated cases

A single infected person was simulated in the CFD model. As indicated with the red lines in Fig. 1, the infected person enters the grocery store from one of the doors on the west side, passes through one of the southern aisles in a straight line, moves across the grocery store from south to north through a corridor at the eastern side, turns 90° to the left at the end of the corridor, and leaves the grocery store from another door at the west side of the store. A cuboid (0.26 m wide, 0.26 m long, and 1.75 m tall) was used in the CFD model to represent the person. The moving speed of the person was assumed to be 0.3 m/s [29]. Therefore, the total time the person stays inside the grocery store is 356 s (about 5.9 min). Three cases were simulated in this study:

- **Case 1:** The person passes through the grocery store without wearing a face mask.
- **Case 2:** The person passes through the grocery store wearing a face mask and coughing several times inside the grocery store. At times when the person is not coughing, there is regular breathing.
- **Case 3:** The person passes through the grocery store wearing a face mask and breathing regularly (no coughing).

To simulate the coughing scenario (Case 2), the person was assumed to cough once per minute when inside the grocery store. For Case 3, an ordinary surgical mask with particle removal efficiency of 75% [30] was selected in this study. By wearing the surgical mask, the number of particles released into the atmosphere during each breath was reduced from 44 (Case 1) to 11 (Case 3).

Fig. 3. A schematic view of (a) the patient ward and (b) locations of measured data points. TG: tracer gas.
2.7. Modeling dispersion of particles released from a moving person

Because the body of the infected person will block the air and heat the air surrounding it, the body must be included in the CFD model. Because the average breathing frequency of a human being is about 15 times per minute (i.e., one breath every 4 s) [25], considering the 0.3 m/s walking speed, the infected person was assumed to walk 1.2 m between two breaths. Thus, the person did not release aerosol particles continuously due to breathing. Instead, aerosol particles were released every other 1.2 m due to breathing, which provides a simplified model of the moving person. In this study, a quasi-steady method was employed to model the moving person. A series of identical cuboids were placed along the walking path of the infected person with a spacing of 1.2 m where the particles were released. The quasi-steady approach worked as follows:

1. When the person reached a certain position, the cuboid in that position was set as a solid boundary, which will block the air and heat the air surrounding it.
2. Other cuboids were treated as air without a solid boundary, which will not block and heat the air.
3. A steady-state simulation was conducted to obtain the airflow and temperature distribution results.
4. Then, the DPM simulated the person releasing particles in each position.
5. Once the person moved to the next position, steps 1, 2, and 3 were repeated.

Because in present study, the infected person is walking in a long distance in the grocery store, the quasi-steady method models the moving person in a simplified way and avoids the extra computational expense of other methods (e.g., dynamic mesh [22]). A script was developed within Ansys Fluent to control the quasi-steady simulation.

This approach to the representation of a moving boundary is not without precedent, and because the primary interest is not upon the details of the wake and its impact upon particle transport but on the larger scale transport characteristics of the order of tens of meters, pursuit of this approach is justified. The technique shares some of the properties of the immersed boundary technique used in numerous applications in the literature [31]. Unlike traditional applications of immersed boundaries, the moving body was not represented by a force field but was explicitly represented in the mesh. The treatment of the cells inside the moving boundary was controlled by the script mentioned previously, which turns on and off the appropriate boundaries to control which cuboid is treated as the person. Because the boundary was explicitly represented in the mesh, there are similarities to the Chimera grid approach [32]. However, instead of moving one mesh relative to another through time, the treatment of the mesh by the solver changed with time. Numerical tests indicated that this approach well represented the flows of interest here while only coarsely representing the wake of the infected person.
the moving person. In the DPM, after releasing the particle dispersion is mainly affected by the air flow and the buoyancy force. The quasi-steady approach includes the effects of the moving body on the air flow by treating the person’s body as the moving boundary body (see boundary condition 8). As a result, in the quasi-steady approach, the moving body does affect the particle dispersion.

In the DPM, the trajectories of the particles were computed by the model based on the force balance on the particle as shown in Eq. (17).

\[ \frac{d(\rho u_p)}{dt} = F_D (u_p - u_p) + F_p, \]

(17)

where \( F_D \) is the drag force per unit particle mass, and \( F_p \) is the gravity force. \( F_D \) is defined in Eq. (18):

\[ F_D = \frac{18 \mu C_D Re^2}{d_p^2}, \]

(18)

The details of the governing equations can be found in the supplementary materials.

In Eqs. (17) and (18), \( u_p \) is the particle velocity, \( d_p \) is the particle diameter, \( Re \) is the relative Reynolds number, and \( C_D \) is the drag coefficient. \( Re \) and \( C_D \) are calculated with Eqs. (19) and (20), respectively:

\[ Re = \frac{\rho d_p |u_p - u|}{\mu}, \]

(19)

\[ C_D = a_1 + a_2 Re + a_3 Re^2, \]

(20)

where \( a_1, a_2, \) and \( a_3 \) are fixed constants in the Fluent program [33].

The steady-state simulation took about 8 h while the DPM took about 17 h.

3. Results and discussion

The CFD simulation predicted the distribution of airflow, temperature, and the viral aerosols in the grocery store in the three cases. A collection of simulation results was visualized to reveal the spreading patterns of viral aerosols after being released from the infected person.

3.1. Airflow patterns

Fig. 5 shows the simulation-predicted airflow path from each diffuser using path lines. Path lines from each set of diffusers are separately visualized based on the supply airflow rate of each diffuser. As shown in Fig. 5(a), most of the air supplied from the diffusers on the east side of the store—each of which supplies 550 cfm air toward the east wall—returns to the grille of the AHU at the east side of the store, and some of the air escapes from the store through the exhaust hood at the northeast corner. Fig. 5(b) shows that air from one of the 650 cfm diffusers next to the west grille directly returns to the west grille, which creates a short circuit. Most air from other 650 cfm diffusers go through the aisles to the east return grille and the exhaust. It creates some air recirculation (eddies) at the southeast corner and between the aisles of the grocery store. The 800 cfm diffusers blow air toward the west wall, so the reflection of the air from the wall creates numerous eddies near the west wall, and the air eventually goes into the west grille as shown in Fig. 5(c). Some of the air from the 800 cfm diffusers close to the west grilles directly returns to the grille after reflecting from the west wall. Fig. 5(d) indicates that the 850 cfm diffusers blow air to the central area of the grocery store, generating eddies between the aisles. Because of the high flow rate, air supplied from the 850 cfm diffusers reaches almost everywhere in the grocery store and returns to both grilles, and some escapes from the exhaust hood. Because all diffusers have the same size, a higher flow rate from a diffuser means a higher velocity of air supplied from the diffuser.

Fig. 5 shows that there are three airflow patterns in the grocery store. The first pattern is fast air movement in one direction, which is created by the 650 and 850 cfm diffusers. Some examples of the first pattern are marked using circles in Fig. 5. The cold air blown from these diffusers goes toward the center of the grocery store and travels through the aisles in the west-east direction before returning to the AHUs. The second pattern is slow air movement in certain regions. For example, in some regions in the east end of the aisles, air from the 850 cfm diffuser is
entrained as shown in Fig. 5(d) (marked as a rectangle). The third pattern is persistent eddy formation. The eddies are usually near the west and east walls, where the airflow is blocked by the walls and bounces back toward the diffusers. Some of the reflected air is then drawn back to the wall by the shear force induced from the supply air and thus forms a closed circulation pattern confined in a space. Persistent eddies exist in all four corners and aisles of the grocery store. The eddies in the northeast corners are more obvious because of the exhaust hood entraining airflows. Some typical eddies are marked as squares in Fig. 5.

The MAA, $t_{\text{mean}}$, was used to quantify the air quality in the grocery store. MAA indicates the mean value of residence time of local air and is calculated by solving the following partial differential equation, Eq. (21), where $D$ is the material derivative, $\rho$ is the density, $t$ is time, and $x$ is the location:

$$\frac{D(\rho t_{\text{mean}})}{Dt} - \frac{\partial (\rho t_{\text{mean}} u_i)}{\partial x_i} = \rho .$$  

(21)

The iso-surfaces of the MAA are shown in Fig. 6, in which (a), (b), (c), and (d) represent MAA iso-surfaces of 15–19 min, 20–22 min, 23–25 min, and 26–30 min, respectively. An iso-surface of MAA represents the surface of same value of MAA in the grocery store. If two iso-surfaces are combined, it shows the volume, in which the value MAA is between the two values. For example, the MAA iso-surface of 26–30 min indicates that the MAA in the volume confined by the iso-surfaces is between 26 and 30 min. The selection of the time periods is because in most part of the grocery store, the MAA is between 20 and 25 min. To divide the MAA to the 4 periods helps to identify the MAA distribution. The steady-state simulation indicates the maximum MAA in the grocery store is 30 min. Fig. 6 shows that the MAA in the east side of the grocery store is older i.e., has higher MAA value) than that in the west side because the 550 cfm diffusers, which deliver air at the lowest velocity, are in the east side. Therefore, air spends more time in the grocery store before returning to the grille or escaping through the exhaust. Fig. 6(a) reveals that in addition to the regions close to diffusers, a region in the central west part of the grocery store also contains air at a young age because this region is close to the grilles, and the diffusers nearby have a high flow rate (800 cfm). Therefore, airflow from the 800 cfm diffusers goes straight to the west grilles after being reflected by the west wall (i.e., a short circuit of the air). Fig. 6(d) indicates that the oldest air is located at the aisles in the east side of the store, which coincides with the low air speed region under the 550 and 850 cfm diffusers. The viral aerosols released in these areas are likely to float in the air for up to 30 min. Fig. 6(e) depicts a vertical profile of the MAA at a cross-section marked in Fig. 6(d). This profile shows that in the aisle, the oldest air is within 4 m above the ground, which covers the entire breath zone.

To compare with the MAA, the turn-over time of the air, $t_\text{to}$, was calculated with Eq. (22), which is the shortest possible time it takes to replace all the air in the grocery store:

$$t_\text{to} = V/Q .$$  

(22)

where $V$ is the total volume of the grocery store, and $Q$ is the total circulation airflow rate.

Fig. 6. MAA iso-surfaces in the grocery store. (a)–(d) Iso-surfaces of different MAA bins; (e) vertical profile of MAA at a cross-section marked in (d).
Given 11,440 m$^3$ total volume of the air in the grocery store and 8.967 m$^3$/s total airflow rate, $\tau$ is about 21 min, which is 9 min less than the maximum MAA. This comparison indicates that the air distribution system in the grocery store is effective to circulate air in the entire building.

### 3.2. Temperature distribution

In addition to the airflow, steady-state temperature distribution in the grocery store was also predicted with the CFD simulation, as buoyancy forces are another major driving forces that determine macroscopic flow field characteristics. Fig. 7 depicts the temperature distribution in two cross-sections of the grocery store—one along the west-east central line and the other along the north-south central line. A vertical temperature stratification in the grocery store is shown in Fig. 7. Although the indoor air temperature within 3 m above the floor is about 18 °C, it is much warmer near the roof. Fig. 8 shows the vertical temperature change from floor to roof at five locations in the grocery store as shown in Fig. 7. The large air temperature gradient near the roof is caused by the higher interior surface temperature of the roof (39.85 °C) and the buoyancy force that keeps hot air near the roof. The airflow path from diffusers is depicted in Fig. 5. Cold air supplied from diffusers moves downward because of its higher density than the surrounding air. On the other hand, the high temperature at the ceiling keeps warm air (with a temperature near 30 °C) at $y > 3$ m as shown in Fig. 8 (a). The recirculating airflow pattern helps to mix the air within 3 m above the floor. As a result, the air temperature is at 18 °C at $y < 3$ m as shown in Fig. 8 (a).

### 3.3. Particle transport

Fig. 9 depicts the particle distribution at different times after the infected person walks through the grocery store and breathes without wearing a mask (Case 1). The colors of the dots shown in Fig. 9 indicate how long the particles have been in the grocery store. For example, red indicates oldest particles and blue indicates newly released particles. The figure shows that the particles are initially behind the person after being released and then spread away from the walking path with the surrounding airflow. Fig. 9 shows particles spreading widely in the south side of the grocery store, where the person initially entered the store. It also shows that some particles are gathering near the east grille and the exhaust.

Fig. 10 demonstrates the particle distribution after the infected person walks through the grocery store and coughs once in each minute without wearing a face mask (Case 2). After 5.9 min, the first cluster of particles occupy the entire southwest part of the grocery store and the second cluster of particles, indicated by the orange dots, occupy the aisles at the south side of the store, where eddies also exist, as shown in Fig. 5 as the third pattern. The third and fourth clusters of particles, indicated with the yellow and green dots, do not expand as much as the other particles because they are released in a region with slow air movement (the second flow pattern in section 3.1), and some of these particles are moving toward the return air grille at the AHU at the east side of the store. Because the last cluster of particles, indicated with the blue dots, do not have time to travel before the infected person leaves the grocery store, these particles linger near the walking path. Fig. 10 shows that the aerosol particles released by the coughing infected person without wearing a face mask (Case 2) spread throughout nearly one-quarter of the grocery store in less than 6 min.

Fig. 11 shows the particle distribution after the infected person walks through the grocery store wearing a face mask and not coughing (Case 3). Because 75% of the particles released from the infected person are blocked by the face mask when breathing, the particle density in Case 3 is much lower than that in Case 1.

Fig. 11 through 13 show the mass concentrations of the particles from Cases 1, 2, and 3 respectively. In Cases 1 and 3, the particle mass concentration reaches $10^{-13}$ kg/m$^3$ only at a few locations, and the iso-surfaces of $10^{-13}$ kg/m$^3$ are only depicted for Case 2. Fig. 12 indicates that when the person breathes without wearing a face mask, the resulting particle concentration reaches $10^{-14}$ kg/m$^3$ near the infected person. However, after the person leaves, airflow dilutes the particle concentration by one order of magnitude.

Fig. 13 shows the particle concentration in Case 2 at different times when the infected person walks and coughs in the grocery store. As shown in this figure, a few areas have $10^{-13}$ kg/m$^3$ particle concentration, which is higher than that in other places in the grocery store. These areas are below the return grille of the east side AHU, near the exhaust hood, and where the infected person coughs. The higher viral particle concentration means higher risk for being infected by the virus. Also, the particle concentration is relatively low ($10^{-13}$ kg/m$^3$) in areas with eddies (the third flow pattern), such as the southwest corner and aisles in the south side of the store. The eddies appear to create forced convection and make air circulating (see Fig. 5) in a localized space with relatively high velocities, which spread and dilute the particles quickly, which is similar to the previous study from Ref. [34].

If the infected person wears a face mask (Case 3), particle concentration in the grocery store is much lower than that in the two other cases. Fig. 14 shows that particle concentration in Case 3 is much lower than that in Case 1 because of fewer particles being released.

### 3.4. Limitations of this study

This study highlights some major patterns of viral particle dispersion within the grocery store. However, this study has several limitations that future studies can address. First, the grocery store was not modeled as a transient and unsteady flow-field. The model also did not consider the localized thermal plume effects, jets, and air curtains produced by equipment such as refrigerator display cabinets within the store, disturbances and wakes caused by the movement of people and equipment, and the effects of door opening. The shelves were also modeled as solid objects and all parts of the simulation domain were simplified in geometric details. Although the addition of these finer details can give more detailed insight into the actual particle dispersion patterns, the major drivers of prominent airflow patterns have been captured with reasonably sufficient detail through the steady-state simulations used in this study. We do not anticipate major alterations in the airflow patterns introduced by these smaller perturbing factors when compared to the airflow rate magnitudes introduced by the HVAC system and exhaust fans, which are considerably greater than these smaller factors. Humidity is not considered in the model. The impacts of air humidity on the evaporation and transportation of the particles (tiny water droplets containing the virus) are recommended for future work.

In terms of the assumptions regarding the viral particles themselves,
the size of the aerosols themselves says little about the infective dose of viruses carried by the particles. In most cases, influenza-like viruses such as SARS-CoV-2 do not always remain airborne in singular forms as a virion but are generally encapsulated inside an aerosolized droplet of saliva or sputum, and there can be many such virions within each aerosol particle [35–38]. Based on how many virions are present inside such an aerosol particle, and whether the number of viruses contained within each aerosol particle is sufficient to transmit infection from one person to another, the infectious quantum has been defined and used by many previous studies to quantify the risk of infection [18,39–44].

Because of the lack of data at the time of publication of this study regarding a widely accepted quanta generation rate and infectious dose that are representative for SARS-CoV-2, the scope of this study is also limited to only identifying the physical characteristics of dispersion patterns of biologically and chemically inactive particles within the setting of a grocery store. Also, the reduction of aerosol sizes over time due to evaporation was not considered in this study to simplify the analyses. Simulations performed in this study did not account for the recirculation of viral aerosols through the HVAC system, and the use of a HEPA filter is unlikely to be practically used in a real grocery store. However, given that the objective of this study was to get a firsthand visualization of how far viral particles can disperse within a single and continuous air-conditioned zone of a grocery store, our simplified setup provides an unobstructed view of the scenario.

4. Summary and conclusions

A CFD model was developed based on information of a typical medium-sized grocery store in the United States. Computer simulations...
with the CFD model predict the airflow patterns, temperature distribution, and dispersion of aerosol particles released from an infected person in three cases: (1) walking without wearing a face mask or coughing; (2) walking and coughing without wearing a face mask; and (3) walking and wearing a face mask without coughing.

Our analyses provide a glimpse of the macroscopic length-scale airflow patterns inside a typical US grocery store which directly drives the aerosol dispersion patterns. The duct layout of the HVAC system used in this study represents a typical design for medium sized grocery stores in the US. The qualitative as well as quantitative results we present here is not only applicable to this specific layout of the grocery store but can be expanded to other layouts of the buildings of similar geometry and size when the results are viewed from the perspective relative to the supply, return, and exhaust grilles of the HVAC system. Irrespective

Fig. 12. Particle mass concentration iso-surfaces when the infected person walks through the grocery store, breathing only and without wearing a face mask.

Fig. 13. Particle mass concentration iso-surfaces after the infected person walks through the grocery store while coughing without wearing a face mask.
the release location, orientation of the aisles, and specific locations of the supply, return and exhaust grilles, a few general observations can be made from the characteristics of the simulated flow field:

- The air distribution system in the grocery store can create some persistent airflow eddies in the aisles, close to the walls, and near the corners. These eddies make air circulating in a localized space with relatively high velocities, which spread and dilute the particles quickly. However, these eddies keep the aerosol particles suspended in the air for a long time.
- The maximum MAA in the grocery store was less than 30 min, which is 9 min longer than the average turn-over time of the air for the given volume and total airflow rate of the grocery store. This MAA indicates that the HVAC system is effective in circulating air throughout the grocery store without significant short circuits between the supply air diffusers and the return air grilles.
- Without wearing a face mask, the aerosol particles released from a coughing infected person could spread throughout nearly one-quarter of the grocery store in less than 6 min.
- The concentration of aerosol particles was highest not only near the infected person, but also in areas where airflows merge, such as below the return grilles of the AHUs and near the exhaust hood. Additional virus disinfection methods, such as UV light, may be needed in these areas to reduce the risk of being infected by the virus.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at [https://doi.org/10.1016/j.buildenv.2021.108652](https://doi.org/10.1016/j.buildenv.2021.108652).

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