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A Computational Fluid Dynamics Model for the Assessment of SARS-CoV-2 Aerosol Dispersion inside a Grocery Store

Abstract

During the COVID-19 pandemic, grocery stores provide essential services to communities all over the world. It is necessary to understand the transport and dynamics of aerosolized viruses in grocery stores for the assessment of infection transmission risk. A 3D computational fluid dynamics (CFD) model was developed for a medium-sized grocery store in the United States. Different cases are simulated to predict the transportation of viral aerosols released from an infected person in the grocery store. The influences of air circulation improvement on transportation of the viral aerosols are discussed. Results show that air circulation enhancement in the grocery store can affect the virus-laden particles distribution in a grocery store from an infected person.

Introduction

In March 2020, the World Health Organization declared the COVID-19 outbreak a global pandemic, which is caused by the SARS-CoV-2 virus. By the end of 2021, more than 287 million cases were reported worldwide, in which there are more than 54 million cases in the United States leading to more than 800,000 deaths (WHO). It has been confirmed that airborne transmission of the SARS-CoV-2 virus is the dominant route to spread the virus compared with other transmission media, e.g. contact transmission (R. Zhang et al. 2020). As a result, a lot of studies have reported focusing on the airborne transmission of SARS-CoV-2 virus since the outbreak of COVID-19. Just after the outbreak, it was reported studies in a poorly ventilated restaurant in China in which customers were infected by the virus through airborne transmission (Kutter et al. 2018; Y. Li et al. 2021). The results show some dead zones of air flow in the restaurant aggravated the possibility of infection. Recently, Cui et al. (Cui et al. 2021) reported their study of airborne transmission of virus-laden particles in a supermarket. In their work, 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 addition to the investigations on airborne transmission to control the spread, it also has been shown that the proper use of face coverings can be effective against viral infection transmission in pandemics. For example, it has been concluded from strudies on previous influenza and coronavirus pandemics that wide and effective use of face masks can make an important contribution to reducing the spread and, consequently, delaying the pandemic (Brienen et al. 2010; Tracht, Del Valle, and Hyman 2010; Leung et al. 2020). Similarly, the use of masks along with social distancing has been shown to effectively reduce community transmission of the SARS-CoV-2 virus in the COVID-19 pandemic (Eikenberry et al. 2020; T. Li et al. 2020).

During the pandemic, one may select to avoid traveling and gathering to keep safe, but some activities are still unavoidable, one of which is grocery shopping. Grocery stores provide essential needs and supplies to everyone, which are necessary for sustaining life during the pandemic. Although some customers choose grocery delivery services, grocery store employees and in-store customers may still be at a high risk of being exposed to the SARS-CoV-2 virus because of the high occupancy circulation rate. For example, it was reported 20% of the 104 grocery workers tested at a store in Boston had COVID-positive results in the beginning of the pandemic, May 2020 (Lan et al. 2021). It would be helpful to understand the virus spread in grocery stores from a study of the airborne transmission of SARS-CoV-2 in grocery stores. Therefore, the authors developed a 3-dimensional (3D) computational fluid dynamics (CFD) model to investigate the SARS-CoV-2 aerosol dispersion in a grocery store setting in the United States (M. Zhang et al. 2022). The model describes an infected person in moving in a grocery store. Particles containing SARS-CoV-2 are released along the trajectory of the person in the grocery store. In present work, the CFD model was employed to investigate the effects of ceiling fans on the SARS-CoV-2 aerosols transmit in a grocery deployed to improve the air circulation. The results from this paper show how the air circulation enhancement induced by the ceiling fans influences the virus-laden particles distribution in a grocery store. As a result, the infection risk may change due to the air circulation enhancement.

Simulation Method

A 3D CFD model was developed using a commercial software Ansys Fluent (Ver. 17.2), which is installed in a workstation with an Intel Xeon E5-2630 v3 processor and 64 GB memory, to simulate the indoor air flow, temperature, as well as dispersion of the virus-laden particles.

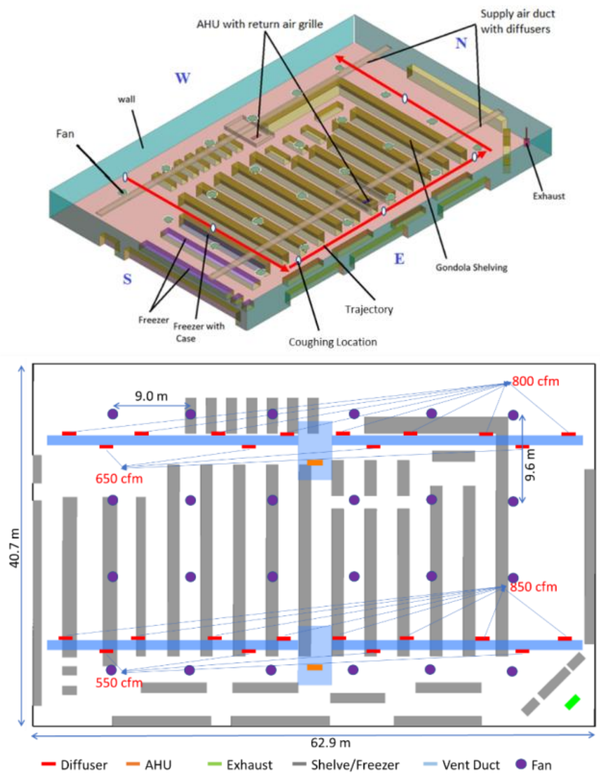

Figure 1. Layout of the grocery store and its air distribution system: (a) a 3D rendering, and (b) a top-down view.

Simulation Domain

Figure 1 depicts 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 m and 1.32 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 m^3/s (550 cfm), 0.31 m^3/s (650 cfm), 0.38 m^3/s (800 cfm), and 0.40 m^3/s (850 cfm), respectively, as shown in Figure 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. A matrix of fans is deployed in the grocery store 3 meters above the floor, following the spacing guidelines (Canarm Ltd.). The distance between two adjacent fans is shown in Figure 1 (b). The diameter of the fans is 1.44 m with 9.67 m^3/s (20500 cfm) speed (Canarm Ltd.).

Governing Equations and Boundary conditions

The momentum equation with continuity equation were used to model the airflow in the grocery store:

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

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right) - \rho\overline{u_i' u_j'}\right] + F \, , \tag{2}$$

where u, ρ, p, and μ are air velocity vector, density, pressure, and dynamic viscosity, respectively. a Boussinesq approximation was employed to calculate the gravitational body force F. In the CFD model, a basic renormalization-group (RNG) k-ε model was adopted to describe the turbulence airflow in the grocery store, which is based on the examples of previous studies on indoor airflows (Yan et al. 2017; Isukapalli et al. 2013; Z. Zhang et al. 2007). The Reynolds stress term is

$$-\rho\overline{u_i' u_j'} = \mu_t\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right) - \frac{2}{3}\left(\rho k + \mu_t \frac{\partial u_k}{\partial x_k}\right)\delta_{ij} \, , \tag{3}$$

where μ_t is the turbulence dynamic viscosity and calculated by introducing turbulence kinetic energy k and turbulence dissipation rate ε as

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \, , \tag{4}$$

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] - \rho\overline{u_i' u_j'}\frac{\partial u_j}{\partial x_i} - \rho\varepsilon, \tag{5}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho\varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] - C_{1\varepsilon}\frac{\varepsilon}{k}\left(\rho\overline{u_i' u_j'}\frac{\partial u_j}{\partial x_i}\right) - C_{2\varepsilon}^{*}\rho\frac{\varepsilon^2}{k}, \tag{6}$$

where

$$C_{2\varepsilon}^{*} = C_{2\varepsilon} + \frac{C_\mu\eta^3(1-\eta/\eta_0)}{1+\beta\eta^3} \tag{7}$$

η is

$$\eta = Sk/\varepsilon, \tag{8}$$

where

$$\rho\overline{u_i' u_j'}\frac{\partial u_j}{\partial x_i} = -\mu_t S^2. \tag{9}$$

In the equations above, the parameters $C_\mu = 0.0845$, $C_{\varepsilon 1} = 1.42$, $C_{\varepsilon 2} = 1.68$, $\sigma_k = 0.7194$, $\sigma_\varepsilon = 0.7194$, $\eta_0 = 4.38$, and $\beta_0 = 0.012$ are from (ANSYS 2017).

The energy equation is also included in the CFD model, as:

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial(\rho E u_i + p u_i)}{\partial x_i} = \nabla\cdot(\lambda_{\text{eff}}\nabla T), \tag{10}$$

where

$$E = h - \frac{p}{\rho} + \frac{v^2}{2}, \tag{11}$$

and

$$\lambda_{\text{eff}} = \lambda + \lambda_t\,. \tag{12}$$

where λ is the thermal conductivity of air, and λ_t is the turbulent thermal conductivity. In Eq. (10) and (11), T and h represent the temperature and the enthalpy of the air, repectively, which are related with Eq. (13).

$$h = \int_{T_{ref}}^{T} c_p \mathrm{d}T + \frac{p}{\rho}\,. \tag{13}$$

where $T_{\text{ref}} = 298.15$ K and c_{p} is the specific heat of air.
The standard wall functions (ANSYS 2017) were employed as the near-wall treatment in the model.
The boundary conditions are as follows:

1. Cold air at 14.85°C is supplied to the grocery store through a series of diffusers from the supply air ductwork at various flow rates as shown in Figure 1. Moreover, the turbulence intensity (ratio of the root-mean-square of the velocity fluctuations to the mean flow velocity) and viscosity ratio (ratio of μ_t and μ) are 5% and 10 at the diffusers, respectively.
2. 8,500 cfm of air at room temperature returns to each of the AHU through two return air grilles, and 1,000 cfm of air exhausts from the grocery store through an exhaust hood.
3. 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 ignored.
4. Because the envelope of the grocery store is thermally insulated, the adiabatic boundary conditions are applied to all the exterior walls and floor.
5. Zero airflow is assumed at all boundaries except at the supply air diffusers, return air grilles, and exhaust hood.
6. In the discrete phase model (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) (EPA 2019) 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 (Hang, Li, and Jin 2014) 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.
9. When the fans are on, a 9.67 m^3/s is applied to every fan's surface directing to the floor.

Particle Characteristics and Moving Person Modeling

The SARS-CoV-2 virus is usually carried by droplet particles blowing out to a space through human behaviors, such as breathing and coughing. In this study, the physical properties of airborne SARS-CoV-2 aerosols were adopted from a previous study (Shao et al. 2021). About 44 particles are released during each breath, while the average breath frequency of the person is 15 times per minute (Shao et al. 2021). Because most particle diameters range from 0.3 to 3 μm (Hartmann et al. 2020), a series of particle size parameters, including the minimum diameter, maximum diameter, mean diameter, and spread parameter were defined in the model to describe the size distribution of the particles. The particles are assumed to be released from the mouth of the person (opening size 16 cm^2) during normal breathing with a speed of 0.3 m/s in a cone shape with a total angle of 25° (Shao et al. 2021). Since the exhaled respiratory aerosols comprise mostly of saliva which largely resemble the physical properties of water (Xie et al. 2009), the particles density is assumed to be 1 g/mL.

Other than normal breathing, when a person coughs without wearing a face mask, approximately 13,000 particles are released into the atmosphere with every cough (Hartmann et al. 2020). The release speed is 11.2 m/s for coughing, while the particle size distribution and releasing cone are assumed to be the same as that for breathing according to an experimental measurement of a previous study (Gupta, Lin, and Chen 2009).

The body of the infected person is also considered in the CFD model since it will block the air and heat the air surrounding it. If the walking speed of the person in the grocery store is 0.3 m/s (cite), considering the average breathing frequency above (15 times per minute), the infected person walked 1.2 m between two breaths in the grocery store. Therefore, aerosol particles were released every other 1.2 m due to breathing, which provides a simplified quasi-steady method of the moving person in this study. 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 (Hang, Li, and Jin 2014)). 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. A script was developed within Ansys Fluent to control the quasi-steady simulation.

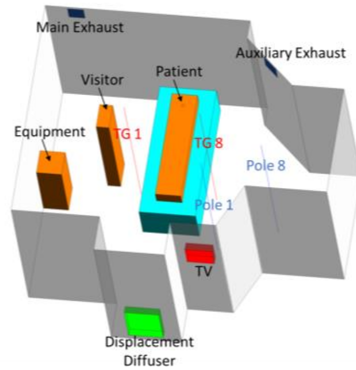

Figure 2. A schematic view of the patient ward and locations of measured data points. TG: tracer gas.

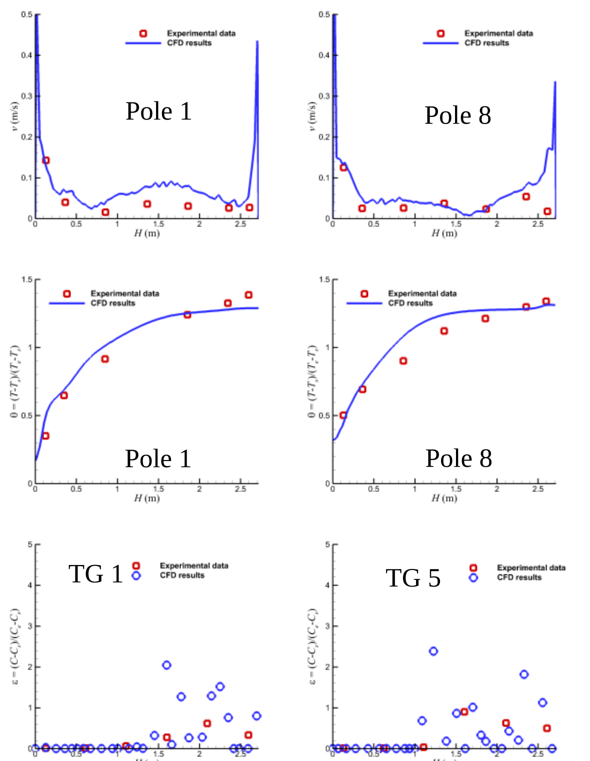

Figure 3. Comparisons between experimental data and CFD results of the air velocity, nondimensional temperature, and nondimensional particle concentration in a patient ward. TG: tracer gas.

Model Validation

The numerical methodology employed in the CFD model was validated using experimental data provided by by Yin et al. (Yin et al. 2009) about a single-patient ward. A CFD model for the single-patient ward was built following the description detailed by (Yin et al. 2009) shown in Figure 2. The airflow, temperature distribution as well as particle concentration were predicted from the

CFD model and compared with the measured data in the patient ward. Figure 3 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 θ was calculated with Eq. (14), and the nondimensional concentration ε was calculated with Eq. (15):

$$\theta = (T-T_s)/(T_e-T_s) , \quad (14)$$

$$\varepsilon = (C-C_s)/(C_e-C_s) , \quad (15)$$

where C is the particle concentration, subscript e is the average value, and subscript s is the value at the ventilation supply vent. The comparison reveals a very good agreement between the CFD model's prediction and the measured data, indicating that the methodology employed in the CFD model can accurately predict the indoor air velocity, temperature distribution, and particle concentration.

Results and Discussions

A single infected person was simulated in the CFD model. As indicated with the red lines in Figure 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 (Larsen et al. 2020). Therefore, the total time the person stays inside the grocery store is 356 s (about 5.9 min). In this paper, a case was simulated in this study, in which the person passes through the grocery store without wearing a face mask and coughing several times inside the grocery store. At times when the person is not coughing, the person is regular breathing. The person is assumed to cough once per minute when inside the grocery store. The coughing locations are marked in Figure 1.

Airflow Patterns

Figure 4 depicts the flow path lines of the air flow in the grocery store. The figure indicates that the fans push the air flow moving to the floor when it passes the fans. Even the air flow that is just released from each diffuser is pushed to the floor by the fans shown in the figure. As a result, low-pressure zones are generated above the fans, leading to the air flow filling the low-pressure zones. Since the fans are deployed in the entire grocery store, they significantly enhance the air flow circulation in the store. In addition to the fan, the wall, shelvings and freezers also create air flow circulations by blocking the air flow path direction. For example, the 800 cfm diffusers blow air toward the west wall. When the airflow is blocked by the walls and bounces back toward the diffusers, it creates air flow circulations. The existence of exhaust hood makes the flow pattern more complicated. Since it sucks air from the grocery store, a horizontal air flow is generated. As a result, the combined effect of exhaust hood and the fan in the northeast corner generate a hurricane shaped flow pattern near the northeast corner of the grocery store, as shown in the circle of Figure 4.

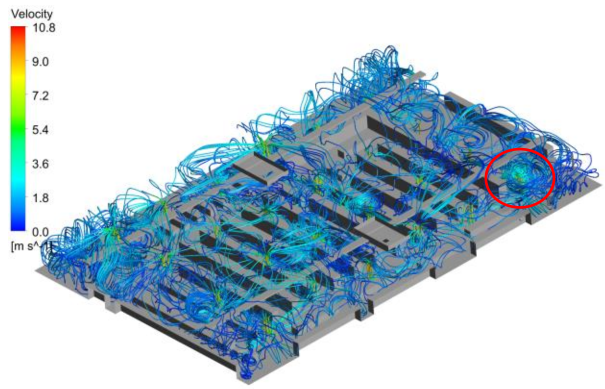

Figure 4. Flow path lines of the air flow in the grocery store.

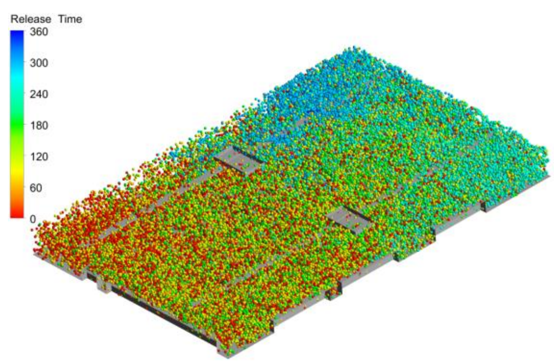

Figure 5. Particle distribution 5.9 min after the infected person walks through the grocery store while coughing without wearing a face mask with fans.

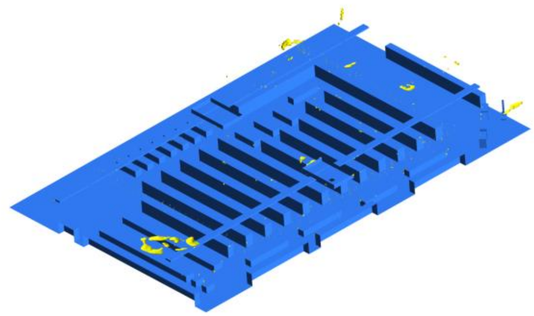

Figure 6. Particle mass concentration iso-surfaces of 10^{-14} kg/m^3 after the infected person walks through the grocery store while coughing without wearing a face mask with fans.

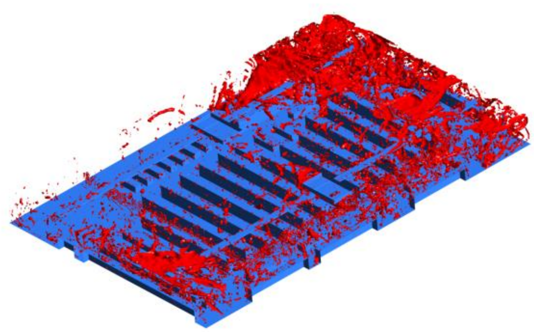

Figure 7. Particle mass concentration iso-surfaces of 10^{-15} kg/m^3 after the infected person walks through the grocery store while coughing without wearing a face mask with fans.

Particle Transport

Figure 5 depicts the particle distribution 5.9 min after the infected person walks through the grocery store and coughs once in each minute without wearing a face mask. To demonstrate the effects of fans on the particle distribution, this case was under the same conditions as the coughing case in the literature (M. Zhang et al. 2022). It can be found from the literature that (M. Zhang et al. 2022) that without fans, after 5.9 min, the red particles (from the 1st coughing) and the orange particles (from the 2nd coughing) occupy the entire southwest part of the grocery store and the aisles at the south side of the store, respectively. The yellow, green, and blue particles do not expand as much as the other particles because of the poor air circulation. On the other hand, when the fans are on, after 5.9 min, the red, orange, yellow, and green particles have been spreading to the entire grocery store. Even the newly released blue particles can be found widely in the northwest of the grocery store. Therefore, the air circulation from the fans significantly enhances the particle mixing in the grocery store.

Figure 6 and Figure 7 represent the particle mass concentration iso-surfaces of 10^{-14} kg/m^3 (high concentration) and 10^{-15} kg/m^3 (low concentration) after the infected person walks through the grocery store while coughing without wearing a face mask with fans. Figure 6 reveals that there are four high concentration locations in the grocery store which are near the south wall, near the north wall, near exhaust hood and near the east return air grille. The gathering of particle near the south wall is due to the 1st and 2nd coughing, while the high concentration near the south wall is because the last two coughing. The exhaust hood and return air grille collect air from the grocery store leading to the gathering of particle near them. It can be found from Figure 6 that due to the air circulation from the fans, the high concentration region in the case with fans is much smaller than the case without fans (M. Zhang et al. 2022). However, due to the enhanced mixing from the fans, the particles are spreading more widely in the case with fans than the case without fans. As a result, figure 7 shows that low concentration region is much larger in the case with fans than the case without fans (M. Zhang et al. 2022). Therefore, the fans can effectively dilute particle concentration and reduce the high concentration particle region in the grocery store. However, since it is lack of data to link the particle concentration to the infection risk, it is hard to determine whether the effects of the enhanced circulation would be helpful to control the infection risk. If the concentration of 10^{-15} kg/m^3 leads to low infection possibility, the fans would benefit to reduce the infection risk in the grocery store. However, if the infection threshold is lower than 10^{-15} kg/m^3, the enhanced circulation helps to spread the particle, which would cause an even higher infection risk in the grocery store.

Conclusions

A CFD model was developed based on information of a typical medium-sized grocery store in the United States with enhanced air circulation by ceiling fans. The duct layout of the HVAC system used in this study represents a typical design for medium sized grocery stores in the US. The 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. Computer simulations with the CFD model predict the airflow patterns and dispersion of aerosol particles released from an infected person when the person is walking and coughing without wearing a face mask. This paper concentrates on the effects of enhanced circulation caused by ceiling fans in the grocery store. Some conclusions were obtained from the simulation results:

- The pressure difference generated by the fans creates a dramatic air circulation in the grocery store.
- The particle mixing is significantly enhanced by the enhanced air circulation to spread the particle rapidly in the grocery store.
- The rapid particle spreading leads to a smaller high concentration region and larger low concentration region in the case with fans than the case without fans.
- The fans could help to reduce the infection risk in the grocery store if the infection threshold concentration is high. However, if the infection threshold is low, the fans would cause a higher infection risk in the grocery store.

Acknowledgments

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