# Estimation of infection risk through airborne transmission in large open spaces with different air distributions

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**Abstract.** Respiratory diseases such as COVID-19 can be spread through airborne transmission, which is highly dependent on the airflow pattern of the studied room. Indoor air is typically not perfectly mixed even using a mixing ventilation, especially in large spaces. Airflow patterns in large open spaces such as hotel banquet rooms and open plan offices, are of particular concern, as these spaces usually accommodate more occupants and thus have the potential to spread diseases more rapidly leading to outbreaks. Therefore, understanding airflow patterns in large open spaces can help to estimate the detailed infection risk at certain locations in the space, which can prevent the spread of virus and track the potential new infections. This study estimated airflow patterns in a typical banquet room under theatre and banquet scenarios, and a large open plan office using computational fluid dynamics (CFD) simulations. Typical ventilation and air distribution approaches, as well as room layouts and occupant configurations in these scenarios were studied and applied in simulations. According to current results, the air distribution in a typical hotel banquet room with mixing ventilation can be very complicated, particularly for the banquet scenario. For a typical theatre scenario, under typical ventilation design, people sitting in the middle and lateral area were exposed to the highest infection risk. The front rows may be exposed to short-range transmission as well. For a banquet scenario, people sitting on the same table were more likely to be cross contaminated. But cross-table infection was still possible. The results can provide guidance on designing ventilation and air distribution approaches in large spaces with similar settings.

## 1 Introduction

Respiratory diseases such as COVID-19 can be spread through airborne transmission, which is highly dependent on the airflow pattern of the room. Infectious virus-laden aerosols can travel in a longer distance and infect more susceptible people than short-range transmission routes such as droplets or contacts [1]. The Wells-Riley model, which determines the infection probability by the inhalation dose of infectious viruses, has been widely used to estimate the infection risk in perfectly mixed spaces [2]. However, indoor air is typically not perfectly mixed even using a mixing ventilation, especially in large spaces, which limits the application of the model in the spaces with realistic air distributions. Airflow patterns in large open spaces such as hotel banquet rooms and open plan offices, are of particular concern, as these spaces usually accommodate more occupants and thus have the potential to spread diseases more rapidly leading to outbreaks.

Some retrospective analyses have shown that poor ventilation and air distribution in large spaces can likely cause superspreading outbreaks of COVID-19 in certain scenarios. Therefore, understanding airflow patterns in large open spaces can help to estimate the detailed infection risk at certain locations in the space, which can prevent the spread of virus and track the potential new infections. This study estimated airflow patterns in a typical banquet room under theater and banquet scenarios using computational fluid dynamics (CFD) simulations. Typical ventilation and air distribution approaches, as well as room layouts and occupant configurations in these scenarios were studied and applied in simulations.

## 2 Methodology

The airflow pattern in a certain space can be very complicate depending on the space layout (e.g. furniture and cubicle layout) and the air distribution method of the ventilation system. The virus distribution is also closely associated with occupant locations, particularly the source location (i.e. infector) and the location of susceptible individuals. Mixing ventilation is the most common air distribution method of ventilation systems. Traditional mixing ventilation controls the density of indoor pollutants by bringing in enough outdoor air to dilute emissions from indoor sources uniformly. But from the airborne transmission perspective, air mixing will likely mix the airborne pathogens and cause cross contamination between infectors and susceptible people

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when there are infected cases in the confined space. In this study, mixing ventilation was applied in the study cases.

## 2.1 Space layout

A ballroom in the Marriott Hotel of Syracuse is selected to study the mixing ventilation in the large space. The room is around 17.1×9.1×4.0m in size (56.0×30.4×13.1ft), which is generally a regular hotel ballroom size (Fig. 1). Typical settings of the studied ballroom mainly include theater (e.g. speech and lecture), and banquet (with round tables) [3]. According to the information of Marriott Hotel, the occupant configuration for different ballroom settings is shown in Table 1. The occupant density for the banquet scenario is generally consistent with the ASHRAE standard for dining spaces [4]. In this study, we simply assume 120 people in the space for the banquet setting and 121 people for the theater setting (120 audience + 1 presenter). For the theater setting, people sitting on dense seats in rows (10 rows × 12 columns). There are 120 audience seated while a presenter standing and talking in front of the audience. Regarding the banquet setting, there are 120 guests sitting around 12 round tables (1.8m in diameter). Each round table serves 10 guests, and the guests are eating and talking. The models for theater and banquet settings are illustrated in Fig. 2.

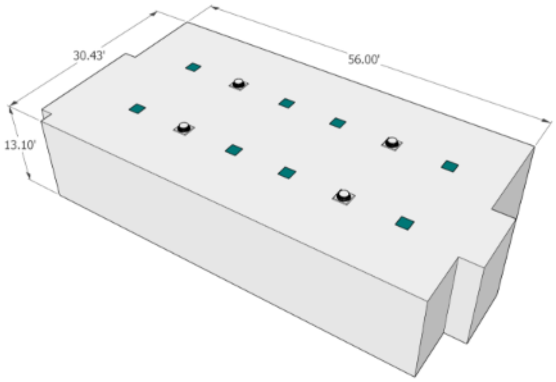

**Fig. 1.** Space layout of the studied ballroom.

**Table 1.** Occupant configurations of different settings for the ballroom.

| Setting | | Theater | Banquet |
|---|---|---|---|
| Occupant density [#/m$^2$] | Marriott Hotel Guidance | 0.68 | 0.65 |
| | ASHRAE standard | 0.35 (school theater) | 0.70 |
| Occupant activities | | Audience seated; Presenter standing and talking | Seated around round tables; Eating and talking |

**Fig. 2.** Theater and banquet settings of the studied ballroom.

## 2.2 Ventilation and air distribution

There are eight 0.5×0.5m (1.6×1.6ft) omnidirectional square diffusers evenly located on the ceiling of the room (green squares in Fig. 1). Four 0.6×0.6m (2×2ft) perforated ceiling grille returns are installed on the ceiling. Each diffuser can provide 501.2m$^3$/h (295CFM) conditioned air to the space and 25% of the supply air is assumed to be outdoor air [5]. Based on the volume of the studied ballroom, the air change rate is around 1.53ACH. The diffusers are assumed to be 3-cone square diffusers, which supply air at an angle of 30° to the horizontal direction.

## 2.3 CFD settings

CFD models are established for the theater and banquet settings of the ballroom. Tetrahedron grids are generated with a resolution of 0.2m for global mesh sizing and 0.02m for mesh close to the manikins and diffusers (Fig. 3). The inlets provide 20°C conditioned air to the space. Simple manikin models are created to simulate the occupants in the room and each manikin can produce 20.7W/m$^2$ convective heat flux on the surface [6]. Constant passive source is setup in the breathing zone of the manikin to simulate the droplet nuclei expelled by breathing or talking. Typical droplet nuclei are approximately in micron size, which are set up as passive pollutant sources in CFD models.

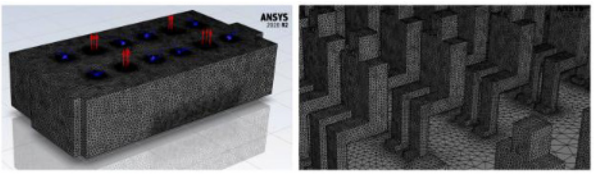

**Fig. 3.** Simulation mesh (theater setting as the example).

In this study, the breathing zone is a 4in-diameter sphere below the nose location. The breathing zone is around 0.523L in volume (Fig. 4), which is generally consistent with the breathing zone defined by Rai et al. [7] and Rim et al. [8] (0.5L). ANSYS Fluent is used to simulation the models. Realizable K-epsilon viscous model is adopted, and the SIMPLE algorithm was used to solve the Navier–Stokes equations. Second-order precision is adopted for solving other parameters.

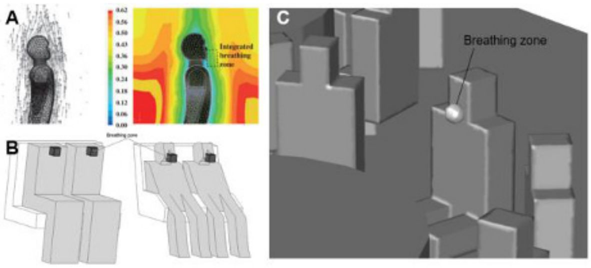

**Fig. 4.** Breathing zone defined in (A) Rim et al. [8], (B) Rai et al. [7], and (C) this study.

## 3 Results and discussions

### 3.1 Theater scenario

The air distribution inside a large space under mixing ventilation can be very complicated. The air velocity and temperature distributions in the studied large-space ballroom of the theater scenario were shown in Fig. 5. The air velocity distribution was very complex as the airflow pattern was very complicated (Fig. 6). The room air temperature in the space was around 23-24°C while the temperature around occupants was higher due to the heat generation from human bodies.

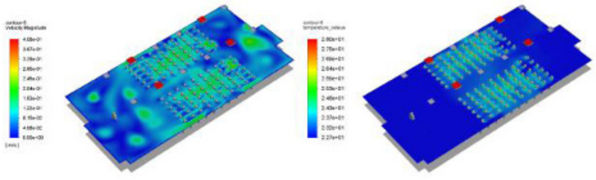
Airflow velocity distribution
Air temperature distribution

**Fig. 5.** Airflow velocity and temperature distribution of the theater scenario.

Fig. 6 shows the airflow pattern in the space. The conditioned air supplied by the diffusers in the front and back tend to go down until the floor level as the cooler air (conditioned supply air) has higher density and has the tendance to stay at the lower level. However, due to the thermal buoyancy driven by the thermal plumes around occupants, the supply air in the middle of the room cannot fully reach the floor level as people are sitting approximately in the middle of the room. The airflow pattern of the supply air was disturbed by the thermal plumes around occupants. Large vortex may generate above the occupants. The supply air in that area tended to flow towards lateral sides of the room, then flow up to the exhausts. Therefore, at the lower level (near-floor and breathing-height), two different flow patterns exist. The first one is that air flows from the front and the back towards the middle of room. People who sit in the middle were more likely to be exposed to the pollutants expelled by the people who sit in the front and back rows.

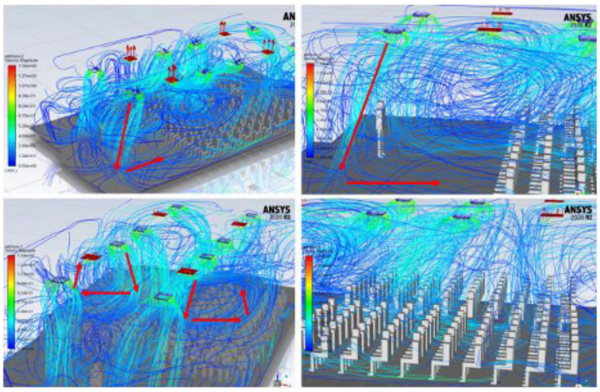

**Fig. 6.** Airflow pattern in the space.

This finding is supported by the velocity vectors and pollutant distributions illustrated in Fig. 7. The pollutant distribution in Fig. 7 shows that people sitting in the front and back rows are unlikely to be exposed to airborne pathogens and get infected. The middle seats are the high-susceptible area with highest exposure risks. They are exposed to the pollutants exhaled by people sitting in front of them and in the back of them. However, the pollutants exhaled by the presenter who is standing and speaking in front of the room, are possible to be transmitted to the people who are sitting in the front rows. Considering the potential transmission through short-range droplets, the front rows may actually be exposed to a considerable infection risk. Therefore, the front rows also need certain attentions on preventing airborne and droplet-borne transmissions. The other flow pattern at the breathing level is mainly occurring in the middle area. Air tends to flow from the center columns to the lateral columns of seats, also likely due to the impact of the thermal plumes as aforementioned. Therefore, people who are sitting in the middle and lateral area are likely exposed to the highest risk level.

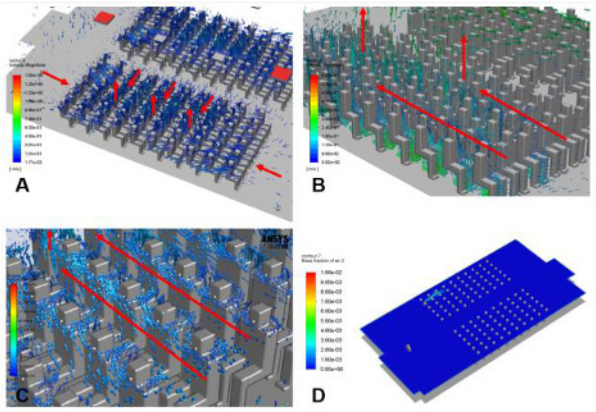

**Fig. 7.** (A-C) Airflow vectors and (D) pollutant distributions.

The simulation results indicated that mixing ventilation actually cannot really mix the indoor air perfectly. Certain airflow patterns still exist. Understanding such airflow patterns can be helpful for optimizing indoor ventilation and layout designs. More quantitative analysis is required in future to extend the case in this study.

### 3.2 Banquet scenario

The airflow pattern in the large-space ballroom of the banquet scenario is more complicated than the patterns of the theater scenario as occupants in a banquet are more evenly distributed/located in the room. Fig. 8 shows the airflow velocity and temperature distributions of the banquet scenario.

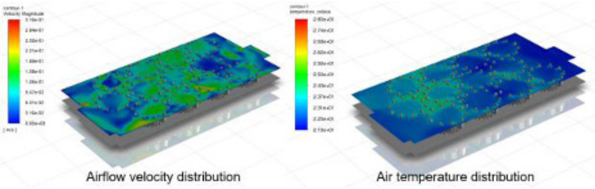

**Fig. 8.** Airflow velocity and temperature distribution of the banquet scenario.

The airflow pattern is shown in Fig. 9. Thermal plumes around the occupants contacted with the supply air (cooler). There is no specific pattern can be observed significantly for the air flow in the space. Fig. 10 shows the pollutant distribution when the pollutant sources were setup at different locations. It can be observed that people on the same table are usually exposed to highest risk when they are on the same table as the infector. But cross-table contamination/infection is still possible to occur. But the pattern can be very complicated. More quantitative analysis is required.

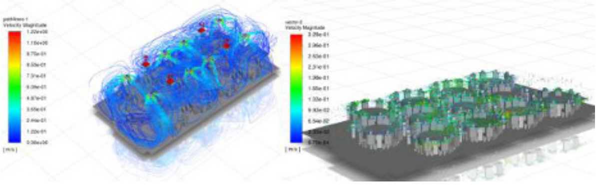

**Fig. 9.** Airflow pattern in the space.

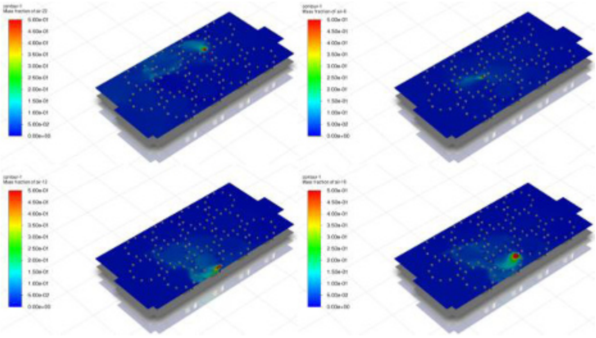

**Fig. 10.** Pollutant distribution for different sources.

## 4 Conclusions

The air distribution in a typical hotel banquet room with mixing ventilation can be very complicated, particularly for the banquet scenario. For a typical theatre scenario, under typical ventilation design, people sitting in the middle and lateral area were exposed to the highest infection risk. The front rows may be exposed to short-range transmission as well. For a banquet scenario, people sitting on the same table were more likely to be cross contaminated. But cross-table infection was still possible. The results can provide guidance on designing ventilation and air distribution approaches in large spaces with similar settings. The research will be further explored by developing reduced-order (physics-based, data-driven, and hybrid) models to estimate the infection risk quickly and reliably at different locations in large spaces considering various room and ventilation configurations.

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