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Impacts of human movement and ventilation mode on the indoor environment, droplet evaporation, and aerosol transmission risk at airport terminals

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ABSTRACT

The dispersion of the coronavirus pandemic has caused immense damage worldwide, and people have begun to ruminant epidemic prevention strategies for public places. Airport terminals with a high number of occupied passengers have become potentially high-risk regions for aerosol transmission of coronavirus disease 2019 (COVID-19). In this study, the Eulerian–Lagrangian approach and realizable k-ε turbulence model were used to numerically simulate airflow organization and aerosol transmission when passengers are moving slowly in a line. During the aerosol transmission period, evaporation was considered a key factor influencing the particle size distribution at the beginning of aerosol transmission from humans. Moreover, passenger movement at the airport terminal was attained by employing dynamic mesh algorithms. Based on the relative direction of passengers and air vents when queuing in the terminal building, we studied three conditions: windward walking, leeward walking, and crosswind walking. The results of this study showed that the walking has an important influence on droplet distribution. Droplet distribution indicates that individuals standing behind patients during queuing movements have a higher risk of infection than those standing in front of them. A significant aerosol accumulation was discovered at 0.5 m behind the patient when passengers moved simultaneously. An aerosol transmission distance of 15 s aligned with the passenger’s walking direction could reach up to 9.32 m. Furthermore, although the evaporation time of the large droplets was longer than that of the small droplets, both large and small droplets evaporated rapidly after exhalation. The crosswind influence caused the droplets to travel farther away in a direction perpendicular to human movement, which increased the distance by approximately 1.26 m compared to the absence of the crosswind influence.

1. Introduction

Viruses are the most common cause of infectious diseases acquired in indoor environments, some of which are widespread but not severe (such as the common cold), while others are relatively serious (such as influenza, severe acute respiratory syndrome (SARS), and coronavirus disease 2019 (COVID-19)) [1]. Recently, COVID-19, which has spread worldwide, has a strong ability to infect people and cause vast harm. To date, the epidemic has not been completely controlled, and our lives have entered the stage of normalizing epidemic prevention and control.

Airport terminals have also undergone significant changes with societal development and progress. Recently, the number of airport terminals has increased rapidly, becoming an important transportation hub owing to large passenger flow [2,3]. Passenger breathing, speaking, coughing, and sneezing continuously generate aerosol particles, which can cause major transmission of the virus. High population densities and long stay times make exposure to these aerosol particles at airports more dangerous than in other environments. Airports such as Haikou, Shenzhen, Nanjing, Shanghai, and Chengdu have confirmed passengers or staff who are positive for the disease, resulting in serious transmission issues [4]. In particular, during the queuing process for check-in luggage and boarding, individuals are near each other, move almost simultaneously, and have close contact. Once an infected person is present, a stronger infection force is established. Studies show that human motion has a strong effect on the surrounding airflow, disturbing the local velocity field, and affecting the dispersion of particle concentrations [5].

Researchers have previously studied the relationship between indoor ventilation and airborne particle aerosol transmission at different

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locations, including elevators [6, 7], conference rooms [8], large rooms [9, 10], fever clinics [11], hospital isolation rooms [12], medical centers [13], and supermarkets [14]. Moreover, many studies have focused on the transmission characteristics and infection tendency of droplets exhaled by people in transportation environments such as airplanes [13], long-distance buses [13, 15], and high-speed rail carriages [16]. However, these studies have focused on ventilation effects and droplet dispersion in static environments, whereas the movement of individuals in the environment has rarely been considered; this must be amended. The dispersion and propagation characteristics of droplets or particles differ from those in static environments owing to airflow disturbances caused by the movement of individuals. Mazumdar et al. [17, 18] showed that moving objects or individuals can influence the temporal and spatial distribution of pollutants. Cao et al. [5] proposed a new momentum theory approach to study the impact of human motion on indoor environments. Several studies [19–21] on hospital operating rooms and infection isolation rooms have reported that human motion plays an important role in the indoor dynamic airflow and pollutant dispersion. These studies show that few scholars have studied the effects of pollutants during human movement, and these studies have mainly focused on airflow and gaseous pollutants. Studies [22, 23] have shown that human movement increases the risk of pollution through aerosol particle analysis.

In summary, there have been many studies on the transmission characteristics of droplets and aerosols in conference rooms, normal rooms, carriages, aircraft cabins, and other places. However, these studies only considered the steady-state environment of people standing still or sitting still, ignoring the influence of human movement. Existing studies have little research on airflow distribution and pollution diffusion in people walking, especially aerosol transmission; however, people walking in an airport environment are the most common situations. The airflow distribution and aerosol transmission characteristics under the double superposition of personnel walking and air conditioning system operation are of great significance to the risk of virus transmission in the airport environment and optimization of the ventilation system.

This study aims to investigate the transmission characteristics of droplets exhaled by people in the following conditions: windward walking, leeward walking, and cross-wind walking during common queuing scenes at airport terminals. To date, among the currently available methods for monitoring airfield environmental pollutant patterns, owing to the shortcomings of time consumption and poor repeatability of on-site and PIV measurements, we believe that computational fluid dynamics (CFD) technology is a suitable method with reasonable simulation accuracy and flexible repeatability [24]. In addition, overlapping grids were used to simulate human motion, and Lagrangian methods were used to track particle trajectories. The significance of this study lies in its investigation of the transmission characteristics and infectivity of droplets during human movement. The results of this study provide recommendations for personal protection and ventilation optimization in airport terminals and other similar environments in which individuals travel.

2. Methodology

2.1. Turbulent flow model

The realizable k-ε model developed by Shih et al. [25] has been proven to perform well for a variety of flow conditions, including vortices, rotations, round jets, and thermal buoyancy plumes [26–28], and it is suitable for indoor environment modeling in terms of accuracy, computing efficiency, and robustness [29–32]. The accuracy of the results in our previous studies [33–37] is also acceptable for truly reflecting turbulence patterns. Thus, we also used the realizable k-ε turbulence model to simulate wind flow in the environment. The governing equations include the continuity, momentum, energy, turbulent kinetic, and turbulent dissipation rate equations, which are expressed in Eq. (1). Based on the Boussinesq approximation, the velocity and temperature fields were coupled.

\[
\frac{\partial \rho \Phi}{\partial t} + \nabla (\rho \mathbf{U} \Phi) = \nabla (\Gamma \nabla \Phi) + S
\]

(1)

where \( \rho \) is the fluid density (kg/m\(^3\)); \( \Phi \) is a general variable that represents the velocity components \( u \) (m/s), \( v \) (m/s), and \( w \) (m/s) in the momentum equation; \( T \) (°C) is the temperature in the energy equation; \( k \) is the turbulent kinetic energy (J) in the turbulent kinetic equation; \( \epsilon \) is the dissipation rate in the turbulent dissipation rate equation; \( \tau \) is the time (s); \( \nabla \) indicates divergence; \( U \) is the velocity vector; \( \Gamma \) is the generalized diffusion coefficient; \( \text{grad} \) represents the gradient; and \( S \) is the generalized source phase.

2.2. Droplet trajectory model

The Lagrangian method was used to trace the droplet trajectories. The Lagrangian approach splits the particle phase into a representative set of individual particles and tracks these particles separately through the flow domain by solving particle movement equations. To simplify the calculation, the following assumptions were made:

1. the particle dynamic process including nucleation, collision, and coagulation is neglected;
2. the droplets were all in ideal sphere shape.

This method calculates the trajectory of each droplet by solving a single droplet motion equation based on Newton’s second law:

\[
\frac{d\mathbf{u}_i}{dt} = \sum F_i - \sum F_{ext,i}
\]

(2)

where \( \mathbf{u}_i \) is the droplet velocity in the i direction (m/s) and \( \sum F_i \) is the sum of all external forces exerted on the droplet (per unit droplet mass) in i direction (m/s\(^2\)). The external forces consist of drag force \( F_{drag,i} \), gravity \( F_{g,i} \), and additional forces \( F_{ext,i} \).

The drag force and gravity [38] on the droplet in i-direction are defined by the following equation:

\[
F_{drag,i} = \frac{1}{\tau_p} \left[ u_i - u_{i,v} \right]
\]

(3)

where \( f_d \) is Stokes’ drag modification function for a large aerosol Reynolds number (Re\(_p\)), which is defined in Eq. (4); \( \tau_p \) is the aerosol characteristic response time, which is defined by Eq. (5).

\[
f_d(Re_p) = 1 + 0.15 Re_p^{0.867}
\]

(4)

\[
\tau_p = \frac{\rho \phi d_i^2 C_i}{(18 \mu)}
\]

(5)

where \( \rho \phi \) and \( \rho \) are the densities of the droplet and air; \( d_i \) and \( \mu \) are respectively the droplet diameter and turbulent viscosity (kg·m\(^{-1}\)·s\(^{-1}\)), respectively, and \( C_i \) is the Cunningham correction to the Stokes drag law.

\[
C_i = 1 + 2\lambda \left( 1.257 + 0.4c_1^{1/3} \right) \left/ d_i \right.
\]

(6)

where \( \lambda \) is the molecular mean free path of air.

The gravity on the droplet in i direction is defined by the following equation:

\[
F_{g,i} = g \left[ (\rho_i - \rho) \right] / \rho \phi
\]

(7)

where \( \rho_i \) and \( \rho \) are the densities of the droplet and air, respectively, and \( g \) is the gravitational acceleration in the i-direction (m/s\(^2\)).

The term \( F_{ext,i} \) represents the additional forces exerted on the particles depending on the flow conditions and particle properties. These forces include the pressure gradient, Basset, virtual mass, Brownian, and lift forces.
forces owing to shear (Saffman’s lift force) [39,40]. However, when considering the size and density of the particles in indoor environments, some of the forces are sufficiently small to be considered negligible. Only the Brownian force and Saffman’s lift force are considered here, as they may play an important role in the motion of submicron droplets near the wall, where the velocity gradient is large enough to dominate the lift force of Saffman.

2.3. Droplet evaporation model

Vaporization of the droplets was also considered. In general, the indoor relative humidity changed the evaporation timescale of the studied droplets. However, as the indoor environment of the airport terminal is mainly controlled by the air-conditioning system, the relative humidity is relatively stable, especially in the breathing zone, which is usually 1–2 m above the ground. In our study, a stable relative humidity of 55%, which was consistent with our field measurement results, was used for the simulation. The impact of relative humidity differences on aerosol transmission patterns was not discussed in this study. The terminal is mainly controlled by the air-conditioning system, the relative humidity of 55%, which was consistent with our field measurement results, was used for the simulation. The impact of relative humidity differences on aerosol transmission patterns was not discussed in this study. The impact of differences in body limbs when a single human body walks on the indoor environmental quality and aerosol transmission. However, to our knowledge, when several people walk simultaneously, the traffic wind induced by a group of walking people is much stronger than that of a single human body, and the impact of body limb movement might be weakened. The distance between pairs of the human body, walking speed, and the duration period considered in the study became more important factors than body limb movement in several people walking conditions. Thus, we ignored personal differences in passenger movement when analyzing the characteristics of several individual’s walking conditions. There were 15 people in the line in the model that used walking in the $+Y$ direction, as shown in Fig. 1. A related study [17] proposed that the shape of the moving body should be a human-like model to accurately simulate the transport of pollutants. Therefore, for the human body model, we established a 1:1:1 geometric model based on the standing posture of adults. The height of the human body is approximately 1.7 m, length of the head is approximately 0.37 m, maximum radius of the head is 0.17 m, and length of the upper body is approximately 0.7 m. The nose is simplified to two circles with $r = 0.005$ m, and the mouth is simplified to an ellipse with a primary and secondary radius of 0.03 m and 0.02 m, respectively.

Owing to the epidemic, the check-in area of the airport was usually fenced off into a serpentine-shaped area. Based on the relative direction of passenger queuing and the air outlet in the airport, we established three geometric models: (1) windward walking: the walking direction of people is opposite to the blowing direction of the air outlet; (2) leeward walking: the walking direction of the person is the same as the blowing direction of the air outlet; (3) cross-wind walking: the walking direction of the person is perpendicular to the air supply direction of the air outlet. The geometric and human body models established in this study are illustrated in Fig. 1. Indeed, there are so many environmental and personal factors including heat sources, ventilation modes, personal movement patterns, etc. having great influences on the indoor environmental quality and aerosol transmission risk. Thus it is quite a complex process for aerosol transmission, especially when considering human movement. Through literature reviews, current studies have concluded several key factors such as airflow organization [24,25], queuing form, personnel distance [47–49] having more significant influences compared with others for aerosol transmission evaluation. Therefore the key factors mentioned above were considered in our study. In addition, the three conditions cover the common situations when passengers walked in the queue for baggage check-in and boarding. Three queues were selected because the usual number of queues for one check-in counter or one boarding gate is no more than three based on our observation during the field measurement. The distance of 1 m between each pair of passengers were selected based on the regulation of airport terminals during the COVID-19 pandemic.
3.2. Simulation conditions

The boundary conditions for the airflow are summarized in Table 1. According to a study on the respiratory rate of Chinese residents [50], the average respiratory rate is 0.59 m$^3$/h, so the human respiratory rate was set to 1.05 m/s. The velocities of the air flows for speaking and coughing were 3.9 m/s and 11.7 m/s, respectively, from Chao et al. [51]. Compared to the above behavior, sneezing has a higher exhaled air velocity, which can reach 50 m/s [52]. The effects of human breathing and heat flux on the body surfaces were considered. Under light labor conditions, the human body releases approximately 181 W of heat, of which radiation, convection, and latent heat account for 40%, 20%, and 20%, respectively [53]. The surface area of the human body is approximately 1.6–2.0 m$^2$. Thus, the human body was set to have a constant heat flow boundary of 100.5 W/m$^2$. For the airflow to diffuse through the vertical boundaries, the walls with and without air supplies in the vertical direction were set as no-slip walls and slip walls, respectively. The geometric model used in this study is shown in Fig. 1. Because a partial lining-up area was established, sidewalls 1 and 3 were imaginary air walls, and the sliding-wall condition was used. All the other walls used anti-skid boundary conditions.

In this study, the human walking speed was set to 0.8 m/s. It was assumed that people would exhibit four different types of behavior during the queuing process: breathing, talking, coughing, and sneezing. Breathing and talking can be continuous, but coughing and sneezing are generally short lived. The duration of a cough or sneeze is generally 700 ms [54, 55].

The droplets were injected into the space through the mouth of the passenger at the initial velocities of breathing, speaking, coughing, and sneezing. Most of the droplets produced during breathing were small particles, and we selected 1 μm as the representative particle size for the simulation [56]. Moreover, droplets were ejected from the human mouth at 444 droplets/s [57]. Chao et al. [51] showed that the geometric mean diameter of droplets from coughing was 13.5 μm and it was 16.0 μm for speaking (counting 1–100). To simplify the calculation, we set the droplet size for both speaking and coughing at 15 μm. The total number of droplets expelled per cough was estimated to be 947, and 4539 droplets were expelled by speaking (counts 1–100), resulting in droplet flow rates of 78 and 1053 droplets/s during speaking and coughing, respectively [51]. Sneezing produces droplets that are larger than those in other exhaled behaviors, representing a particle size of 50 μm [55]. Simultaneous sneezing produces a larger number of droplets at a flow rate of approximately 5000 droplets/s [52].

| Boundary name | Boundary conditions |
|---------------|---------------------|
| Air supply vent | Velocity inlet, velocity is 3.72 m/s in windward walking and leeward walking, velocity is 2.48 m/s in cross-wind walking, temperature equals to 18 °C |
| Air return vent | Pressure exit, pressure is 2.1 Pa |
| Mouths | Breathing speed is 1.05 m/s, speaking speed is 3.9 m/s, coughing speed is 11.7 m/s, sneezing speed is 50 m/s, temperature equals to 34 °C |
| Noses | Pressure exit, pressure is 0.754 Pa |
| Body surface | Standard wall function, no slip wall, heat flux is 100.5 W/m² |
| Side wall 1,3 | Standard wall function, slip wall in windward walking and leeward walking, no slip wall in cross-wind walking |
| Side wall 2,4 | Standard wall function, no slip wall in windward walking and leeward walking, slip wall in cross-wind walking |
| Floor, top surface | Standard wall function, no slip wall |

![Fig. 1. Geometric and human body models used in this study.](image-url)
The discrete phase boundary conditions are summarized in Table 2. For the floor, body surfaces, side wall 2, and side wall 4, the quit condition was applied with the assumption that droplets were deposited as soon as they touched the wall surfaces, and the trajectory calculation was terminated. Escape conditions were applied to the nose and mouths, as well as air-conditioning vents and side walls 1 and 3.

The simulations were performed by solving the realizable k-ε model for the flow, pressure, and turbulence parameters using the CFD software STAR-CCM+ 12.0.2. A second-order upwind scheme and the SIMPLE algorithm were applied to all convection terms contained in the governing equations and the pressure-velocity coupling, respectively. Convergence was assumed to be achieved at each time step when:

1. All scaled residuals, except those of continuity and energy, reached $10^{-4}$.
2. The continuity and energy residuals simultaneously reached $10^{-6}$.

### 3.3. CFD mesh establishment

The speed, precision, and convergence of the simulation calculations were closely related to the quality of the mesh. In this study, the STAR-CCM + software was used to mesh the model. The mesh model used was an unstructured mesh and was used for surface reconstruction. The mesh generator included a polyhedral mesh generator and a prism-layer mesh generator. The basic size of the grid was 0.2 m, and custom grid sizes were set in specific areas such as the air supply outlet, return air outlet, and surface of the human body. For the manikin, the mouth area was approximately $5 \times 2 \times 4$ with 117 refined surface meshes, and the nose area was approximately $5 \times 10-5$ $m^2$ with 81 refined surface meshes. To overcome the disadvantages of the realizable k-ε model when simulating low-Reynolds-number flows within the near-wall region, all y + wall treatments were used in this study [58]. The all y + wall treatment is a hybrid treatment that attempts to emulate the high-wall treatment for coarse meshes and the low-wall treatment for fine meshes. It is also formulated with the desirable characteristic of producing reasonable answers for meshes of intermediate resolution (i.e., when the wall cell centroid falls within the buffer region of the boundary layer). According to the simulation results, the y + value surrounding the human body was approximately 0.3–1. To reduce the effect on stability, the skewness angle was 0-85°. According to Ref. [58], no bad meshes with large skewness angles were included in the model.

Overset meshes were used as a dynamic meshing method to simulate the motion process of human queuing. When employing overset mesh methods, the calculation regions are typically divided into two parts: background region and overlapping grid region. The background region encompassed the entire computational domain and was set as static during the numerical simulation. The overlapping grid region contained a moving body in the computational domain, which moved at a certain speed in this study. Structured hexahedron meshes were built for the background and overlapping grid regions (CD-Adapco, 2013). At the border between the two regions, overset mesh conditions were applied, and the meshes were refined to the same sizes to ensure the update and overlap of the meshes at the overlapping grid region to the background region at each time step (CD-Adapco 2013). Refined meshes between the two regions are shown in Fig. 2.

### 3.3.1. Mesh and time step independence test

The independence of the grid number and time step were tested to evaluate the capability and robustness of the established numerical model for droplet transmission. In order to ensure the computational efficiency, we selected the time steps of 0.005, 0.01, and 0.02 s for the time step independence test, and selected the grid numbers 1,213,113; 1,974,799 and 2,803,738 for the grid independence test. The initial and boundary conditions for the grid and time-step independence tests were the same as those used in this study. For comparison, we selected the mean temperature and mean wind speed across the model and the particle concentration behind the passengers. The results of the grid- and time-step independent experiments are presented below. As can be seen from Figs. 3 and 4, the particle concentration distributions and wind speeds (calculated using the arithmetic mean) were similar for the different time steps and grid numbers, with an apparent difference of <10%. This confirms that the numerical simulation with a time step of 0.01 s and a hexahedral mesh scheme with 1,974,799 structures ensures computational accuracy and therefore improves simulation efficiency.

### 3.3.2. Model validation

Therefore, it is important to evaluate the validity of this model. We performed a model validation of particle diffusion in human motion by comparing the numerical simulation results with field measurements of queuing. Field measurements were initially conducted at the airport terminal. However, owing to the short test time and the fact that the walking speed of the experimenter in a real queuing scene is not easy to control, the experimental data are not ideal. In addition, because the current domestic epidemic control in Dalian is still very strict, especially because we were unable to go out and conduct a field measurement again according to the epidemic prevention and control policy from the university, we retested in an experimental chamber that is similar to our physical model shown in Fig. 1 with an air-conditioning system. For better represent the real-life situation of airflow diffusion across the vertical boundary at the airport terminal, the doors were all open during the test. Our research adopts the dynamic meshing method, and the calculation of the dynamic meshing method is complicated. Therefore, the local area is selected for the simulation of the airport. The door opening test of the environmental cabin conforms to the characteristics of the air flow between the local area and the neighborhood of the large space of the airport.

The chamber was 6 m × 5.5 m × 4 m, with two doors, as shown in Fig. 5. To better represent the real-life situation of airflow diffusion across the vertical boundary, two doors were open during the test. Through the actual measurement, the air supply outlet is a 0.4 m × 0.4 m celling diffusers with a wind speed of 3.65 m/s. The return air outlet was a 0.5 m × 0.3 m louvre return air outlet. As the queuing distance is usually set to 1 m in airport terminals in China, the distance between the three volunteers in the field measurement was set to 1 m. The behaviors differed in some aspects: breathing and speaking continued for a long time, coughing and sneezing were instantaneous behaviors, and sneezing was difficult to freely control by the human body. Therefore, we selected speaking and coughing among the four behaviors for field measurements. Moreover, the total number of grids in this model was 152,248 with a 0.2 m base size. The customized mesh sizes were also set in specific areas, such as the supply air outlet, return air outlet, and body surface, for encryption. A 0.01 s time step was used for model validation. The other grid conditions are described in Section 3.3. A figure of the refined mesh for model validation is provided in Fig. 52 in the Supporting Information.

Three volunteers were recruited for queuing simulation. Before the start of the experiment, we asked the volunteers to breathe, speak, and cough directly against the experimental apparatus, and recorded the airflow velocity and particle concentration at their mouth outlet. Outlet airflow velocities during breathing, speaking, and coughing were 1.05 m/s, 3.9 m/s, and 11.7 m/s, respectively. The numbers of particles were 67,547/L, 69,325/L, and 70,447/L, respectively. Furthermore, we took

---

**Table 2**

Boundary conditions in the simulations of droplet dispersion (discrete phase).

| Boundary name                      | Boundary conditions                                      |
|------------------------------------|----------------------------------------------------------|
| Air supply vent, air return vent, | Escape (trajectory calculations are terminated here)     |
| mouths, noses                      |                                                           |
| Side wall, top surface, floor, body| Stick (trajectory calculations are terminated here)      |
| surface                            |                                                           |
pictures when a volunteer opened their mouth and measured the mouth area to be 3.3 cm². In the field measurement, we opened the door of the room and then opened the air-conditioning system in the room. The indoor environment was stabilized for a period of time; we placed the instrument used in the experiment into the chamber and removed the instrument 1 h later. Particle number data were collected using a KornoGT-1000 composite contaminant detector with a 1 s sampling interval. After data processing, the average particle concentration during that period was taken as the background concentration. The first individual in the queue was instructed to speak or cough each time they walked forward, whereas the next two maintained their normal breathing activities. The experimental instrument was placed on the back of the first individual in the queue to record data during the experiment. The equipment and experimental instruments used are shown in Fig. 6. Particle number data were also collected using a KornoGT-1000 composite contaminant detector. Temperature and wind
The measuring instrument specifications and accuracy.

| Instrument                        | Range          | Resolution | Accuracy |
|-----------------------------------|----------------|------------|----------|
| KornoGT-1000 composite contaminant detector | 0–9, 999, 999 PC/L | 1 PC/L     | ±3%      |
| WFWZY-1 universal wind speed and temperature recorder | –20–40 °C | 0.01 °C | ±0.5%    |
|                                   | 0–30 m/s       | 0.01 m/s   | ±0.05%   |
entire environment is consistent no matter which ventilation form is used. This shows that the movement of the human body may not have a substantial influence on the temperature of the overall environment of a tall space. The temperature of the respiratory region is slightly higher than the overall ambient temperature, due to the higher temperature of the air exhaled by the human body. Moreover, from the perspective of the queuing area near the human body, the temperature has increased considerably, which was significantly higher than the surrounding environment by about 0.1–0.15 °C in three conditions. This shows that individual’s movements have an important impact on the surrounding air.

4.2. Wind velocity

4.2.1. Wind velocity analysis at the respiratory range

The movement of the human body will inevitably cause disturbance to the surrounding air, just as when a person passes by, we will feel the gust of the wind blowing. The distribution characteristics of the wind-speed field of the breathing plane under the three walking modes are shown in Fig. 11. First, it is evident that the airflow ejected from the nozzle sinks after a certain distance, which is clearly reflected in the breathing plane. There were two areas with high wind speed in front of the human body walking in the wind, two areas with high wind speed behind the human body walking leeward, and three areas with obvious high wind speed in the first column of the human body walking in the crosswind. Second, the wind speed near the human body is significantly higher than that of the surrounding environment. The figure shows that a wake forms behind the human body when walking. From the individuals in the last row, the area of the wake was longer, with a distance of at least 1 m. From the front of the first row of individuals, there was a small area with a significantly high wind speed of approximately 0.3 m/s. This area was small, indicating that the movement of the human body also had an impact on the front, but this impact was significantly smaller than that on the back of the human body. In addition, the wind speed distribution near the human body moved to the right of the human body along the airflow direction in the crosswind model, and the airflow obviously promoted disturbances near the human body. If adjacent columns are proximate, this can affect individuals in other columns.
4.2.2 Wind velocity analysis of the vertical directions near the human body

To clearly identify the airflow changes caused by walking near the human body, a vertical cross-section at the center of one return airflow outlet (the location is shown in Fig. S1 in the Supporting Information) was established, and the airflow vectors are shown in Fig. 12. By

![Temperature distribution of the vertical direction near the human body](image1)

*(a) Windward walking. (b) Leeward walking. (c) Cross-wind walking.*

![Respiratory plane velocity field for the three walking conditions](image2)

*(a) Windward walking (b) Leeward walking (c) Cross-wind walking.*

**Fig. 11.** Respiratory plane velocity field for the three walking conditions (when individuals walked for 8 s).

![Average temperature of the three walking conditions.](image3)

**Fig. 10.** Average temperature of the three walking conditions.

**Fig. 9.** Temperature distribution of the vertical direction near the human body (when individuals walked for 8 s).

**Fig. 12.** Respiratory plane velocity field for the three walking conditions (when people were walked for 8 s).
comparing the wind speed of the surrounding air and the vicinity of the human body, the wind speed near the human body is high. Human body movement disturbs the surrounding air and causes the wind speed to increase. Concurrently, in the center of the human body, the airflow direction is forward because when an individual moves, the center airflow tends to move forward and then moves backward from both sides of the body. The effects on the air in the vicinity of the human body are usually due to this type of airflow. Furthermore, when the wind crosses, we can see that the people in the first column closest to the spout under the model are in the place where the airflow of the vent is sinking, and they are seriously affected. This indicates that the distance from the air outlet is an important factor when queuing.

4.2.3. Wind velocity analysis across the overall environment

The average wind speeds of the whole model, respiratory, and queuing regions are shown in Fig. 13. It is clear that the average wind speeds in the different areas are quite different. The average wind speed of the entire model region was approximately 0.03 m/s, and that of the respiratory region was approximately 0.1 m/s, which means that people’s breathing affects the wind. Perhaps the more people there were, the bigger the impact, as there were only 15 individuals in our model. Furthermore, the wind speed in the queuing area was approximately 0.18–0.21 m/s, which was significantly higher than the ambient wind speed. This shows that the movement of individuals causes a disturbance that can significantly affect the surrounding air.

4.3. Droplets patterns

In the droplet transmission simulations under three different walking conditions, we selected four representative locations to assume that the location is a patient exhaled by breathing, talking, coughing, and sneezing while walking. Nine locations in the first, third, and fifth columns in the walking direction were initially chosen to analyze the impacts of ventilation and human impeding on the aerosol transmission risk from patients. Through pre-simulation, we found that the exhaled droplets mainly dispersed backward when the individual moved. Thus, the passengers in the fifth column in the walking direction were meaningless, as no other passengers were behind in the cases. Moreover, the positions of the humans are symmetrical with respect to the axis in the model for the windward and leeward walking conditions. Thus, it is not necessary to choose the passenger in the right location in the first and third columns from the top view in Fig. 14. Meanwhile, for cross-wind walking conditions, similar to windward and leeward walking, the abovementioned two right locations in the first and third columns are unnecessary, as no other passenger exists along the crosswind direction. Therefore, four positions located in the front and middle of the left and middle columns were studied as representative positions, as shown in Fig. 14.

With the easing of the epidemic and the relaxation of epidemic control, wearing mask is not compulsive at the indoor environment including the airport terminal in the western countries. Thus, many people took off their masks inside the airport terminal. Meanwhile, even in the airport terminals in the mainland China, several passengers took off the masks during eating or drinking, but forgot wearing the masks again when they finished the meals. The situations were also observed during our field measurement. Therefore, the most unfavorable conditions when taking off masks sometimes exist, without the protect of mask, the aerosol transmission risk should be several times higher than the situations with mask on. In the study, we focused on those high aerosol transmission risk situation and neglected the lower risk conditions with masks.

4.3.1. Droplet distribution

To clearly represent the distribution of the patient’s exhaled droplets, we selected the distribution of the droplets at different times when the patient was at position 1 and sneezed while walking in the wind, as shown in Fig. 15. Owing to the large number of simulations for different conditions, the distribution of droplets at different times for other conditions is included in the Supporting Information. From the droplet distribution, the droplets exhaled during human walking mainly affect people in the back row of a patient. Therefore, in a public environment where there are moving patients, being behind infected patients allows for an increased chance to be infected than if an individual was standing in front of them. Furthermore, as observed from the figure, as the queue moves forward, the droplet distribution area continues to expand. At 5 s, the droplets from the sneeze only affected the position in the row behind the patient, but at 10 s, the droplets had already affected the people in the fifth row behind the patient, and at 15 s, they would spread farther. Moreover, the distribution of the droplets becomes more dispersed as the queue moves forward. For example, the distribution of droplets at 5 s and 10 s will be more densely distributed, and the distribution of droplets at 15 s will be more dispersed. This phenomenon shows that the droplets were indeed spread by airflow in the surrounding environment.
We simulated the condition of a stationary human body, and the results are shown in Fig. 15. In the static state, after the droplets were exhaled, they mainly spread upward owing to the influence of the thermal plume. As there is no human walking influence, the droplets did not have a tendency to spread behind the human body. Moreover, when the human body remains stable without walking in the crosswind, the droplets not only spread upward but also spread to the right of the human body owing to the effect of the wind.

As the patient walks, the droplets exhaled are carried by the surrounding air and circulated. To observe the distance traveled by the droplets, we counted the distance of the droplet spread in the walking direction (Y-direction), as shown in Fig. 16. According to our statistics, the distribution distance of the droplets exhaled by the passenger in the direction of walking increased with time. At approximately 3 s, there was a distance of 1 m; after 15 s, there was a distance of 9.32 m. We believe that breathing and speaking are continuous behaviors that last for a long time, and as the human body only walked for 15 s in our study, the droplet spread was strongly affected by the traffic wind near the person; hence, the droplet moving distance is approximately the same. The results confirmed that during continuous exhaust conditions, the change in size from 1 μm to 15 μm was insufficient to change the particle concentration distribution around the human body, which has been verified [23,59,60]. Currently, according to China’s epidemic prevention requirements, people are required to maintain a 1 m distance in public environments. However, the public environment is complex, often with many moving individuals. Through our research, we believe that a 1 m distance is far from sufficient, and individuals need to maintain a greater distance from each other for safety reasons.
From the droplet transmission distance in the walking direction, we also found that the droplet transmission distance from coughing is frequently smaller than breathing, speaking, and sneezing no matter where the patient is located. This may be because coughing is not a continuous droplet exhalation behavior when compared to breathing and speaking, but only within 0.7 s of walking. However, sneezing involves ejecting droplets with a high initial velocity and a large number of droplets. Although coughing is an instantaneous behavior, such as sneezing, the number of droplets exhaled from coughing is smaller than that from sneezing, and the initial velocity is also smaller.

Only considering the transmission distance when evaluating the exposure risk is not enough. We have added the aerosol concentration behind the patient to additionally clarify the inhalation risk at each case. The combined methods have also been employed in several similar studies [10,23,61]. In addition to the droplet propagation distance, we counted the droplet concentration behind the patient at different positions in different situations. The droplet concentration behind the patient at Position 1 is shown in Fig. 17. The results for the other conditions are presented in the Supporting Information. The droplet concentration gradually decreased with distance in the two persistent exhaled droplet behaviors of breathing and speaking. At 0.5 m from an individual, the concentration had a clear upward trend, which is approximately 21.1% higher than that at 0.2 m. That could be attributed to the aerosol accumulation effect induced by the forward airflow just behind the brain of the patient (Fig. S20 in the Supporting Information). This forward airflow causes the particles gathering in the area 0.5 m behind the human body. Furthermore, the concentration increased slightly at 1.5 m from the patient, but the magnitude was smaller. The concentration

(b) Droplet distribution at different times when the patient sneezes at position 1 in the windward direction while stationary

Fig. 15. (continued).
decayed to 0 after 3 m behind the person. In the transient exhalation behaviors of coughing and sneezing, which are only performed at the beginning, the concentration of droplets tended to increase at 1.5–2.5 m behind an individual. This is likely because the droplets are carried forward by the airflow after the initial exhalation; however, as the speed is not as fast as the walking speed of an individual, the particles do not quickly spread over a long distance from the individual.

4.3.2. Effect of evaporation on droplet particle size

The droplets underwent evaporation after exhalation, resulting in a reduction in droplet diameter. We measured the change in the droplet diameter over time after release from the patient’s mouth, as shown in Fig. 18. As the droplet component we used had NaCl, a substance that does not evaporate, the droplets did not evaporate indefinitely until they disappeared. The droplets eventually spread throughout the environment in the form of nuclei. Through our research, the 50 μm droplets exhaled due to sneezing were eventually evaporated into droplet nuclei with a diameter of about 24.14 μm, the 15 μm droplets exhaled due to coughing or talking had a final diameter of 7.24 μm, and the 1 μm droplets had a final diameter of only 0.365 μm.

Droplet evaporation is a rapid process, particularly for small droplets. The smaller the particle size, the shorter the evaporation time. In this study, the breathing droplet was as small as 1 μm, which quickly evaporated to 0.365 μm in less than 0.5 s. Moreover, the evaporation time of a 15 μm droplet was less than 0.5 s. A droplet with a diameter of 50 μm, representative of a large particle-size droplet, took approximately 3 s to completely evaporate. Wells [62] studied the evaporation of falling droplets in a classic study of airborne transmission and...
obtained a classical curve that revealed the relationship between the droplet size, evaporation, and rate of descent. In their study, droplets smaller than 50 μm evaporated completely within 1 s. These results may differ from ours, perhaps because the study did not consider the droplet movement, the effect of surrounding air movement, the jet stream produced by respiratory activity, or the effect of salinity concentration. In a study by Xie et al. [61], who investigated droplet dispersion due to different respiratory activities, the modified evaporative drop curves showed that the evaporation time of 50 μm droplets is close to 3 s. This is similar to our findings, indicating that exhaled droplets due to human
respiratory activities are indeed affected by other factors that differ from
the evaporation of pure water droplets.

4.3.3. Effect of cross wind on droplet distribution

In this study, we simulated the effect of crosswind walking on droplet
transmission by considering the relative position and orientation of indi-
viduals walking, and the air supply vents in the airport terminal. We
counted the droplet transmission distance perpendicular to the walking
direction (X-direction) under three walking conditions. Fig. 19 shows
the distance of the droplet spread for different exhalation behaviors of
the patients at position 1. The results for the other conditions are pre-
sented in the Supporting Information. There was no significant
difference in the droplet transmission distance in the X-direction under
the three conditions in the first 10 s of walking; however, after 10 s, the
distance gradually increased under the different walking modes. When
the patient was in position 1 for 15 s, the maximum distance of the
droplets in the X-direction of walking in the cross-wind walking was 1.7
m, and the maximum distance of walking in the windward and leeward
direction was 0.44 m. It is clear that the crosswind had an effect, causing
the droplet travel distance to be approximately 1.26 m higher when
walking in the crosswind than in the other two conditions. Therefore, it
is evident that the spread distance of the droplets in the X-direction
when walking across the wind was significantly greater than when
walking in the windward and leeward directions. Fig. 20 shows the
droplet distribution of the patient sneezing at position 1 during cross-
wind walking, and it is obvious that the particles move in the direction
of the crosswind. In particular, the distance of droplet transmission in the
X-direction under cross-wind walking increased with time. From the
distribution of aerosols in the crosswind, we believe that the process of
moving forward in the queue may affect the individuals in the next
column.

4.3.4. Comparison with the literature

The results of a series of analytical studies on the extent of droplet
transmission were compared, as listed in Table 4. As the droplet source
and droplet size are important factors affecting transmission, the droplet
source and droplet size in this study and other studies are also listed in
Table 3 for comparison.

Xie et al. [61] showed that the horizontal distance of droplets would
reach approximately 2.25 m after being ejected. However, Pendar
et al.’s study [10] showed that the horizontal distance would reach 4 m,
which is 1.78 times higher than that of Xie et al.’s research [61]. This
may be because Pendar et al. [10] focused on coughing and sneezing. Compared to breathing, coughing and sneezing have a higher exit velocity and a higher number of droplets, resulting in an increased horizontal distance. In addition, Xie et al. [61] investigated the exit jet of a person but did not consider the influence of the surrounding air. These studies were based on a situation in which individuals were stationary and did not consider the impact on droplets caused by the disturbance of the surrounding air caused by the movement of people. Therefore, in this study [45,63], considering the movement of individuals, the transmission distance of droplets was increased compared to the studies by Xie et al. [61] and Pendar et al. [10]. However, in this study, the maximum distance was three times greater than that reported by Wu et al. This may be since the study by Wu et al. [63] was based on high-risk areas of viral aerosols rather than the entire distribution range of aerosols. Furthermore, our results were two times higher than those of Wu et al. [63] as the ward size in Guan et al.’s study [45] was only 5 m, and the movement was performed for 3.8 s.

5. Study limitations

This study had some limitations that should be addressed in future research. First, we only studied the situation of individuals walking in the same direction between different points and did not consider the situation of individuals walking in the opposite direction between different points. However, airports usually plan serpentine areas for passengers to line up, which inevitably causes individuals in different rows to walk in opposite directions. Second, the airport includes some standing individuals and some sitting individuals; we did not consider more complex situations. For example, an infected individual may be sitting down, and when a moving person passes by him, there is a disturbance that causes the particles to disperse and spread. Third, we considered only one form of airflow organization that is commonly used in airport terminals. Moreover, some airports use other air-conditioning systems, such as floor radiation and displacement ventilation systems, which have yet to be studied. We believe that the queuing area in the airport is primarily for check-in and boarding. Finally, we did not consider the effects of heat transfer from the external walls. Envelope heat transfer may contribute significantly to heat balance of the whole space in airports [64]. In our research, we believe that the queuing area in the airport is mainly for check-in and boarding. In the actual airport, the check-in area is generally far away from the outer wall of the airport terminal. As the inner area of the air-conditioning partition, the indoor environment of the check-in queue is mainly affected by the air-conditioning system. Studies have shown that the thermal environment of the terminal building below 5 m is very stable. We believe that the heat transfer from the envelope structure is very small and can be ignored [65,66]. When boarding, because the boarding gate will be closer to the outer wall, it may have an impact. But the boarding process is usually short and the impact might not be such significant in those several seconds considered in the study. In conclusion, heat transfer from the outer envelope could indeed impact the thermal environment, we will continue those related study in the next future.

As the range of key factors in the study was carefully set according to the actual situations in the airport terminal and human movement patterns were determined based on the commonly simultaneous movement condition when queuing, we believe the problem investigated in the study could more represent the real-life situation compared with current studies. Certainly, our study has some shortages that are concluded in the study limitation section. We will continue the study for better reflecting the aerosol transmission risk under real-life situation in similar traffic-related environment including airport terminals, transport environment, etc. In the future, we plan to conduct a more in-depth study to resolve these limitations.

6. Conclusions

This study used computational fluid dynamics simulation technology to simulate the temperature distribution, wind speed distribution, and droplet transmission characteristics of common queuing scenes found in airport terminals. Based on our research, we arrived at the following conclusions.

(1) The respiratory and queuing regions exhibited higher temperatures. The breathing zone temperature was approximately...
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0.02 °C higher than the overall ambient temperature, and the queuing zone was approximately 0.15 °C higher than the surrounding environment.

(2) Human body movement caused disturbances and affects the surrounding air. Human body movement forms a wake, and the speed of the wake can reach 0.8 m/s. The average wind speed in the queuing area is typically 0.15–0.18 m/s higher than that in the surrounding environment.

(3) The droplet diffusion pattern when several individuals walk is different from that in stable cases. The droplets mainly affected individuals behind the patient during walking. At 0.5 m, the droplet concentration has a clear upward trend, which is approximately 21.1% higher than that at 0.2 m. The distribution distance of the droplets in the direction of human motion gradually increased during walking, and the maximum distance reached 9.32 m after 15 s.

(4) The 1 μm and 5 μm droplets will evaporate into solid substances with a particle size of 0.365 μm and 7.24 μm in 0.5 s, and the 5 μm droplets will evaporate into a particle size of 24.14 μm in 3 s.

(5) Crosswinds have a significant impact on droplet transmission. The spread of droplets in the direction perpendicular to the human body is approximately 1.26 m longer than that without the effect of cross-wind.

CRediT authorship contribution statement

Yu Zhao: Writing – review & editing, Supervision, Conceptualization.
Yao Feng: Writing – original draft, Validation, Investigation, Data curation.
Liangdong Ma: Funding acquisition.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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