Relationship between bioaerosol particle size and ventilation removal for airborne infections

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Abstract. It is now suggested that COVID-19 can cause airborne infection by fine particles called droplet nuclei and reducing the risk of indoor infection through ventilation is attracting attention as a part of countermeasures against infectious diseases. However, indoor ventilation planning does not take into account the deposition of fine particles on the floor due to gravitational settling or on the wall due to inertia, and thus there is an urgent need to establish appropriate ventilation rate and methods. Therefore, this study aimed to clarify the effect of gravitational settling of suspended particles and ventilation characteristics by natural ventilation using the temperature difference between indoor and outdoor, and evaluated the outflow characteristics and removal efficiency of suspended particles by natural ventilation using CFD analysis. When the outdoor temperature is 5 ºC, particles with a diameter of 80-100 μm are deposited on the floor by gravitational settling in about 20 seconds and are almost completely removed. Particles with diameters of 10 to 70 μm are also deposited by gravitational settling, but some of them are carried by the circulating flow generated in the room by natural ventilation, so the decay of concentration is slow. When the outdoor temperature is 35 ºC, particles with diameters of 30 to 100 μm are almost completely removed from the space in about 30 seconds due to gravitational settling and floor deposition by downward flow generated near the opening. Particles with a diameter of 10 to 20 μm are partially transported by the circulating flow, so that the concentration decay is slow.

Keywords. Virus, Particle, Ventilation, Gravitational Sedimentation, CFD
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1. Introduction

The first case of coronavirus infection (COVID-19) was reported in Wuhan in December 2019, and then in March 2020, WHO considered COVID-19 a global pandemic based on the spread and severity of the infection. In November 2021, the cumulative number of infected people worldwide was more than 250 million, and the cumulative number of deaths was more than 5 million, and the disease continues to rage. Infectious diseases, such as COVID-19, SARS, MERS, and H1N1, cause symptoms when microorganisms invade and multiply in the human body. Infectious particles emitted by an infected person are dispersed into the air by sneezing, coughing, vomiting, talking, etc., and are then transmitted to the infected person. The size of droplets has a wide distribution, roughly from 1 to 1000 μm in size. The droplets of about 100 μm fall to the floor in a short time. However, droplets of 10 μm in size drift in the air and are transported by air currents, although not for a long time. In addition, it has been confirmed that many droplet nuclei with a diameter of 0.5 to 5.0 μm exist in the respiratory tract of an infected person, and are discharged into the air in the form of particles by coughing, etc., and remain floating in the room for a long time, increasing the risk of infection to the infected person. Ventilation rate and airflow patterns play an important role in airborne transmission of viruses in indoor environments. Currently, many organizations provided COVID-19 ventilation guidance including the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA). However, the guidance does not take into account floor deposition of fine particles such as droplet nuclei due to gravitational settling or wall deposition due to inertial forces, and thus cannot be said to be appropriate ventilation rate or ventilation methods. Therefore, the purpose of this study is to clarify the effect of gravitational settling of suspended particles and ventilation characteristics by natural ventilation using the temperature difference between indoor and outdoor, which is the simplest ventilation method, and to evaluate the outflow characteristics and removal efficiency of suspended particles by natural ventilation by CFD analysis.

2. Research methods

2.1 CFD analysis Model

Fig. 1 shows the CFD analysis model for the study, and Tab. 1 shows the CFD analysis model and boundary conditions. The model consists of an indoor space of 2.5(x) × 2.5(y) × 2.5(z) m and an outdoor space of 10.0(x) × 10.0(y) × 10.0(z) m. The outflow flow of polluted air and particulate matter from the indoor space is calculated through an opening of 2.1(y) × 0.8(z) m. The turbulence model is the Low-Re k-ε turbulence model, and the buoyancy force is the Boussinesq approximation. The concentration of polluted air and particles are uniformly distributed in the room as the initial conditions, and the time variation of the concentration of polluted air and particles in the room for 100 seconds is evaluated by unsteady CFD analysis. The indoor temperature is set to 20 ºC, and the outdoor temperature is 5 ºC and 35 ºC.

2.2 Boundary Conditions

The boundary conditions are Reflect for the indoor ceiling and walls and Escape for the indoor floor. The boundary conditions are shown in Fig. 2. In reflect boundary condition, the particle bounces off the boundary surface with a change in momentum defined by the repulsion coefficient. The normal coefficient of restitution defines the amount of momentum in the direction normal to the wall that is retained by the particle after the collision with the boundary. In escape boundary condition, the particle is reported as having "escaped'' when it encounters the boundary in question.

2.3 Passive Scalar and Discrete Phase Model

Tab. 2 shows the passive scalar and DPM. The initial concentration of polluted air in the room is set to be 1 as a passive scalar. About 530,000 particulate matter is uniformly distributed in the indoor space at intervals of 30 mm from a point 50 mm away from the inner surface of the indoor. The particles are water molecules with a diameter of 10-100 µm, and a non-evaporating model is adopted in this study.

As a preliminary study, the number of particles to be generated in a room space is examined. The particle spacing is set to 40-240 mm and particles are uniformly distributed in the indoor space (Tab. 3). The particle size is set to 10 µm, the indoor temperature is 20 ºC, and the outdoor temperature is 0 ºC. Fig. 3 shows the indoor concentration. As the number of particles increases, the concentration transition of the passive scalar tends to approach the concentration trend of the chemical species. The particle spacing of 30 mm, which is applied in the CFD analysis of regarding particle size, is considered to be a reasonable condition, as it appears to approach the concentration trends of passive scalar more closely.

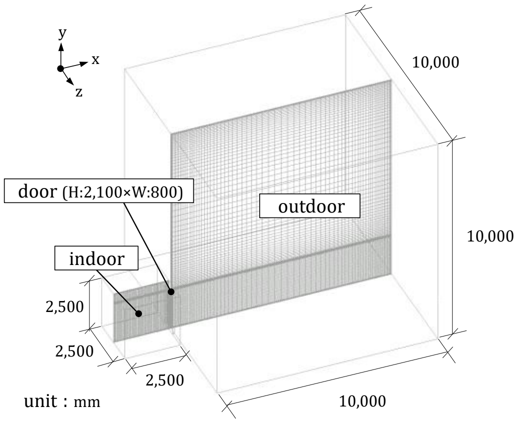

Fig. 1 - CFD analysis model.

Tab. 1 - Models and Boundary Conditions.

Models	
Scale	indoor: 2.5(x) × 2.5(y) × 2.5(z) outdoor: 10(x) × 10(y) × 10(z)
Turbulent	Low-Re k-ε turbulence model
Mesh	1,406,920 ea
Time step	Transient calculation (0.05 [s] × 2000 time steps)
Temperature	Indoor： 20 [ºC] ① Outdoor: 5 [ºC] (in winter) ② Outdoor: 35 [ºC] (in summer)
Buoyancy	Boussinesq approximattion
Boundary Conditions	
Wall, Top	Reflect
Floor	Escape

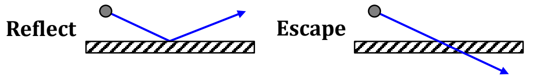

Fig. 2 - DPM Boundary Conditions.

Tab. 2 - Passive Scalar and Discrete Phase Model.

Passive Scalar	
Initial Concentration	Indoor: 1 Outdoor: 0
Discrete Phase Model	
Diameter	10-100 [µm]
Quantity	53,1441
Density	998.2 [kg/m^3]
Type	Inert
Material	Water-liquid
Drag law	Spherical

3. Results

3.1 In winter (outdoor: 5 ºC)

Fig. 4 shows the transition in indoor concentration of polluted air and particles by the natural ventilation system in winter (outside air: 5 ºC), Fig. 5 shows the behavior of particles. Particles with a diameter of 80-100 μm are deposited on the floor by gravitational settling in about 20 seconds, and they are almost completely removed from the space. Particles with a diameter of 10 to 70 μm are also affected by gravitational settling, but some of them are carried away by the circulating flow generated in the room by natural ventilation, so the concentration decay becomes slower.

3.2 In summer (outdoor: 35 ºC)

Fig. 6 shows the transition of indoor concentration of polluted air and particles by the natural ventilation system in summer (outside air: 35 ºC), Fig. 7 shows the behavior of particles. Particles with a diameter of 30 to 100 μm are almost completely removed from the space after about 30 seconds due to gravitational settling and deposition on the floor by the downward flow generated near the opening. Particles with a diameter of 10 to 20 μm are also affected by gravitational settling and downward flow, but as in the case of winter, some of them are carried away by the circulating flow, so the concentration decay becomes slow.

4. Conclusions

The results indicate that the particle removal efficiency of the natural ventilation methods across single-side opening depends on particle size and airflow characteristics. Large particles with diameters of 80-90 μm were deposited on the floor surface and removed in a short time due to the effect of gravitational settling, while small particles with diameters of 10-20 μm tended to decrease outflow to the outdoor by the circulating airflow, resulting in slow concentration decay.

5. References

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Tab. 3 – Particle space.

Space [mm]	Quantity
240	1,331
200	2,197
160	4,096
120	9,261
80	29,791
40	226,981

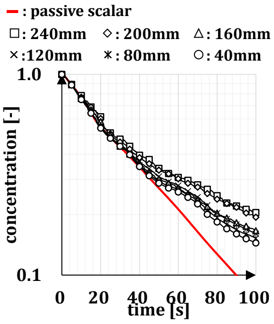


Fig. 3 – Concentration.

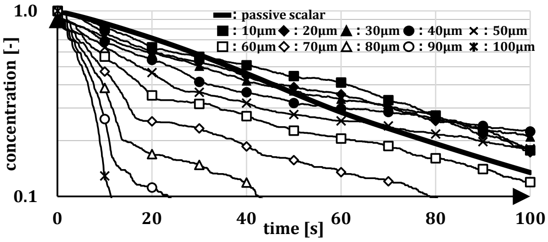
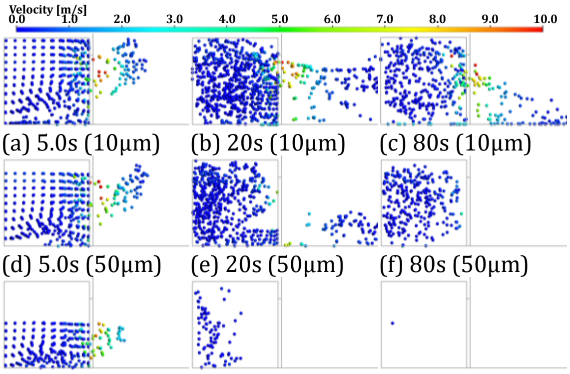


Fig. 4 - Concentration (in winter).



(a) 5.0s (10μm) (b) 20s (10μm) (c) 80s (10μm)
(d) 5.0s (50μm) (e) 20s (50μm) (f) 80s (50μm)
(g) 5.0s (100μm) (h) 20s (100μm) (i) 80s (100μm)

Fig. 5 - Particle behavior (in winter).

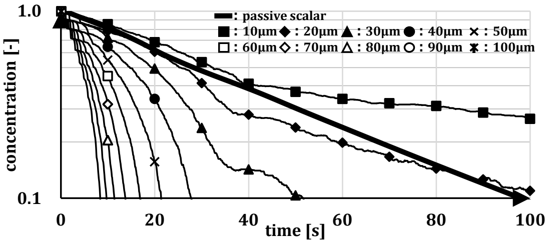
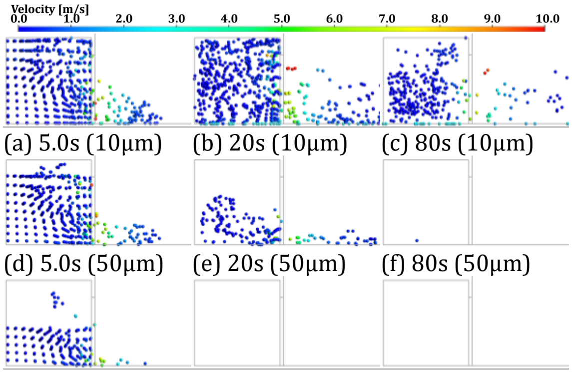


Fig. 6 - Concentration (in summer).



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(g) 5.0s (100μm) (h) 20s (100μm) (i) 80s (100μm)

Fig. 7 - Particle behavior (in summer).