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FUNDAMENTAL INVESTIGATION ON VENTILATION METHODS OF INDOOR AIR FOR PREVENTING INFECTIONS BY COMPUTATIONAL FLUID DYNAMICS ANALYSIS

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Abstract. *Droplets including virus such as COVID-19 are easily influenced by the indoor airflow and spreading around everywhere. In general, areas with higher residence time of airflow in the room are more likely to have droplets. Therefore, it is important for predicting the infection risk to use the residence time. In this study, office models with ventilation devices are used and volume-averaged residence time is evaluated as indoor air quality. After making typical office models for the ventilation, indoor air flow motions were predicted by Computational Fluid Dynamics (CFD). By setting the proper boundary conditions for ventilation, effects of ventilation methods for ventilation devices were obtained. It was found that 1) by controlling the operation of devices, ventilation ability can be evaluated by calculating volume-averaged residence time, 2) the value of volume-averaged residence time depends on the degree of angles of device inlets, and 3) volume-averaged residence time for most areas can be decreased by opening a door.*
Keywords: Infection prevention, Ventilation, CFD, Volume-averaged residence time

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1. **Introduction.** Regardless of the variant, the COVID-19 virus is primarily transmitted by airborne droplets. If the influence of wind is not considered, most viruses are transmitted by droplets. Airborne viruses are highly dependent on airflow conditions. In previous research, virus transmission is influenced by the relative humidity [1-4], amount of the airborne virus content [5] and amount of the airborne dust and PM (particulate matter) absorbing virus [6].

COVID-19 spreads when people inhale air contaminated with droplets and tiny airborne particles. Then indoor transmission of the infection is influenced by indoor ventilation, temperature of air [7] and distance from the virus source [8]. As for the indoor ventilation, it depends on location of the air inlets and outlets [9] and distribution of concentration of the droplets including virus [10-13].

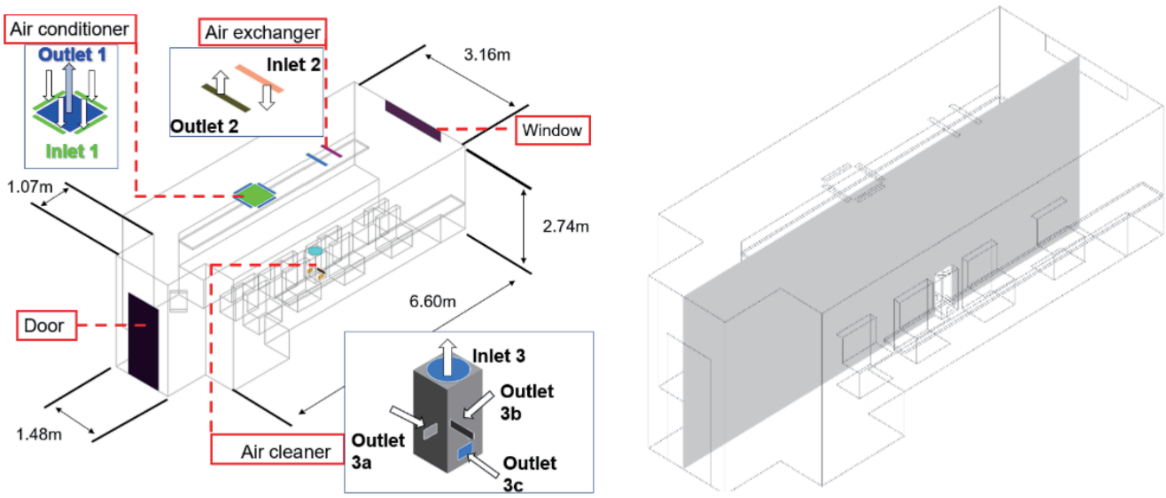
Although such studies pointed out that there are factors that affect virus transmission, they have not provided an evaluation method for indoor air ventilation yet to predict the degree of the infection possibility. Therefore, it is necessary to provide a method to make the evaluation without vast computational time for analyzing many particle motions such as droplets.

The volume-averaged residence time of air is an effective method which can help people assess the distribution of viruses. In this study, office models with ventilation devices are used and volume-averaged residence time is evaluated as indoor air quality. In these models, the devices such as air conditioner and air cleaner to improve air quality are included. All computational results are obtained by the actual daily setting value of the devices.

In this paper, there are 4 sections including an introduction. The computational method for the ventilation process is described in Section 2. In Section 3, results of volume-averaged residence time during 120 s are shown and some problems are discussed. Finally, the concluding remarks are described in Section 4.

2. **Computational Methods.** To verify the effect of ventilation method on the residence time for evaluating the risk of virus infection, simplified computational model based on fundamental equations for air flows without droplets is proposed, and the volume-averaged residence time is specified.

2.1. **Computational target and governing equations.** Figure 1(a) shows the office model consisting of the main area (6.60 m × 3.16 m × 2.74 m) and the porch area which includes the door (1.48 m × 1.07 m × 2.74 m). The entire volume is 55.68 m^3.



(a) Name of devices and size of the model (b) The reference plane

FIGURE 1. Boundary conditions in this study

To analyze fluid motions in this office model, the continuum equation and incompressible Navier-Stokes equation are used as the governing equations:

$$\frac{\partial \rho}{\partial t} + \overrightarrow{\nabla} \cdot \left(\rho \overrightarrow{V}\right) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho \overrightarrow{V}\right) + \overrightarrow{\nabla} \cdot \left(\rho \overrightarrow{V}\overrightarrow{V}\right) = -\overrightarrow{\nabla} p + \mu \Delta \cdot \overrightarrow{V} + \rho g \tag{2}$$

where t is time, $\overrightarrow{V}$ is velocity vector, p is static pressure, μ is viscosity of air, ρ is density of air, and g is gravity worked for only z-axis direction. As for the turbulent model, realizable k-ε model is used because this model is likely to provide high accuracy for flows involving rotation, boundary layers under strong adverse pressure gradients, separation, and re-circulation [14]. In addition to these equations, following transport equation of temperature T is used as the convection-diffusion equation:

$$\frac{\partial}{\partial t}(\rho T) + \overrightarrow{\nabla} \cdot \left(\rho \overrightarrow{V} T\right) - \overrightarrow{\nabla} \cdot \left\{(\lambda_L + \lambda_t)\, \overrightarrow{\nabla} T\right\} = S_T \tag{3}$$

where T is temperature, ρ is the fluid density, S_T is the source term of temperature, $\lambda_L = 2.05 \times 10^{-5}$ m^2/s is laminar diffusion coefficient, and turbulence diffusion coefficient λ_t is calculated by

$$\lambda_t = \frac{\upsilon_t}{Sc_t} \tag{4}$$

where the turbulent Schmidt number Sc_t is assumed to be 0.7. In general, it is difficult to obtain by the experiment for the current study. As the CFD results using 0.7 by other researcher's work related similar indoor air flow agree with experimental results [15], the value 0.7 is used for Sc_t. To obtain the volume-averaged residence time in the office model, local volume-averaged residence time defined by the following equation can be used:

$$\frac{\partial}{\partial t}(\rho \tau_i) + \overrightarrow{\nabla} \cdot \left(\rho \overrightarrow{V} \tau_i\right) = S_\tau \tag{5}$$

where i is the number of each computational cell, τ_i is residence time for the i-th computational cell, and S_τ is the source term of residence time. To evaluate the ventilation efficiency, the volume-averaged residence time in the room is used by the following equation:

$$\bar{\tau} = \frac{1}{V} \int \tau \mathrm{d}V = \frac{\sum(\tau_i \times \Delta v_i)}{V} \tag{6}$$

where $\bar{\tau}$ is volume-averaged residence time, V is volume of the model, and Δv_i is the velocity of air in the i-th computational cell. By using Equation (6), $\bar{\tau}$ will be evaluated with changing Δv_i and τ in the following section.

2.2. **Boundary conditions.** The flow rate and temperature used in this study are shown in Table 1. The wall is assumed to be adiabatic, and there is no heat flux through the wall. There are no heat sources or sinks on outlets. The other boundary conditions are given by measurements or specific values of the devices. Boundary conditions are considered as 1) Air conditioner and Air exchanger: airflow from inlet 1 and inlet 2 is kept at an angle of 135deg to outlet 1 and outlet 2, respectively; 2) Air cleaner: outlet 3a, 3b, 3c are distributed on 3 sides; 3) Door is considered as an inlet.

3. **Result and Discussion.** In this study, choose middle section of the room as the reference plane to show the residence time distribution in Figure 1(b).

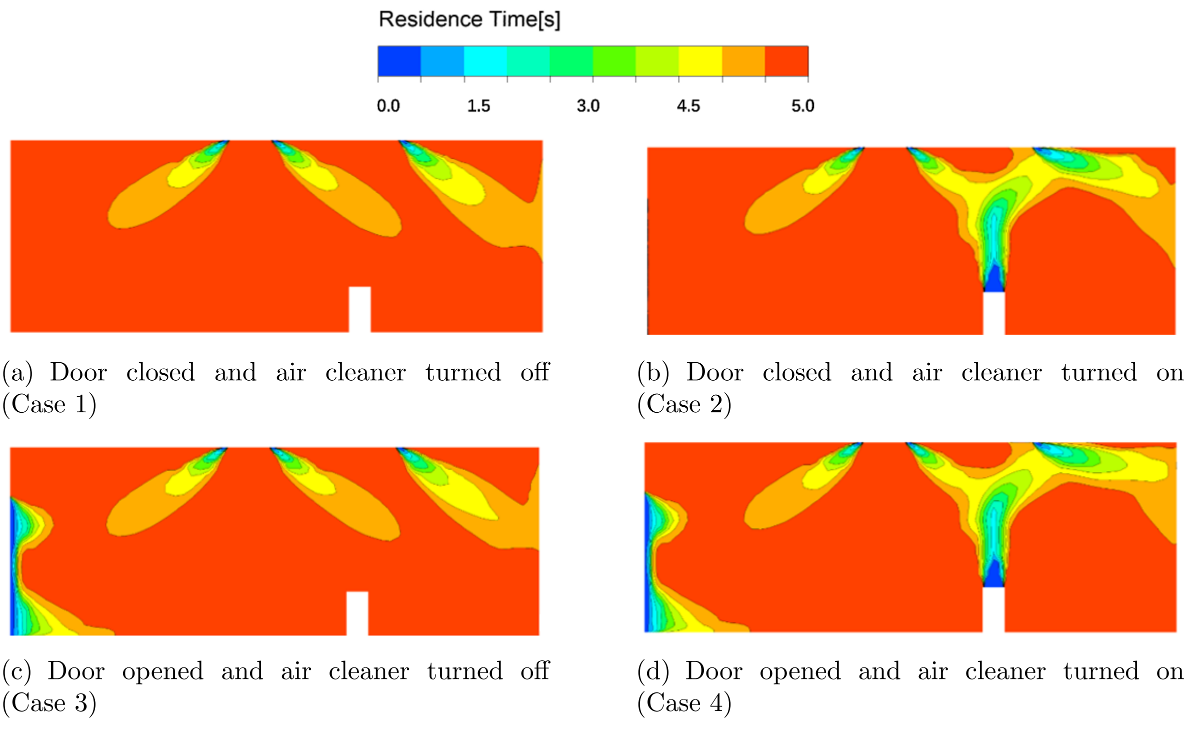
3.1. **Definition of 4 computational cases for ventilations.** Before showing results, 4 computational cases are defined. In case 1, the door is closed, and the air cleaner is turned off. It means that only the air conditioner and air exchanger worked. From inlet 1 and inlet 2, fresh air is flowed. In case 2, the air cleaner is turned on, new fresh air is

TABLE 1. Boundary conditions for inlet and outlet

Place	Flow rate	Temperature
Inlet 1	15.00 [m^3/min]	29.11 [°C]
Inlet 2	5.76 [m^3/min]	28.01 [°C]
Inlet 3	5.94 [m^3/min]	25.00 [°C]
Outlet 1	15.00 [m^3/min]	$\partial T/\partial n = 0$ [°C/m]
Outlet 2	5.76 [m^3/min]	$\partial T/\partial n = 0$ [°C/m]
Outlet 3	5.94 [m^3/min]	$\partial T/\partial n = 0$ [°C/m]
Wall	0 [m^3/min]	$\partial T/\partial n = 0$ [°C/m]

flowed out from the device, and the direction of airflow from inlet 2 is changed. In case 3, the door is opened, and the air cleaner is turned off. More fresh air is flowed into the room. In case 4, the door keeps opening, and the air cleaner is turned on.

3.2. **Effects of ventilation devices.** As for the effects of ventilation devices, residence time distributions for 4 cases at 6.6 s are shown in Figure 2. It is found that with increasing the number of airflow devices, high residence times area is decreasing. It is also found that there is the lowest residence time area at case 4.



(a) Door closed and air cleaner turned off (Case 1)

(b) Door closed and air cleaner turned on (Case 2)

(c) Door opened and air cleaner turned off (Case 3)

(d) Door opened and air cleaner turned on (Case 4)

FIGURE 2. (color online) Residence time distribution in 4 cases

3.3. **Effects of flow rate on the volume-averaged residence time.** The volume-averaged residence time in all 4 cases is calculated by Equation (6) and shown as the line of 3 different flow rate models in Figure 3. With increasing of the flow rate for devices, the volume-averaged residence time in the same cases will keep decreasing. According to this discovery, improving air quality and eliminating the spread of the virus by increasing the number of the devices should be an efficient and easy way to achieve.

However, the value in case 3 (door is opened and air cleaner is stopped working) and case 4 (door is opened and air cleaner is kept working) with normal flow rate model and

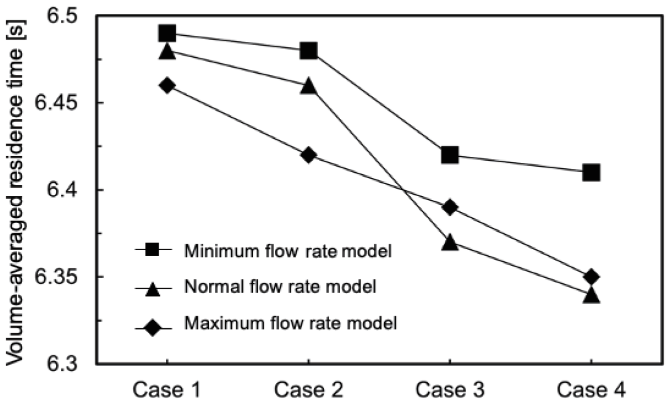


Figure 3. Volume-averaged residence time of 4 cases in 3 flow rate models

maximum flow rate model is inconsistent with this conclusion. In these two different flow rate models, the tendency of volume-averaged residence time is reversed. In case 4, although the door is opened, which means that more fresh air flow should exist in the model, the value of volume-averaged residence time is higher than in case 3. For this situation, the reason is discussed in Section 3.5.

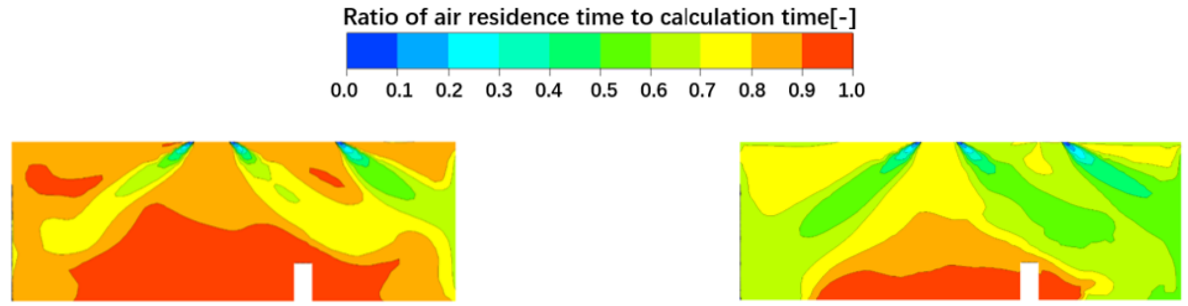
3.4. **Effects of ventilation case on the time history of volume-averaged residence time distribution.** Figure 4 shows residence time distribution of air for 4 cases in maximum flow rate model. With the time increasing, the low residence time area in all cases is increased. When the door is closed, there is an area in the middle of the room that is not influenced by time. After the door opened, such area disappeared. On the other hand, compared with case 3 and case 4 at 120 s, the residence time distribution on the right side of the model is different. In case 4, there is a relatively higher residence time area than in case 3. Figure 5 shows the ratio of volume-averaged residence time to calculation time at each time in case of maximum flow rate model. It is clearly found that the ratio decreasing with time, which means the room is gradually occupied by relatively fresh air. However, from 72 s, the value in case 4 is higher than that in case 3 with time increasing.

3.5. **Discussion for the effect of angles.** The flow direction of air from inlet 2 may impact volume-averaged residence time distribution, as it is higher in case 4 than that in case 3 in the previous subsection. To elucidate this phenomenon, the simulation with 3 types of flow angle of inlet 2 in the maximum flow rate model at 120 s, the opened door and the turned off air cleaner were conducted. Figure 6(a) shows effects of the angle of inlet 2 on volume-averaged residence time distribution. Most fresh air from inlet 2 is kept indoor at 30 deg, part of the air flow out from the window at 45 deg, and most of the airflow from inlet 2 directly flowed out from the window at 60 deg. Figure 6(b) shows the value of volume-averaged residence time for these 3 angles. The above hypothesis is supported by this calculation result. The value at 30 deg is much smaller than other. It means that there is no fresh air from inlet 2 flowed out of the model.

4. **Conclusions.** In this study, indoor ventilation models were simulated by CFD and the following issues are concluded.

1) Ventilation effect can be evaluated by calculating volume-averaged residence time.
2) The degree of angles of device inlets can also affect the results.
3) Opening door can decrease volume-averaged residence time for most areas.

This study provides a method to determine air quality, and how to reduce the spread of COVID-19 indoors. The merit of this method is smaller CPU time for CFD computation



$t = 48$ s $t = 120$ s

(a) Door closed and air cleaner turned off (Case 1)

$t = 48$ s $t = 120$ s

(b) Door closed and air cleaner turned on (Case 2)

$t = 48$ s $t = 120$ s

(c) Door opened and air cleaner turned off (Case 3)

$t = 48$ s $t = 120$ s

(d) Door opened and air cleaner turned on (Case 4)

FIGURE 4. (color online) Residence time distribution of air for 4 cases in maximum flow rate model

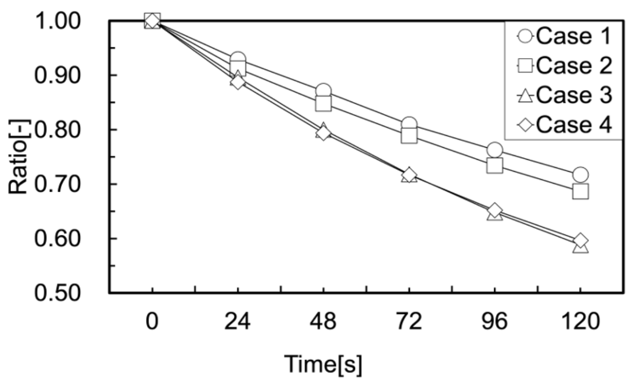
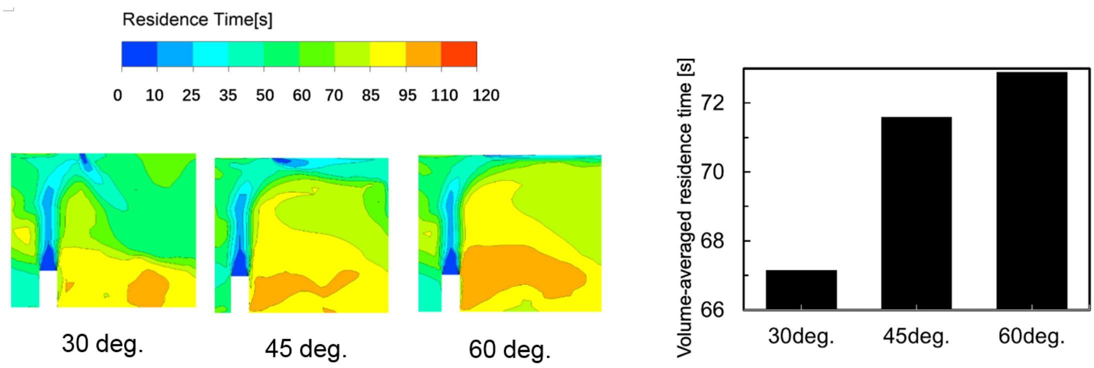


FIGURE 5. Time history of the ratio of volume-averaged residence time



(a) Residence time distribution in different angles

(b) Volume-averaged residence time for 3 different angles

Figure 6. (color online) Effects of the angle of inlet 2 on volume-averaged residence time distribution

compared with the previous research works, and to check the indoor ventilation situation quickly.

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