



Effect of under-floor air distribution system to prevent the spread of airborne pathogens in classrooms

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ABSTRACT

This study investigated the effect of the under-floor air distribution (UFAD) system compared to conventional mixed-mode ventilation system to prevent airborne pathogen spread in elementary school. To analysis airborne pathogen spread pattern, STAR-CCM+ is used. By applying the UFAD system airborne infection risk at region around the exhaust area of conventional ventilation system can be significantly reduced. However, increased infection risks around exhaust area of UFAD system still existed. Thus, it is recommended to install the exhaust vents (outlets) away from the breathing area. In addition, since both of conventional ventilation system and the UFAD systems have a high infection risk at the front of the classroom, novel method to reduce the infection risk from students to teachers should be considered.

1. Introduction

Concerns over the spread of airborne infection are increasing worldwide. Airborne pathogens can spread rapidly because an anonymous patient may infect multiple people. Wearing masks [1] and proper ventilation [2] are excellent countermeasures to lower the probability of infection. The airborne infection rate is high in poorly ventilated spaces. School buildings are vulnerable to the spread of airborne pathogens because several occupants stay in the same space over extended periods for classes.

Recently, many studies were conducted on ventilation systems to respond to airborne infection in school buildings [3–6]. The under-floor air distribution (hereafter, UFAD) system, which is an effective system for discharging polluted air quickly and improved thermal comfort. In UFAD system, air inlet is on the floor plenum and air is directly supplied to occupied zone. B. Rahmati et al. [7] investigated the combining the UFAD system with improved desk displacement ventilation to improve the local thermal comfort and energy saving. M.H. Fathollahzadeh et al. [8,9] reported that the UFAD system with combined and separate return and exhaust air vents has a significant impact on thermal comfort in a dense occupancy (80 occupants) environment. J. Zhao et al. [10] reported that well designed UFAD system with HVAC system could provide an improved indoor air quality and energy saving in and education building in a hot and humid area. Many research has reported the UFAD system advantages which are to improve thermal comfort and indoor air quality. It can be used as an alternative to prevent the spread of airborne infection in school buildings [11,12].

In South Korea, ventilation systems must be installed in school buildings to remove the indoor air pollutants. Generally, conventional ventilation systems installed in school in South Korea are the mixing ventilation system with heat recovery function.

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Implementation of the UFAD system to school in South Korea will have significant effect on preventing airborne disease spread. However, in general, inlet and outlet location of the ventilation system in a room determines the air pollutant exhaustion efficiency. Establishment of effective ventilation system to prevent airborne infection in elementary schools can bring benefits to public health and national risk management. Therefore, CFD was usefully used to analyze the spread of bacteria and the effectiveness of the sterilization system [13]. In this study, the effect of UFAD system and its' design properties relating inlets and outlets to prevent the spread of indoor air pathogen in elementary school buildings was analyzed by using STAR-CCM+ (computational fluid dynamics software).

2. Method

2.1. Target space

An elementary school classroom in Korea was selected as the analysis target. The classroom was $(8.4 \times 8.1 \times 2.6)$ m ($w \times d \times h$) in dimension and had 30 occupants.

2.2. Simulation tools and boundary conditions

The spread of airborne pathogens discharged through the respiratory system of the occupants to the surroundings by buoyancy and airflow was analyzed under the stationary condition by using STAR-CCM+. Segregated flow model and realizable k- ϵ turbulence model are implemented. Van Maele et al. indicated the realizable k- ϵ model performs better than the standard k- ϵ model for predicting various buoyancy plumes [14]. Shin et al. was the mostly used realizable k- ϵ turbulence model for air distribution in the indoor [15].

Boundary conditions for simulation are described in Table 1. The airborne pathogens are released from the mouth of the infected person (Fig. 1). Droplet bigger than $5\mu\text{m}$ from infected person, tend to goes down to floor in a short time. However droplet nuclei smaller than $5\mu\text{m}$ or aerosol rise up and spread through long-range route by buoyance effect like gas substances. This study focuses on the long rout transmission of airborne pathogens such as droplet nuclei or aerosol. Therefore, passive scalar is used to reflect long range movement of the airborne pathogens. Exhalation rate of infected person are set to $15 \text{ m}^3/\text{day}$.

This study focused on the features of ventilation systems for the air quality control in the classroom. In this situation setting human body temperature as temperature boundary condition can be a reasonable method [16–18]. So, body temperature of each occupant are set to 310 K isothermally to consider the risky situation.

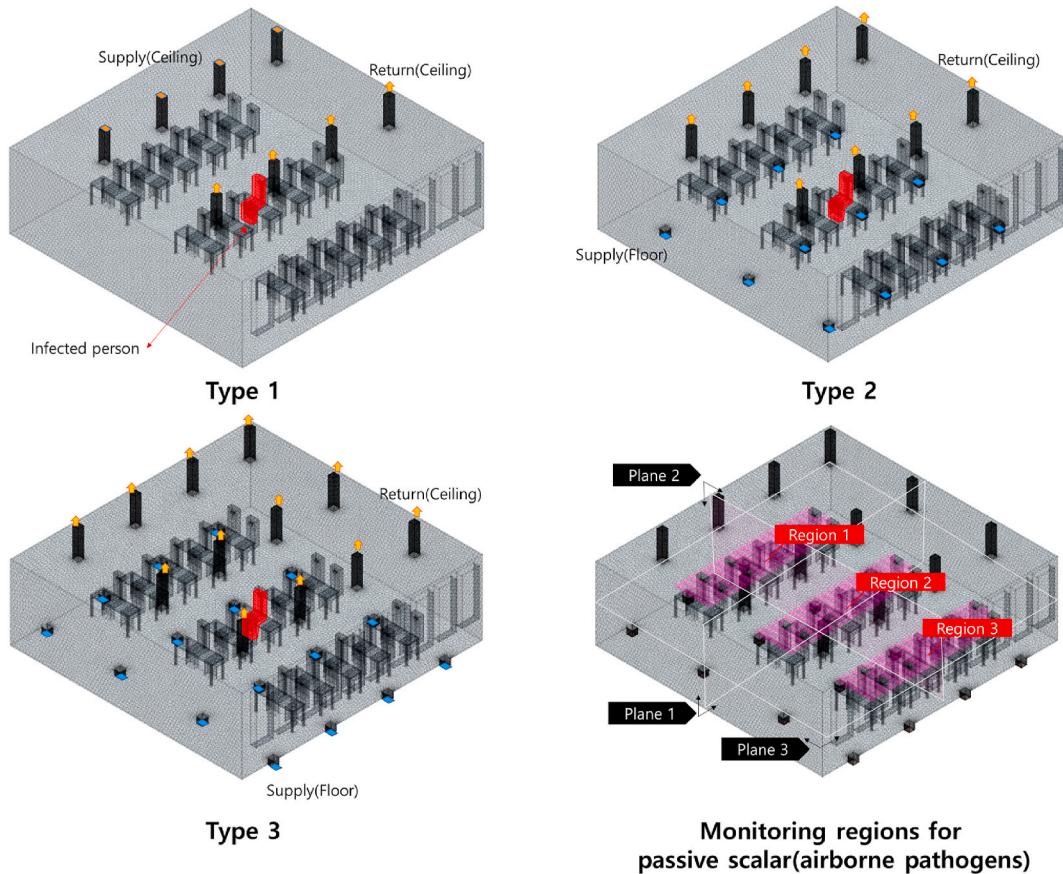
Internal heat gain from lighting devices and other thermal devices impacts the indoor thermal environments. This study focuses on the inlet and outlet layout of ventilation system and intended to minimize these disturbances by interior design components. The simulations focused on the intermediate season. Thus, inlet airflow and wall temperatures are set to 300 K .

2.3. Suggested ventilation system

The UFAD system was proposed as an alternative to the conventional ventilation system. Table 2 shows the inlet and outlet setting conditions of ventilation systems. In the conventional system (Type-1), ventilation happens through air inlets and outlets installed in the ceiling. In UFAD system (Type-2 and Type-3), fresh air introduced from the inlets installed on the floor is discharged through the outlets in the ceiling in the shortest possible path. For Type-2 and Type-3, more inlets were installed than outlets to decrease the inflow air velocity to reduce occupant discomfort. The ventilation rate of the entire classroom, which was evenly distributed between each inlet, was set to be 800 CMH .

Table 1
Boundary conditions.

Type	All models
Physical conditions	Steady state Flow: segregated flow Energy: segregated fluid temperature Turbulence: realizable k- ϵ turbulence model Gas: air, ideal gas, incompressible Gravity: -9.81 m/s^2 Solver: steady state
Meshing conditions	Type: polyhedral mesh Prism layer thickness: 33% of the base (4 layers)
Ventilation rate for classroom Airborne pathogen source (Velocity inlet)	800 CMH Exhalation: $15 \text{ m}^3/\text{day}$ (for children) Airflow velocity: 0.35 m/s Mouth size: 0.005 m^2 Airborne pathogen concentration in exhalation: 1.0 (Passive scalar)
Thermal conditions	Inlet flow and walls: 300 K Human body and exhalation: 310 K
Convergence criteria	$<10^{-4}$

**Fig. 1.** Geometric features of Simulated Types.**Table 2**
Inlet and outlet properties of ventilation systems.

Models	Type-1	Type-2	Type-3
Inlet (velocity inlet)	Size	(0.2 × 0.2) m	(0.2 × 0.2) m
	Number of installations	4	12
	Location	Ceiling	Floor
	Air flow velocity	1.39 m/s	0.46 m/s
	Outlet	(0.2 × 0.2) m	(0.2 × 0.2) m
	Size	4	8
Outlet	Number of installations	(0.2 × 0.2) m	(0.2 × 0.2) m
	Location	Ceiling	Ceiling

2.4. Simulation models of suggested ventilation systems

Three inlet/outlet types were considered for the classrooms. Type-1 represents the conventional ventilation system. Type-2 is a UFAD system, where inlets are installed on the floor, and inlets and outlets of Type-1 are used as outlets. Outlets of Type-2 are installed above the aisles between the occupants. Type-3 is also a UFAD system, where the number of inlets and outlets are increased, and outlets are installed above the head of occupants to exhaust the airborne pathogens as soon as possible. Fig. 1 show the mesh models of the classrooms including inlet/outlet setups and probe locations for monitoring the concentration of airborne pathogens (passive scalar).

Table 3
Meshing conditions of models.

Models	Number of cells (volume mesh)
Type-1	936,976
Type-2	1,137,884
Type-3	1,477,657

The classroom was divided into 3 regions also, and the average concentration of each region was analyzed. Each region represents the breathing area of each occupants' group at 1.0 m above the floor. Airborne pathogens were emitted from the infector in the center of Region-2. The Plane 1 and Plane 2 are the sectional planes that cut through the center of each wall, and plane 3 is 1 m above the floor. Table 3 shows the number of cells in each model. M. Lee et al. (2020) analyzed the optimal grid setting for the grid independence and concluded that the grid resolution range from 20 ($R^2 = 0.94$) to 24 ($R^2 = 1.00$) is appropriate for Realizable k- ϵ model. Therefore, in this study the grid resolution was set to 20 [19].

3. Results

Table 4 shows the average passive scalar concentrations that represents airborne pathogen concentrations of the three regions ($h = 1.0$ m). Figs. 2–3 show the passive scalar concentration on the 3 planes via simulation.

In all Types, the airborne pathogen concentrations at Region-2, source of airborne pathogens, of all cases shows the highest value. The airborne pathogen concentration around outlet of ventilation system has the second highest values, Region-3 for Type-1 and Region 1 for the other types.

The airborne pathogens emitted from the respiratory system of the infected person showed a tendency to rise to the top of the room due to buoyancy and then spread to the surroundings. Additionally, the airborne pathogens tended to spread toward the front of the occupant. Thus, the passive scalar concentration tended to be relatively low in the rear of the occupants (Fig. 3). This tendency corresponds to the fact that the occupant looks at the front during class.

The average velocities at breathing area (Plane 3) for Type-1, Type-2 and Type-3 are 0.07 m/s, 0.05 m/s and 0.05 m/s, respectively. The overall air velocities of total cells and breathing level are maintained at 0.50 m/s or less, confirming that the feeling of indoor airflow was maintained at an appropriate level (Table 5 and Fig. 4).

In Type-2 and Type-3, the number of air inlets on the floor increased compared to Type-1, and the inflow air speed decreased. These settings reduced the overall indoor airflow velocity. In Type-3, the air velocity around students was low compared to that in Type-2. However, this reduction in air velocity seems to accelerate the spread of airborne pathogens in the horizontal direction. Type-3 also shows less turbulence around outlet of ventilation system than Type-2. These results come from the positions of the outlet are located on top of the occupant causing buoyancy.

Fig. 5 illustrates indoor temperature pattern of each Type. The stratification of room air temperature is most evident in Type-3. Type-2 shows slightly lower temperature around occupants' body due to inlet position located near the occupants' feet.

4. Discussion

The simulation results shows the well-designed UFAD system can reduce indoor airborne pathogen concentrations than conventional ventilation system. The Type-2 has reduced airborne concentrations in all Regions than Type-1.

However, in Type-3, even though the UFAD system was applied, the concentrations of airborne pathogens in Region 1 and Region 2 was higher than in Type-1. These results mean features of inlets and outlets of ventilation systems can affect the performance of UFAD system.

Above all, the outlets the ventilation system was found to collect the adjacent airborne pathogens. Therefore, occupants near the outlet of ventilation system can be more exposed to the airborne pathogens. In Type-1, conventional mixing ventilation system implemented, the students close to the outlets in Region 3 exhibited a high probability of infection. In Type-2 and Type-3, occupants in Region 1 where the closest outlets to the airborne pathogen source are exposed to second highest airborne pathogen concentrations. Especially, in Type-3, the airborne pathogen concentrations around the breathing level is higher than Type-2, due to the outlets of ventilation system located directly above the occupants head in Region 1.

Secondly, when the outlets of ventilation system are arranged in multiple rows between occupants' groups, airborne pathogens concentration of adjacent areas decreased gradually. For Type-2, the average concentration of airborne pathogens in Region 2 and Region 3 were reduced by 32% and 66% respectively, compared to the average concentration in Region 1.

Thirdly, excessively low indoor airflow velocity may hinder the indoor airborne pathogens exhaustion. For Type-3, the overall indoor air velocity was marginally reduced owing to additional inlets. Despite the outlets located above the occupants, airborne pathogens tended to spread from Region 2 to Region 1 because the inflow air velocities and overall indoor air velocity were reduced as shown in Figs. 2 and 4. Owing to the air supply characteristics of Type-3, occupants near the inlets on the periphery of the classroom in Region 1 have relatively lower probability of infection compared to other ventilation types. However, occupants in Region 1 who are close to Region 2 (Source of airborne pathogen) have relatively higher probability of infection. Meanwhile, the spread of airborne pathogens from Region 2 to Region 3 was reduced significantly because airborne pathogens were first discharged through the outlets in Region 2 and discharged again through the outlets in Region 3.

Table 4
Average passive scalar concentration by region.

Types	Region-1	Region-2	Region-3
Type-1	5.76E-04	9.58E-04	7.27E-04
Type-2	5.78E-04	8.51E-04	2.86E-04
Type-3	7.35E-04	1.13E-03	2.78E-04

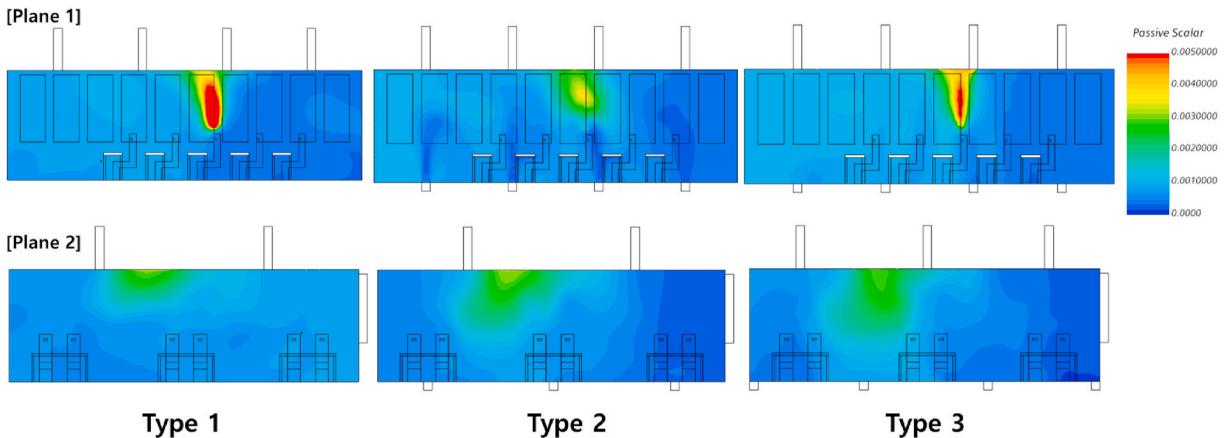


Fig. 2. Passive scalar concentration pattern of each Type at Plane 1 and Plane 2.

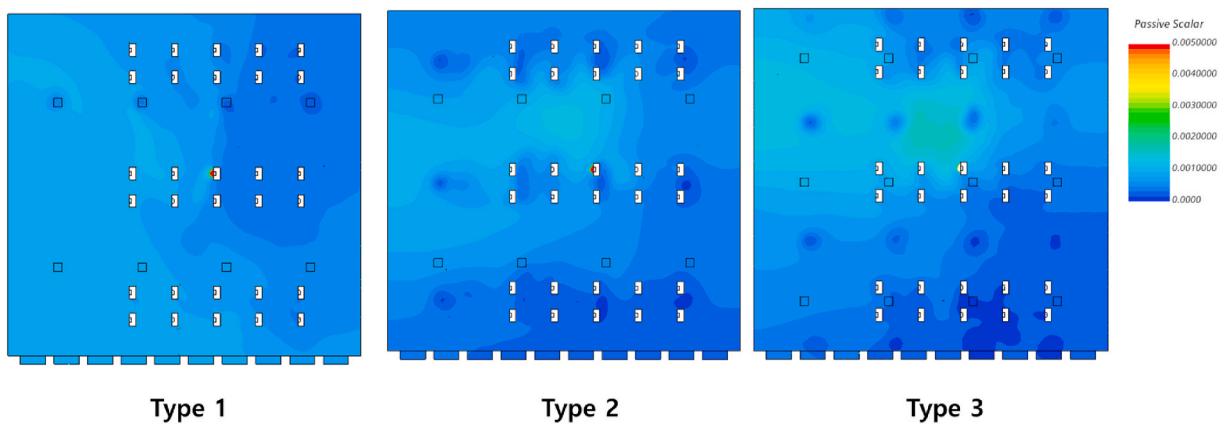


Fig. 3. Passive scalar concentration pattern of each Type at Plane 3.

Table 5

Average airflow velocity of each Type.

Types	Airflow velocity at inlet	Total cells	Breathing level (Plane 3)
Type-1	1.39 m/s	0.08 m/s	0.07 m/s
Type-2	0.46 m/s	0.05 m/s	0.05 m/s
Type-3	0.35 m/s	0.05 m/s	0.05 m/s

As the movement of airborne pathogens tended to spread towards the front of the occupants, there is a possibility that the teacher, who is in front of the classroom, is more likely to be infected. Thus, airborne infection from students to teachers can be accelerated, and the infection may spread to the entire school if an infected teacher infects other teachers in the teacher's room.

In this case study, the piston flow of the floor supply and ceiling exhaust was implemented through Type-2 and Type-3. The analysis results confirmed that the application of the UFAD system reduces the spread of airborne pathogens indoors compared to the conventional system. However, if excessively low indoor air velocity is designed for applying the UFAD system for the occupants' comfort, it may reduce the movement speed of airborne pathogens that rise towards the outlets, thereby allowing the spread of airborne pathogens in the horizontal direction. For the UFAD system implementation to control airborne pathogen spread, inlet and outlet locations of ventilation system and indoor airflow patterns and velocity should be carefully designed.

5. Conclusion

The results of this study can be summarized as follows:

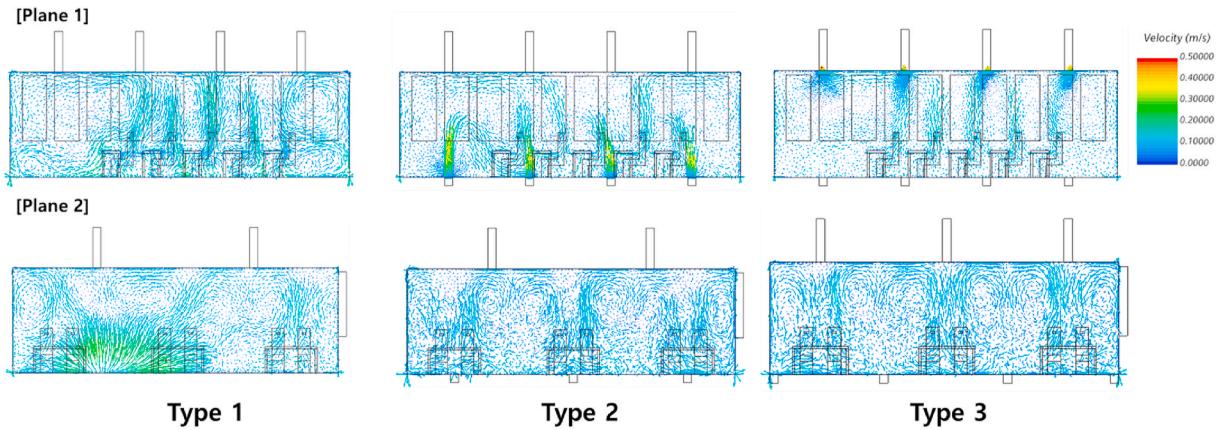


Fig. 4. Indoor airflow pattern at Plane 1 and Plane 2 of each Type.

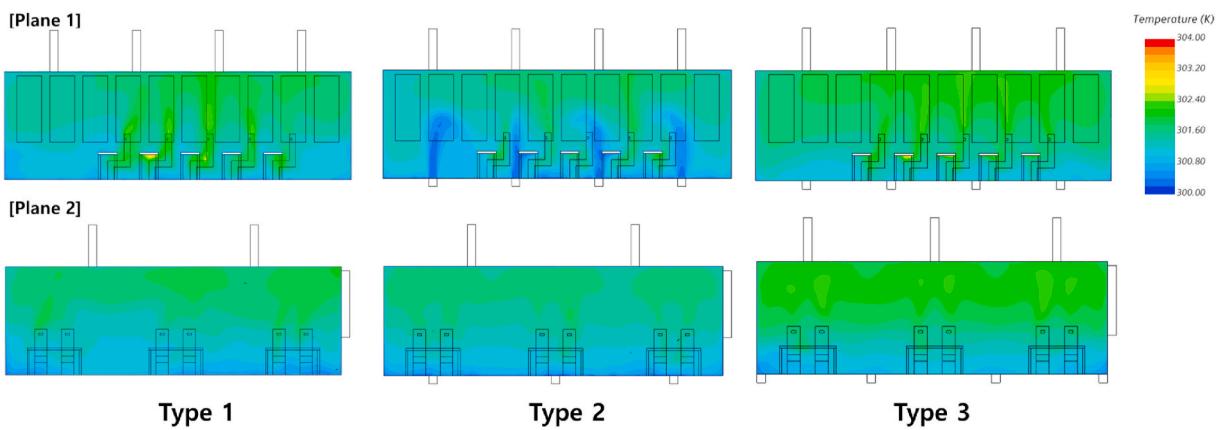


Fig. 5. Indoor air temperature pattern of each Type at Plane 1 and Plane 2.

1. The application of the UFAD system is effective in reducing the concentration of airborne pathogens in places far from the airborne pathogen source, compared to conventional ventilation system.
2. Appropriate inlet/outlet location of UFAD system affects the airborne pathogens distribution in a classroom and sufficient consideration should be made. Even though the outlets are located above the occupants for the rapid removal of airborne pathogens, increased infection risk around exhaustion area still remains (Type-3). It is recommended to install the exhaust vents (outlets) between the occupants' groups to prevent airborne pathogen spread (Type-2).
3. Low indoor air velocity can promote the spread of airborne pathogens. Therefore, securing appropriate indoor air velocity is necessary when using the UFAD system.
4. The concentration of indoor airborne pathogens at the front of the classroom was comparatively higher compared to the rear of the classroom. Hence, the teacher at the front of the classroom is more likely to be infected through airborne infection. Thus, it is necessary to prepare proper alternatives for this situation.

Although properly designed UFAD systems have benefits over conventional ventilation systems that were installed in school buildings, the spread of airborne pathogens can be prevented by utilizing a design that considers the indoor airflow pattern and appropriate air velocity.

Author statement

Chang Heon Cheong: Conceptualization, Methodology, Simulation, Analysis and Writing of the manuscript. Beungyong Park: Analysis and Writing of the manuscript. Seong Ryong Ryu: Review papers and Method writing of the manuscript.

Declaration of competing interest

All authors declare no conflict of interest to this manuscript.

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