DEPARTMENT OF ENVIRONMENT SYSTEMS

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Importance of Ventilation in University Research and Education Activities

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Chapter 1 Introduction

1. 1 Characteristics of University Laboratory and Lecture Room

Merriam-Webster defines university as an institution of higher learning providing facilities for teaching and research and authorized to grant academic degrees. Initially, the university started by renting the place of the church, students put down the straw and sat down to listen to the lecture. If someone has any knowledge, and then someone wants to learn his knowledge, this place becomes an instant learning space. But modern universities are different. It has a vast campus, a large library, elaborate experimental facilities, luxurious classrooms, and state-of-the-art digital equipment[1].

University academic research is an intellectual creation activity for all academic fields, aiming to give full play to the curiosity and free thinking of researchers, and to pursue the truth[2].

The university has a wide range of members, including undergraduate students, graduate students, researchers, faculty members, and collaborators from outside the university, and the university is highly internationalized and has a high degree of human mobility. In addition, not only are the themes of education and research diverse, but they are also novel, specialized, and interdisciplinary. Meanwhile, the risks associated with the chemical substances used and research activities are complex and diverse. In such a complex situation, it is necessary for universities to work on environmental safety as individuals and organizations[3].

1. 1. 1 Characteristics of University Laboratory

In university laboratories, students conduct experiments according to different research topics, the specific work content changes every day, so it’s inevitably composed of non-routine work. On the other hand, the factory, which is the company's production base, performs a fixed job at each work site, and in order to improve production efficiency, each job in the factory is divided into labor. In other words, the difference between a factory and a laboratory is whether it is doing repetitive and fixed work. University laboratories and factories use space and time differently. In a factory, a relatively large space in the factory is divided into work, and specialized workers are assigned to each work place. On the other hand, in a university laboratory, a laboratory table and a local exhaust system are arranged in a narrow space, multiple students share one laboratory in a same time[3].

Various chemical substances are frequently used in university laboratories, especially in chemical laboratories. Therefore, in these laboratories, chemical exposure is an important safety risk that cannot be ignored. According to the data on campus accidents collected by the Osaka University Safety and Health Management Department, from

2004 to 2013, there were 261 chemical substance-related accidents among the reported laboratory accidents on campus, accounting for 60% of all accidents[4]. Besides that, since the university laboratory is a space shared by multiple students, Some accidents in which students are not using chemical substances but are chemically exposed only because they are in the same space have also been reported[5]. In such a practical situation, it is very necessary to conduct safety management in the laboratory.

In general, the air environment of the laboratory can be considered that is affected by the ventilation devices, the operation of FH (Fume Hood), the experimental device that generates heat, the amount, time, and location of volatile chemical substances, and the movement of the experimenter, which caused the laboratory has it's unique and complicated air environment influencing factors. In addition, in order to prevent the laboratory's air environment and experimenters' involuntary exposure to chemical substances, it's necessary to conduct more detailed laboratory risk management on the basis of distribution and changes of chemical substances[6].

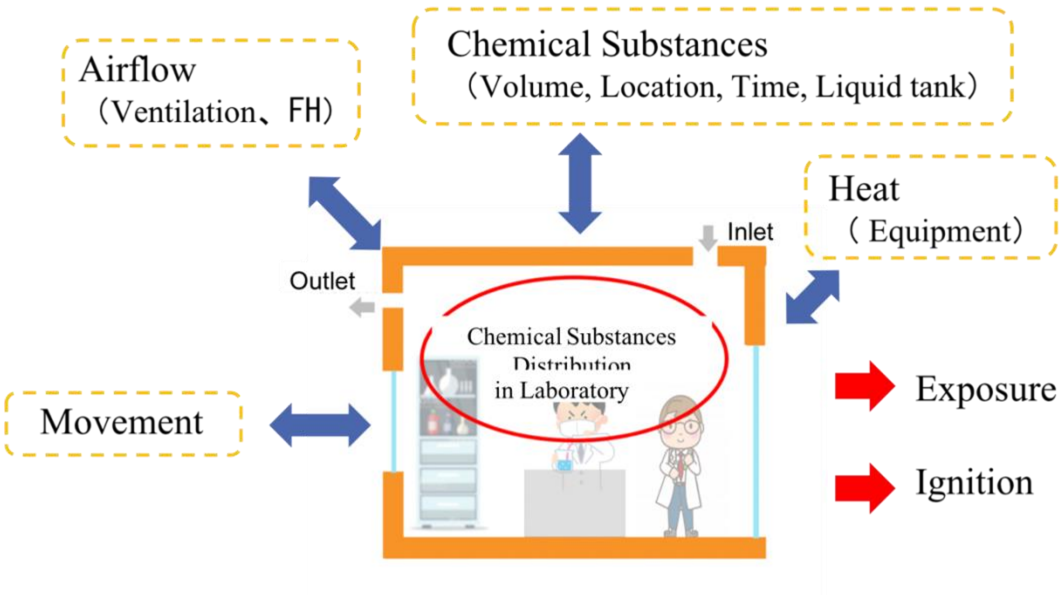


Fig. 1- 1 Factors affecting the distribution of chemical substances in the laboratory.

1. 1. 2 Characteristics of University Lecture Room

In April 2013, the Ministry of education, culture, culture and science began to allow each university to set its own course time. Since then, more and more universities have changed 90 minute courses into 100 minute or 105 minute courses[7]. Although the survey shows that many respondents hold negative opinions on the change of extending the 90minute course to 100 minutes or 105 minutes, it's undeniable that the classroom is a place for students to stay at one place for a long-time during class. On the other hand, compared with the previous teaching model in which only teachers give lectures on the platform, the current universities encourage students to speak actively and discuss in groups. In the university classroom, students are allowed to enter or leave classroom more freely than high schools. Moreover, it’s not rare for hundreds of students to attend lectures at the same time in universities. Ladder classrooms that can accommodate hundreds of students exist in almost all universities. In such a place with active communication and many students staying at the same time for a long time, it’s very necessary to carry out safety management and air environment management for university classrooms.

The air environment of a common university lecture room, it can be considered that is affected by ventilation devices, the operation of air conditioners, windows and entrances (open or close, opening size), people in the lecture room (the number of students, where students sit), course time, lengths of discussions, and the movement of teachers or students. The classroom air environment is essential to protect the health of students and teachers. In today's COVID-19 pandemic, maintaining a good indoor air environment is particularly important.

1. 2 Efforts on the Laboratory Indoor Environment Safety

It can be said that the purpose of work (experiment) in a university laboratory is to search for truth. Of course, experiments should be conducted in accordance with certain experimental specifications and requirements, but research in universities encourages the autonomy and creativity of researchers, and it is these creative results that promote the development of society. This means that it is rare to repeat the same work every day in the laboratory, and most of the researchers will constantly adjust the content of their experiments according to their own research purposes[5]. In this way, it is required to ensure the safety of the experimenter while freely demonstrating creativity and advancing research[3]. How to make researchers realize the existence of safety risks in experiments and how to reduce safety risks is the task of laboratory safety management.

1. 2. 1 Efforts on the Handling of Chemical Substances

Universities possess a wide variety of chemicals and have to comply with laws and regulations regarding chemical substances. In recent years, in order to deal with these problems, many universities have begun to manage chemical substances through chemical substance management systems[8]. For example, The University of Tokyo has a university-wide management system for chemical substances; the University of Tokyo, Chemicals Information Management System (UTCIMS). When chemicals are used in the University of Tokyo, procedures such as "registering UTCIMS", "storing in the reagent library", "posting display stickers in the laboratory", and "separating storage of toxic and hazardous substances" are required.

In the terms of waste management, although the total amount of waste discharged by university laboratories is not large, there are many types and include various hazardous substances[9]. The Environmental Report published by Nagoya University shows that organic waste liquid (non-fluorine) discharged by Nagoya University in 2020 accounted for more than half of the total discharge, followed by organic waste liquid (containing fluorine) about 20%[10]. According to Environmental Reports published by some national universities, the discharge of waste liquid within the university needs to be registered in the university's chemical substance management system firstly, then discharged in accordance with university's regulations , after that, the university will discharge the waste organic liquid by entrusting a qualified waste treatment company.[9][10][11].

1. 2. 2 Industrial Safety and Health Act

Since April 2004, national universities nationwide have been incorporated as independent administrative agencies and been subject to the Industrial Safety and Health Act[12][13]. The Industrial Safety and Health Act is a law enacted for the purpose of ensuring the safety and health of workers in the workplace and creating a comfortable working environment. As a result, many national universities have undergone major changes in the organization of many universities, and are required to change equipment and improve management systems in order to comply with this Act[3].

The Health and Safety Law stipulates that when using chemical substances that are applicable to the Organic Solvent Poisoning Prevention Regulations or the Specific Chemical Substances Control Law, it is necessary to set up local exhaust ventilation, post the hazardous properties of chemical substances, measure the working environment, and conduct health checkups. Many of the chemical substances that are applicable to the Organic Law and the Special Chemical Substances Law are used on a daily basis in experimental research at universities, and the enforcement of this law has inevitably led to the installation of many local exhaust ventilation systems[3].

As mentioned earlier, universities possess a wide variety of chemicals. In manufacturing plants, the amount of chemicals is strictly controlled, even in their laboratories, because they only produce a specified number of products. On the other hand, university laboratories have medicine cabinets filled with large quantities of chemicals, some of which do not seem to have been used for years. In other words, there were many chemicals that had been unused for years simply because "they might be used in the future". When inspections are conducted, even if laboratories are advised to "please purchase the necessary substance and purchase it in the just necessary quantities, and to dispose of substances timely when they are no longer needed," but it's difficult to ensure that this is done as thoroughly as it is done by the average company[12]. Therefore, while actively complying with the Labor Safety and Health Law is the duty of universities, universities should also consider the particularities of each laboratory in their implementation.

1. 2. 3 Working Environment Measurement

According to Article 65 of the Labor Safety and Health Law, business operators are obliged to conduct working environment measurement in the workplace where hazardous work is performed in accordance with the requirements of the Ministry of Health, Labour and Welfare, and need to record the results of the working environment measurement[14][15]. In university laboratories, especially for laboratories that use hazardous chemical substances, a working environment measurement is performed every six months as a part in the management of chemical substance concentration in the laboratory.

Working environment measurement refers to the design, sampling and analysis of the air environment to determine the actual condition of the working environment, and it has two main methods: A measurement and B measurement. A measurement refers to measuring air concentrations at five or more locations in the workplace for an hour or more at equal time intervals, and estimating the distribution of hazardous substances in the workplace under usual conditions based on these results. In this case, the measurements are made while the work is in progress, and A measurements are applicable to workplaces where chemical substances are frequently used. The B measurement complements the A measurement, and the B measurement is conducted mainly in the vicinity of the source of hazardous substances, and sampling is conducted when the concentration of hazardous substances is predicted to be at its highest[3].

However, because of the different conditions of use assumed, working environment measurement is considered to be limiting as a method for controlling the concentration of chemical substances in laboratories. The working environment measurement is designed for situations where hazardous substances are used on a continuous basis, in large quantities and for long periods of time, but the use of chemicals in university laboratories is more likely to be in a small quantity and irregularly. Compare to manufacturing plants repeated one certain task in most instances, innovation and creation pursuing university laboratories are rarely using same chemical substances at a same time for every day.

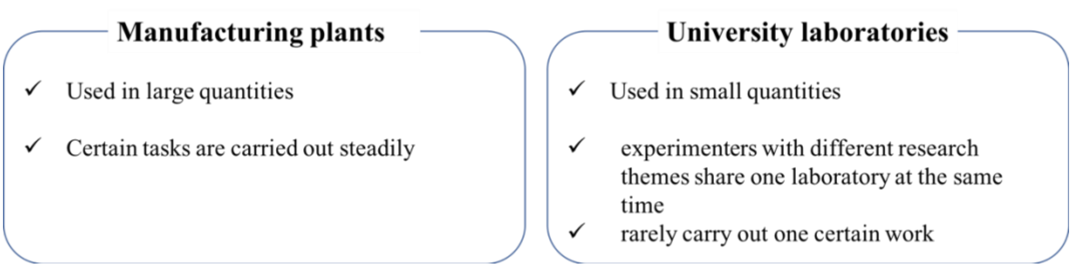


Fig. 1- 2 Differences in the use of chemicals between manufacturing plants and university laboratories.

1. 3 Efforts on the Lecture Room Indoor Environment Safety

Students spend a lot of time in the classroom when they taking a class to learn new knowledges. In order to maintain or improve a comfort environment for learning, it's important to keep a suitable room temperature and clean air in the class room[16]. Aside that, under the condition that COVID-19 pandemic could last a long period, how students can take their class face to face with professor while the infection risk is controlled becomes an urgent task to universities. Anyway, universities have the duty for ensuring students taking class in a health environment.

1. 3. 1 Standard of School Environmental Hygiene

Regarding school environmental hygiene activities, the "School Sanitation Law" promulgated in 1958 stipulates: "In schools, efforts must be made to maintain school daily environmental sanitation, such as proper ventilation, sunlight, lighting and heat retention, and maintaining cleanliness."[17][18], after that, in 2009, the legal status of "Standard of School Environmental Hygiene" has been clarified. As one part of the "school" defined by School Education Law, universities shall also comply with this standard.

This standard was comprehensively revised in 2004, because the items on student health in it, such as air, drinking water sanitation, drainage, swimming pools, pests, etc., have received various criticisms. In the revised item, the air environment of the classroom has received urgent and specific attention, there are also problems of poor air quality and insufficient ventilation that need to be solved urgently in school classrooms[19].

Unlike primary and middle (high) schools, which stipulate how many students there are in each class, in universities, it may have a huge difference in the number of users in each class in one same classroom. If it is a popular professor's class, the number of students in the class could exceed the number that the classroom can normally accommodate. Moreover, in the lecture hall, when hundreds of students gather in one space at the same time, the air quality of the lecture hall needs more attentions.

Standard of School Environmental Hygiene stipulated that the environment of classroom involves the environment of ventilation, sunlight, lighting and heat retention, etc., here is the ventilation part in the standard.

		Items	Standard
Ventilation and Heat Retention	(1)	Ventilation	1500 ppm <
	(2)	Temperature	> 17℃, 28℃ <, is desirable
	(3)	Relative humidity	> 30%, 80% <, is desirable
	(4)	Floating dust	< 0.10 mg/m^3
	(5)	Air flow	< 0.5 m/s, is desirable
	(6)	Carbon monoxide	< 10 ppm
	(7)	Nitrogen dioxide	< 0.06 ppm, is desirable
	(8)	Volatile organic compounds	
		Formaldehyde	< 100μg/m^3
		Toluene	< 260μg/m^3
		Xylene	< 870μg/m^3
		Paradichlorobenzene	< 240μg/m^3
		Ethylbenzene	< 3800μg/m^3
		Styrene	< 220μg/m^3
	(9)	Tick or mite allergen	100 animals / m^2 or less or equivalent amount of allergen.

Table 1- 1 Ventilation and heat retention standard in the Standard of School Environmental Hygiene[17].

1. 3. 2 Standard of Building Environmental Hygiene Management

Article 4 of the Standard of Building Environmental Hygiene Management[20] stipulates that the owners, occupants and other persons who have the right to maintain a specific building should maintain the specific building in accordance with the Standard of Building Environmental Hygiene Management. Meanwhile, if the total area of building is more than 8000 m^2, the building should be classified as specific building[17]. According to this condition, most of universities should be called a specific building.

The following standard were made for the air environment according to Standard of Building Environmental Hygiene Management.

		Items	Standard
Air Environment	(1)	Floating dust	< 0.15 mg/m^3
	(2)	Carbon monoxide	< 10 ppm
	(3)	Carbon dioxide	< 1000 ppm
	(4)	Temperature	① > 17 ℃ , 28℃ ② The temperature difference between indoor and outdoor remains insignificant
	(5)	Relative humidity	> 40%, 70% <
	(6)	Air flow	< 0.5 m/s
	(7)	Formaldehyde	< 0.1mg/m^3 (0.08ppm)

Table 1- 2 Air environment standard refer to the Standard of Building Environmental Hygiene Management[21].

For universities in Japan, not only they should comply with the Standard of School Environmental Hygiene, but also should they comply with the Standard of Building Environmental Hygiene Management even though there are different standards for one item, for example the standard of carbon dioxide.

From the perspective of improving air environment quality, for university classrooms with a large number of students and strong mobility, it is bound to be beneficial to the health of students to reduce the substances that affect the air environment quality as much as possible. However, on the one hand, from the perspective of energy conservation and environmental protection, improving the air environment quality in university classrooms will inevitably use various mechanical ventilations (air conditioners, total heat exchangers, etc.). The increase in electricity usage is contrary to the university's mission of reduction of carbon emissions. Therefore, how to balance the improvement of classroom air quality and the reduction of university carbon emissions is also an important issue.

1. 4 Impact of Airflow on Universities' Indoor Air Environment Under COVID-19 Pandemic

A novel coronavirus pneumonia, first identified in Wuhan City and referred to as COVID-19 by the World Health Organization, has been quickly spreading to other cities and countries[22]. As of the end of June 2021 when this thesis being written, the newest updated coronavirus data refer to **Worldometer**[23] that there have been 180,751,311 coronavirus cases, 3,915,560 deaths, and 165,404,058 recovered patients. This global outbreak has severely threatened global public health[24], and had a huge damage to global economy. On the other hand, under the rapid expansion of the COVID-19 pandemic in 2020-2021, the coronavirus classification and evolution through its multiple mutations that have increased its transmissibility rate up to 70%. Globally, threatening to undermine the promise of a number of emerging vaccines that primarily focus on the immune detection of the Spike trimer. Besides that, what frustrated is COVID-19 mutations do not degrade the virus, they even empower and facilitate its disguise to evade detection. To date the infectiousness of the COVID-19 pandemic is exponentially increasing, denoting the possibility of an even more dangerously elusive, inconspicuous, and sophisticated version of the disease[25].

In the severe period of COVID-19, at universities, to prevent the spread of pandemic coronavirus, whether want or not, the educators must change their way of teaching. Face to face in the class must be avoided[26]. Many issues remain due to the unfamiliarity of online class between students and teachers, both students and teacher complained the online class in many aspects [27]. Some university education activities can only be completed offline. Under the condition that the pandemic could last long-term, in order to fully fulfill one of the basic missions of the university, education and research functions, it is necessary for us to think about how to balance the risk of infection while maintaining research activities, rather than simply waiting for the pandemic to converge[28].

1. 4. 1 Three Transmission Routes of COVID-19

The US Centers for Disease Control and Prevention (US CDC) summarized that infectious exposures to respiratory fluids carrying SARS-CoV-2 occur in three principal ways (not mutually exclusive):

1. **Inhalation** of air carrying very small fine droplets and aerosol particles that contain infectious virus. Risk of transmission is greatest within three to six feet of an infectious source where the concentration of these very fine droplets and particles is greatest.

2. **Deposition** of virus carried in exhaled droplets and particles onto exposed mucous membranes (i.e., "splashes and sprays", such as being coughed on). Risk of transmission is likewise greatest close to an infectious source where the concentration of these exhaled droplets and particles is greatest.

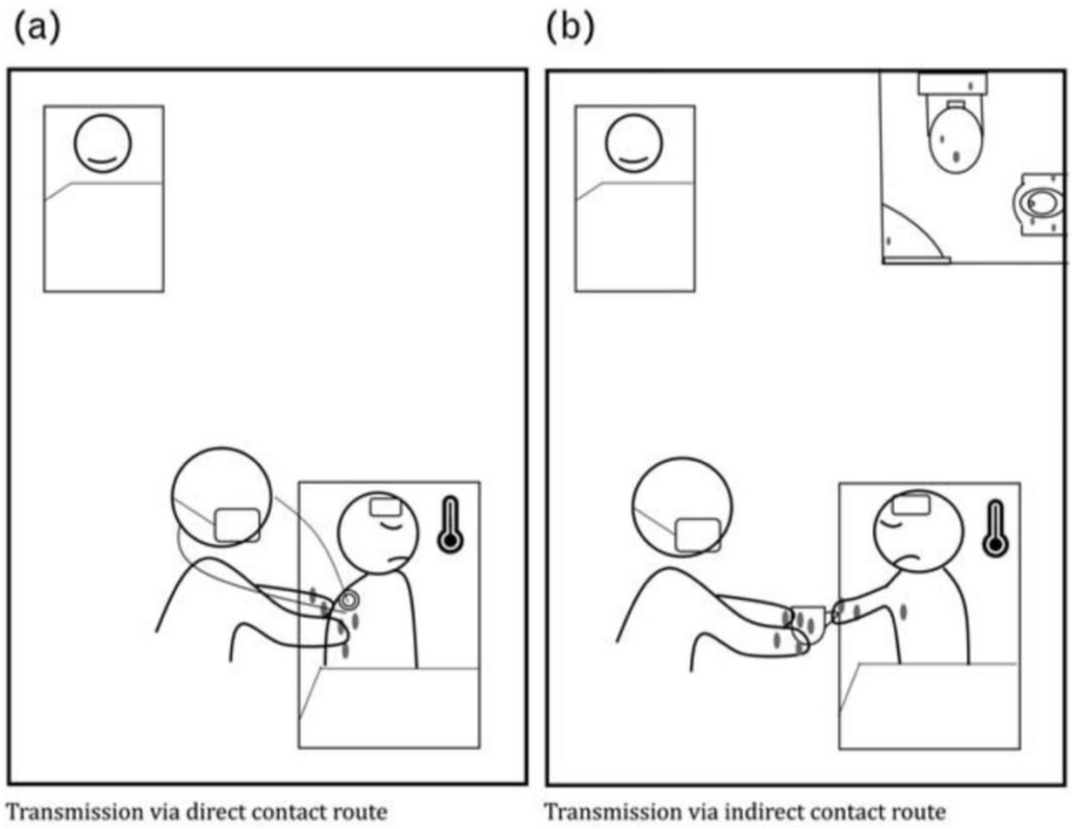
3. **Touching** mucous membranes with hands soiled by exhaled respiratory fluids containing virus or from touching inanimate surfaces contaminated with virus[29].

There are various definitions for the different routes of transmission of respiratory pathogens (typically viruses), and at least three routes are currently thought to play a role[30]:

1. **Contact transmission** involves the transfer of virus-laden respiratory secretions from an infected person to a susceptible person, either directly (via physical contact) or indirectly (via surfaces or objects).

2. **Large-droplet or droplet transmission** involves the expulsion of virus-laden respiratory droplets from an infected person and the subsequent deposition of these droplets on the mucosal surfaces (eg, eyes, nose, and mouth) of a susceptible person.

3. **Airborne or aerosol transmission** involves virus-laden fine, airborne respiratory droplets being generated by the exhalation of an infected person, or by a medical aerosol-generating procedure being performed on an infected person, and these droplets subsequently being inhaled by a susceptible person.



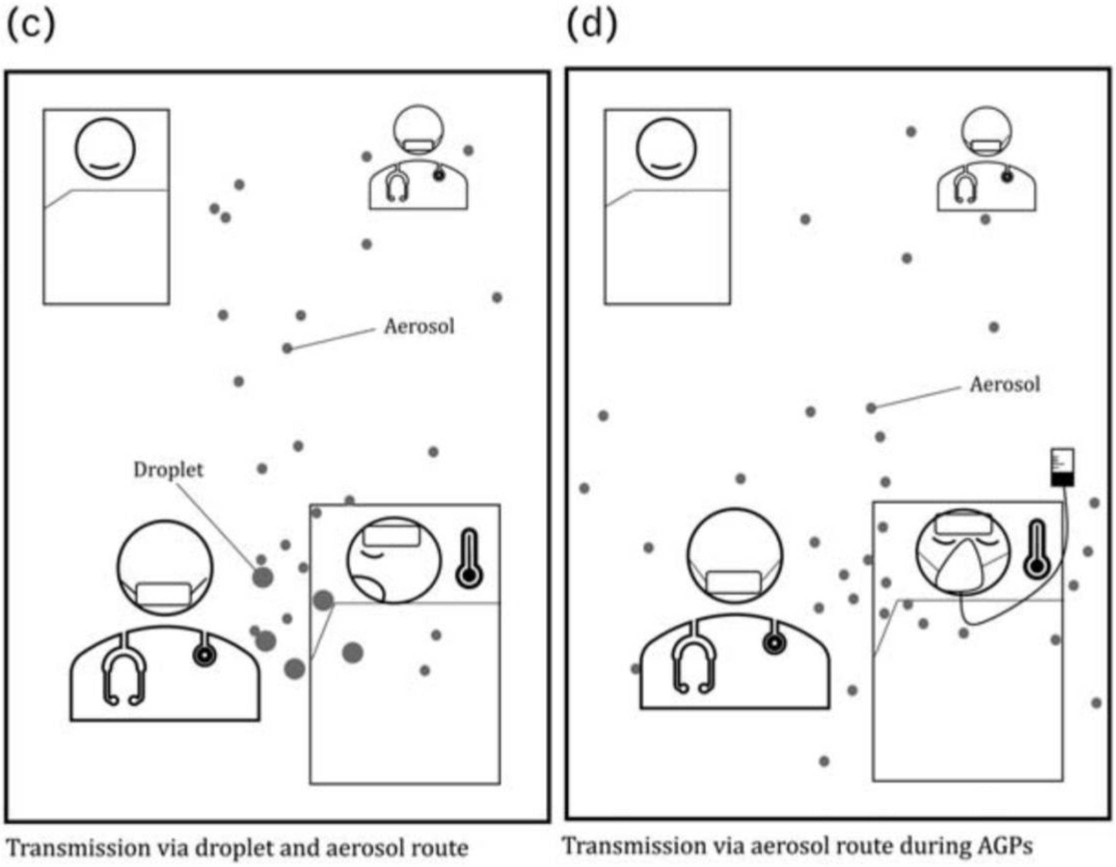


Fig. 1- 3 Different transmission routes of respiratory viruses in a healthcare setting. (a) Direct contact transmission: The healthcare personnel (HCP) is exposed to infectious viruses by direct physical contact with the infected patient. (b) Indirect contact transmission: The HCP is exposed to infectious viruses by physical contact with objects contaminated with infectious viruses (fomites) released from the infected patients. (c) Droplet and aerosol transmission: The infected patient is releasing infectious agents via droplets and aerosols to the HCP in proximity, and via aerosols to other patients and HCP in further distances. (d) Aerosol transmission during aerosol-generating procedures (AGPs): During AGPs, increased amount of infectious virus-laden aerosols is released to the nearby HCP and other patients and HCPs[31].

About the definition large droplet, droplet, and aerosol, there has been great ambiguity in the definitions of the most essential concepts related to potential disease transmission routes, starting from the concepts of “airborne transmission” and “droplet transmission”, along with a dispute of what is considered as an “aerosol”, “small droplet”, or “large droplet”. Throughout this thesis, the following definition will be used[32]:

Droplet size: A highly dynamic quantity which typically reduces very rapidly when a liquid droplet is exhaled. Since the sedimentation time of the respective solid particles (assuming 1.6 m initial height and still air) would be about 30 s, the respective water droplets would evaporate completely before reaching the ground. For mucus, such a drying process would yield left-over droplet nuclei which could potentially carry viruses. Hence, there is no fixed droplet size. Larger droplets than typically thought, e.g. O (100μm) in initial size, may become aerosol particles because of rapid drying.

Aerosol: Aerosol particles in the present context may contain infectious pathogens, epithelial and other cells or remains of those, natural electrolytes and other substances from mucus and saliva, and water typically evaporating rapidly depending on the relative humidity of the surrounding air. Aerosol particles remain in the air for long enough for them to be inhaled and they can be transferred over long distances by indoor air flow.

Droplet nuclei: Residuals of droplets after drying to moisture in equilibrium with ambient air. In addition to equilibrium moisture, droplet nuclei contain non-volatile substances from the original wet droplet. Dynamical transport of droplet nuclei is dictated mainly by external air flow unless the released wet droplets were large enough to sediment before drying, i.e. droplet nuclei are aerosols. If droplets sediment before drying, dried-out residuals on surfaces are not considered droplet nuclei.

Small droplet: Droplets which stay airborne for significant enough times (e.g. tens of seconds, minutes) to be inhaled. These droplets dry into droplet nuclei very rapidly. Precise size cutoff is affected by the ambient conditions, in particular ambient ventilation and air flow patterns. For example, under still ambient conditions $d \leq$ 100μm droplets could be considered to be small.

Large droplet: Droplets which stay airborne only for short times (e.g. seconds). These droplets could be e.g. larger than 200μm. Movement of large droplets is mainly determined by gravitational settling and to less extent by the ambient air flow. Drying rate is typically slow enough for the large droplets to settle to the ground or other surrounding surfaces before becoming an aerosol.

1. 4. 2 The Importance of Airflow on Prevention of COVID-19 Transmission

The current guidance from numerous international and national bodies focuses on hand washing, maintaining social distancing, and droplets precautions. Hand washing and social distancing are appropriate but, many researches have indicated that insufficient to provide protection from virus-carrying respiratory microdroplets released into the air by infected people, it's time to address airborne transmission of coronavirus disease 2019[33]. In particular, a study of video records from a Chinese restaurant observed no close contact or fomite contact, aside from back-to-back sitting between the first symptom onset patron and other parties at three tables where patrons became infected[24]. This study supported the probability of an extended short-range aerosol spread of the SARS-CoV-2 having occurred in the poorly ventilation and crowded indoor environment. And there are also other studies show that better ventilation of spaces substantially reduces the airborne time of respiratory droplets[34][35]. The airborne transmission not only happened on SARS-CoV-2, but also on other viruses, including respiratory syncytial virus (RSV), Middle East Respiratory Syndrome Coronavirus (MERS-CoV), and other influenza. As showed in figure 4, the airborne transmission could drastically increase the infection risk that people sharing same crowded indoor space which has inadequate ventilation[33].

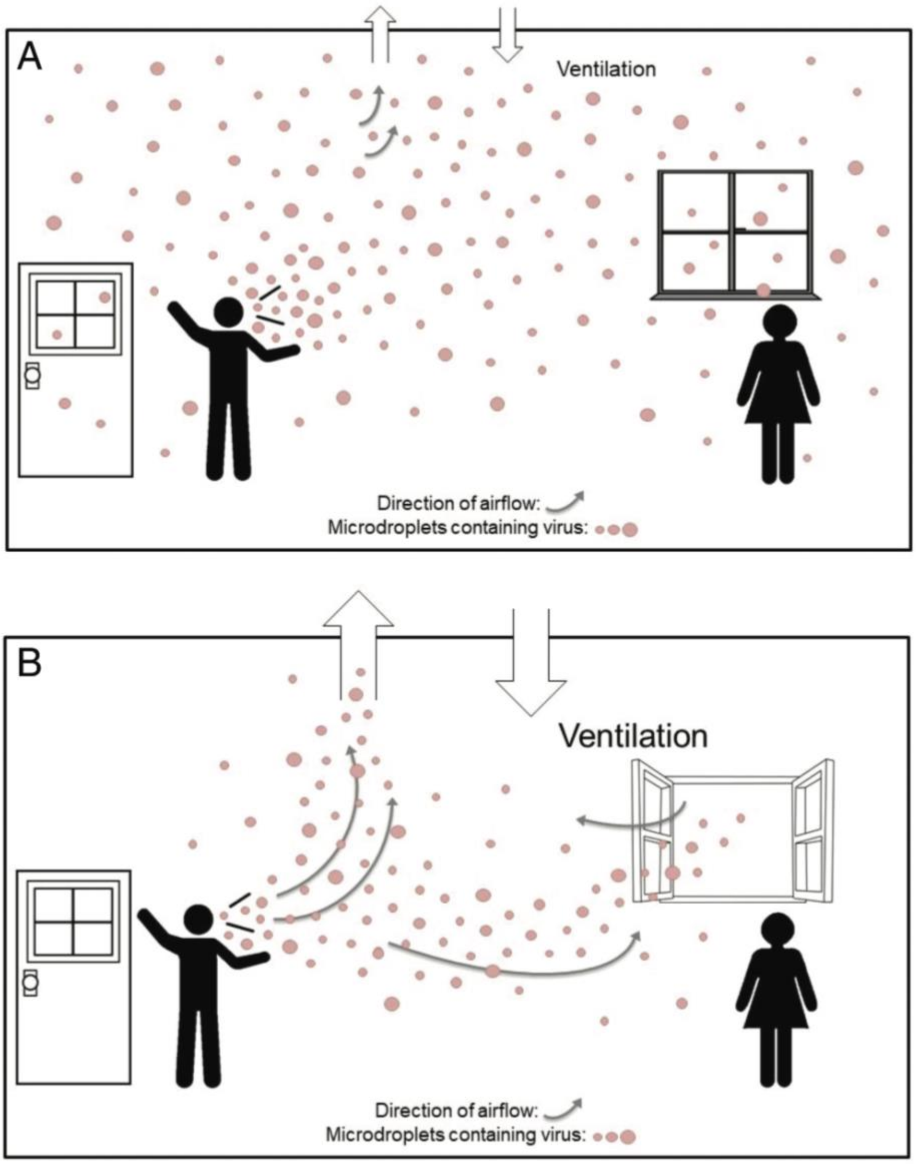


Fig. 1- 4 Distribution of respiratory microdroplets in an indoor environment with (A) inadequate ventilation and (B) adequate ventilation[33].

Aside from the investigations of the integral ventilation condition in an indoor space, the researches about the transmission pathways of coronavirus via air pathway indicate that the difference of mitigation measures for the different transmission routes[36][37]. For example, aerosols can be transmitted over short and long distances. Short-range transmission occurs across the short distance (less than 1 m) from person to person and can be moderated by using of personal protective equipment such as gloves and facemasks with precautions to avoid the usual contact transmission from touching of the eyes, nose and mouth. Long range transmission occurs between distant locations and is primarily governed by air flows generated from ventilation systems or movement of people[38][39].

1. 4. 3 Efforts on Preventing the Spread of Pandemic Coronavirus in Universities

Overseas universities: at the beginning of the outbreak of the Corona virus and spreading to affect most of the world (2020), due to the inability to control the virus, the lack of vaccine and appropriate treatment for it was limited to some drugs to mitigate the effects of infection with the virus, for the sake of preventing its swift spread, countries have followed several prompt health measures, represented in the general and partial closure of some activities and sectors while imposing a quarantine on citizens[40]. As a result, at the beginning of pandemic, in light of the rising concerns about the spread of COVID-19 and calls to contain the Corona virus, a growing number of tertiary institutions also have shut down in regards to face-to-face classes globally[41].

In fact, through a series of epidemic prevention measures such as vaccination, lockdown, and quarantine, the epidemic situation in some countries has indeed improved within a period of time. In that period, students were allowed to back to universities or other schools under some guidelines for reopening schools. For example, Taiwan established general guidelines for college campuses. The guidelines delineated a very detailed vaccination regulations, it includes creation of a task force at each university; school-based risk screening based on travel history, occupation, contacts, and clusters; measures on self-management of health and quarantine, etc. In this general guideline, it also announced that a class should be suspended if 1 student or staff member in it tested positive and that a school should be closed for 14 days if it had 2 or more confirmed cases[42]. Other researches also provided principles to guide how as well as when to reopen schools[43].

1. Reopen schools in a staged fashion.	
	A number of countries have reopened kindergartens and primary schools first (Denmark and Norway).
2. Incorporate social distancing.	
Across the school	▶ Close playgrounds or social distance within playgrounds, for example, single-class groups in playground at a time, implementing social distancing during play. ▶ Stagger school start times and period changes for year, to avoid years mixing and to reduce social contacts in corridors. ▶ Stop all communal activities, for example, dining, assemblies and sports. ▶ Ensure social distancing on school buses and other transports. ▶ Split school into halves so that only half the years attend at one time. This could be half-days (some years in the morning, some in the afternoon, with no mixing), alternating full days or alternating weeks (half the students attend every second week). ▶ Keep children in constant class groups to reduce range of contacts. ▶ Keep all books or equipment at school to reduce potential for transmission through surfaces. Avoid sharing of equipment between children.
Within-year groups	Split each year so that half the classes in a year attend at a time. Again this could be half-days, alternating full days or alternating weeks or fortnights. Fortnights may be epidemiologically more effective at disrupting transmission.
Within classes	▶ Split classes so that only half of each class (or a maximum of 15–20 students) attend at any one time. Splits could be half-days, full days or weekly. ▶ Physical social distancing within classes, separation of desks by 1–2 m; physical barriers between desks have been implemented in some countries.
3. Infection control, testing and tracing.	
	▶ Institute hygiene practices, both personal (handwashing) and institutional (regular cleaning of surfaces) and education of students in hygiene and infection control. ▶ Testing and tracing of contacts of positive cases. ▶ Isolation of suspected cases in students and staff. ▶ National and regional class and school closure policies, depending on infection burden in students.
4. Protect teachers and vulnerable students.	
	▶ (Re)Institute programmes to support vulnerable children before schools reopen and continue them during reopening. ▶ Encourage older or medically vulnerable teachers to provide administrative support or virtual teaching. ▶ Social distancing for teachers within classrooms. ▶ Basic protective equipment for teachers. ▶ Wearing of face masks: the WHO currently does not recommend wearing of face masks in community settings but recognises current uncertainty and that some countries recommend them.
5. Research and evaluate.	

Fig. 1- 5 Strategies for reopening schools[43].

In Japan: for mitigating the risk of Corona virus infection, Japan called on all elementary, junior high, and high schools nationwide to closed beginning March 1, 2020[44]. In light of the pandemic, universities in Japan were also closed during the state of emergency. In Japan, more than 85 universities that disclose information, categorized their activities in order to indicate their action guidelines, and it was found that they are making efforts to visualize the strengthening or easing of vigilance and future prospects. Guidelines for research activities, lectures, and extracurricular activities were listed as items by all universities, and meetings and administrative systems were also listed as items by most of the universities. Many universities listed items related to the closing of school gates, restrictions on the entry of non-university visitors, business trips, and overseas travel[28].

Same as overseas universities, based on the epidemic condition, the education activities in Japanese universities also were obligated to return to normalcy, even if gradually[40]. However, since there were "cluster" occurred in universities, universities were expected to set up strict preventive measures before opening up campuses, where the mobility of thousands students could become a severe issue[45]. In order to maintain the university education activities while minimizing the risk of infection, The Ministry of Education, Culture, Sports, Science and Technology promulgated guidelines for dealing with novel coronavirus infections at universities and other institutions. The most basic guideline is that thoroughly implement countermeasures against infectious diseases, such as avoiding the "three densities"[46].

1. 5 The Comparation of Chemical Substance Distribution and Airborne Transmission

As mentioned earlier, there are experimental accidents reported that students didn't use chemical substances but were exposed just because shared a same experiment room with other students who were using chemical substances[5]. Even though they are totally different substances between chemical substances and SARS-CoV-2, apparently, the indoor airflow plays an extremely important role in their transmission pathway in the indoor environment.

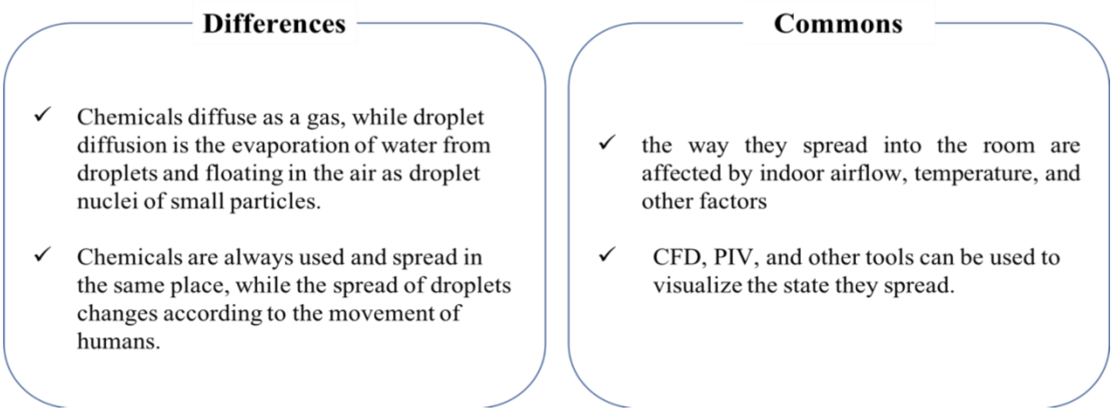


Fig. 1- 6 The differences and commons between chemicals and droplets.

According to "Industrial Safety and Health Act", "Standard of School Environmental Hygiene", and "Standard of Building Environmental Hygiene Management", many regulations have been made on the indoor environment safety in university classrooms.

For university laboratories and lecture rooms, the indoor environment where always many people sharing, if a study could analyze the movement of indoor airflow and control it to meet the demand of indoor environment safety, the result not only can apply to reduce the infection risk in this pandemic period, but also can still play an important role in indoor environment safety management even after the pandemic is over in the future.

1. 6 Research Objectives

Therefore, this study takes the importance of ventilation in university research and education activities as the theme, expecting to understand the ventilation performance in situations where ventilation has special significance and propose corresponding improvement measures. The specific objectives are:

(a) To understand the relationship between chemical substance concentration distribution and airflow in the university laboratory;

(b) To develop a local ventilation device for preventing virus spread in the lecture room.

Chapter 2 Methodology

2. 1 Computational Fluid Dynamics (CFD)

Computational fluid dynamics[47] is the analysis of systems involving fluid flow, heat transfer and associated phenomena such as chemical reactions by means of computer-based simulation[48]. The technique enables a computational model of a physical system to be studied under many different design constraints. If used correctly CFD can provide an understanding of the physics of a flow system in detail, and does so through non-intrusive flow, thermal and concentration field predictions [49]. The following discusses the general methodology and procedure for conducting CFD analysis[49].

2. 1. 1 Governing equations

Continuity equation: the mass flows entering a fluid element must balance exactly with those leaving.

$$\frac{\partial \rho}{\partial \tau} + \frac{\partial}{\partial_{x_i}}\left(\rho u_j\right) = 0 \qquad (2-1)$$

Conservation of momentum (Newtons second law): the sum of the external forces acting on the fluid particles is equal to its rate of change of linear momentum.

$$\frac{\partial \rho}{\partial \tau}(\rho u_i) + \frac{\partial}{\partial_{x_j}}\left(\rho u_i u_j\right) = \frac{\partial}{\partial_{x_j}}\left[-\rho \delta_{ij} + \mu\left(\frac{\partial_{u_i}}{\partial_{x_j}} + \frac{\partial_{u_j}}{\partial_{x_i}}\right)\right] + \rho g_i \qquad (2-2)$$

Conservation of energy (the first law of thermodynamics): the rate of change of energy of a fluid particle is equal to the heat addition and the work done on the particle.

$$\frac{\partial}{\partial \tau}(\rho C_a T) + \frac{\partial}{\partial_{x_j}}(\rho u_j C_a T) - \frac{\partial}{\partial_{x_j}}\left(\lambda \frac{\partial T}{\partial_{x_j}}\right) = S_T \qquad (2-3)$$

CFD is supposed to enforce these conservation law when it conduct numerical computation[48].

Nomenclature	
C	water concentration (kg kg^{-1})
Ca	specific heat capacity (W kg^{-1} K^{-1})
g	acceleration due to gravity (m s^{-2})
T	temperature (K)
t	time (s)
u	velocity component (m s^{-1})
x	Cartesian coordinates (m)
S_T	thermal sink or source (W m^{-3})
λ	thermal conductivity (W m^{-1} K^{-1})
i, j, k	Cartesian coordinate index
c	water concentration
ρ	density (kg m^{-3})
μ	dynamic viscosity (kg $^{-1}$ s^{-1})
δ	Kroneckor delta

2. 1. 2 Numerical analysis and commercial CFD codes

In CFD numerical analysis, there are many different numerical techniques to discretize the modelled fluid continuum. At least three techniques are currently thought to play a role: finite different method (FDM), finite volume method (FVM), and finite element method (FEM)[50][51].

Currently, there are several routinely commercial codes are applied to a wide range of areas: ANSYS CFX, ANSYS FLUENT, FlowDesigner, PHOENICS AND CFD 2000[52][53].

2. 1. 3 The procedures of performing a CFD analysis with a commercial software

To undertake a research by using CFD, it demands to use three predefined environments within the software: the pre-processing environment, the solver environment, and the post-processing environment. These three parts constitute an important operating environment for CFD.

Pre-processing: performing a CFD analysis with a commercial software, all exercises should be defined within pre-processing environment before the simulation going ahead to solving environment. basically, the exercises within pre-processing include problem consideration, geometry creation or import, mesh development, physical property set-up, and the implementation of solving techniques and parameters[49].

Solving: in solver environment, CFD software packages will solve all the mathematical input which were input from pre-processing[54].

Post-processing: after a correct solving, the post-processing is supposed to allow the user to visualize and scrutinize the result. The users are allowed to adjust the contour, vector and line plots to enhance interpretation of results, and output the results for research.

2. 1. 4 CFD in this thesis

FlowDesigner2021 was used in this thesis.

Software	FlowDesigner2021 (Advanced Knowledge Laboratory, Inc.)[55]
Turbulence model	High Reynolds k-ε mode
Number of mesh	1000000

Table 2- 1 The analysis overview with FlowDesigner2021.

Meanwhile, there are several index that commonly used to evaluate the ventilation performance within indoor air environment, the following clarified the definition of indices which will be frequently used in this thesis[56][57].

SVE-1: indoor mean concentration when arbitrary generation sources are assumed.

SVE-2: the radius of the concentration rule region from arbitrary generation sources.

SVE-3: air age, the time it takes for air coming into a room through an opening such as a window or air supply to reach a certain place in the room. It is used to indicate the status of indoor ventilation, and the shorter the air age, the fresher the air is.[58]

SVE-4: the sphere of influence of each supply.

SVE-5: the sphere of influence of each exhaust.

SVE-6: residual lifetime of air, the time it takes for air from one place in a room to reach an outlet such as an exhaust vent or window. It is used to indicate the status of indoor ventilation, and the shorter residual lifetime of air, the faster the polluted air is discharged[59].

Aside from these evaluating ventilation index, there is another index that commonly used in this thesis, **Air life**[60], air life means the amount of time it takes for air to enter a room through an air supply vent or window, pass through a certain part of the room, and be exhausted through an exhaust vent or the like. The shorter the air life, the shorter the time the air stays in the room. In addition, in updated FlowDesigner2021solving environment, which this thesis been used, the infinite dimension of SVE-3 and SVE-6 can be expressed in time units by calculating the air exchange volume (m^3/h) and indoor volume (m^3), the numerical air life can be expressed by summing up SVE-3 and SVE-6 in post-environment.

2. 2 PIV

PIV (Particle Image Velocimetry), refers to a class of methods that are used in fluid mechanics experiments to determine the instantaneous fields of the vector velocity by measuring the displacements of numerous fine particles that accurately follow the motion of the fluid[61].

For a long time, many researchers have been interested in PIV because it offered a highly promising means of studying the structure of turbulent flow[62]. Also, in recent years, PIV has been widely used in the field of epidemiology, for example, using PIV to estimate the droplets size distributions during coughing and speaking[63][64], measure cough flow velocity profiles, average widths of the cough jet, and the maximum cough velocity[65].

In this study, the blocking effect of infection prevention measures on virus-containing droplets transmission will also be visualized by means of PIV.

2. 2. 1 The principle of PIV

PIV is a general term for a method in which fine tracer particles that are mixed in a fluid as markers, the movement of the tracer particles is photographed in chronological order, and the obtained image is digitally processed to obtain a velocity.

The principle of PIV will be illustrated by Fig. 2- 1: fine tracer particles are added to the flow at a location where the flow of interest will not be distributed. The plane of interest within the flow will be illuminated twice by using a laser light sheet. The time delay between pulses must be selected according to the flow rate and the magnification during imaging. For simplicity, it is assumed that the tracer particles move at a local flow rate between the two illuminations. The light scattered by the tracer particles is recorded by the lens of a high-speed camera of a dedicated cross-correlation digital camera. At the end, the output of the digital sensor is transferred to the memory of a computer.

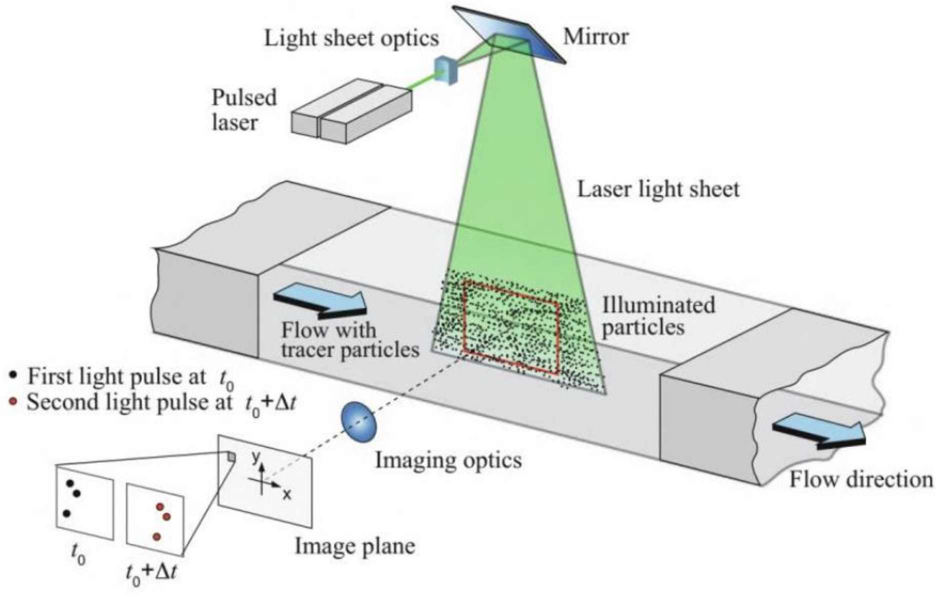


Fig. 2- 1 A brief sketch of a typical set-up for PIV recording of two velocity components within the flow field in a plane in a wind tunnel (2C-2D PIV).

In the following, the basic steps of PIV will be described briefly:

1) Seeding: add the tracer particles to the flow.

2) Illumination: these tracer particles have to be illuminated in a plane or volume of the flow at least twice within a short and known time interval.

3) Recording: the light scattered by the tracer particles must be recorded on two separate frames or on a series of frames of a camera.

4) Calibration: in order to determine the relationship between the displacement of the particle image on the image plane and the displacement of the tracer particles in the flow, a calibration is required.

5) Evaluation: the displacement of the particle images between the light pulses has to be determined through evaluation of the PIV recordings.

6) Post-Processing: in order to detect and remove invalid measurements and to extract complex flow quantities of interest, sophisticated post-processing is required[66].

2. 2. 2 PIV in this thesis

The following shows the PIV experiment schematic of this study.

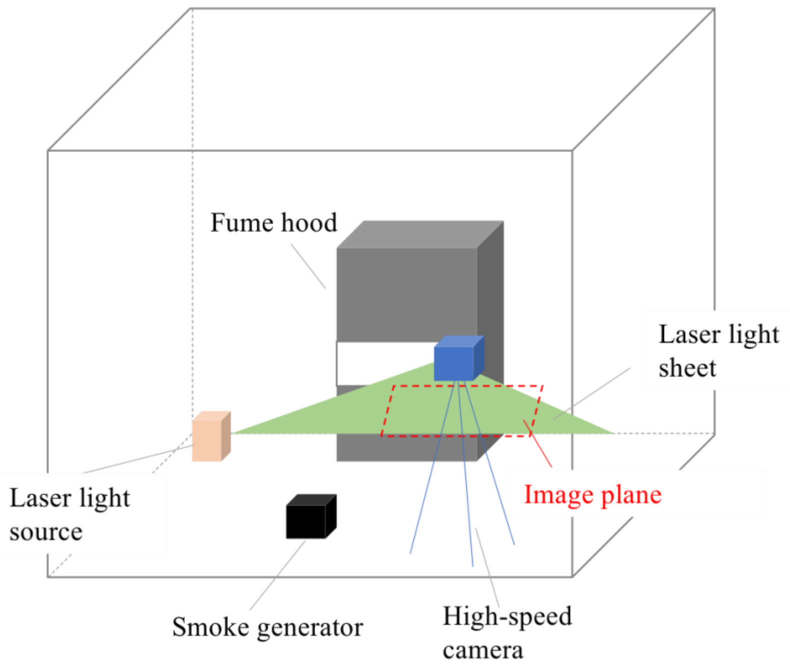


Fig. 2- 2 Schematic diagram of PIV experiment in this study.

Camera	USB high-speed camera K4 (KATO KOKEN)
Laser	High brightness green-line light source LCC SSL-532-3000-10TM-90L 3010801-3W
Software	High-speed camera: k-2Ex/k4 Software for CL-USB3 ver 1.27 PIV analysis: Flow-Expert64 ver 1.2,17
Tracer particle	Smoke generator PS-2006 (KATO KOKEN) Average droplet size: 10 μm

Table 2- 2 Overview of PIV experiment devices.

Image correlation method	Direct cross-correlation method
Image size	1024 × 1024 pixel
Flame rate	150 fps
Interrogation region	32 pixel × 32 pixel
Search region	±52pixel × ±52 pixel

Table 2- 3 The parameters of PIV analysis in this study.

2. 3 Laboratory in 1/9 scale model

To study how airflow affects the distribution of chemicals, this research conducted a chemical distribution experiment in a model laboratory which is only $1/9^{th}$ of a normal experiment.

2. 3. 1 The characteristics of laboratory in 1/9 scale

There's no doubt that the optimistic way to undertake this chemical distribution experiment in a full-scale, actually been used laboratory, however, in sight of the inconvenience of an actual laboratory and the current technical equipment, undertaking this experiment in 1/9 scale laboratory seems to be an optimal solution.

The following shows the advantages of 1/9 scale laboratory:

- Enables monitoring of chemical concentration in the entire room;
- Easy to change the layout of the room;
- Enables to be used as a visualization tool;
- Enables to study the laboratory-specific elements.

2. 3. 2 Model laboratory

As mentioned earlier (Fig. 1), the air environment of the laboratory can be considered that is affected by the ventilation devices, the operation of FH (Fume Hood), the experimental device that generates heat, the amount, time, and location of volatile chemical substances, and the movement of the experimenter, which caused the laboratory has it's unique and complicated air environment influencing factors[6]. In order to reduce the influence of factors other than indoor airflow, it's considered that experiments should be conducted in an empty environment with no extra people, drugs, lab tables, and other items, etc.

The width of a laboratory should be between 6000 ~ 6400 mm, and the depth of the laboratory should be between 7000 ~ 8000 mm[67]. In a result, a geometric of 6 x 7 x 3 m model laboratory was designed, accordingly, there's a 0.67 x 0.78 x 0.33 m 1/9 scale laboratory. Only a Fume Hood (FH) (1200 x 850 x 2250 mm, DFB10-AA15-AA, Dalton Corporation[68]) and an experiment table (1500 x 900 x 800 mm) were thought to be placed in the model laboratory. Similarly, after shrinking 9 times they were printed out by a 3d printer (Value 3D MagiX MF-1100, MUTOH[69]) and then put into the 1/9 scale model laboratory.

Considered the commonly used chemical substances in the laboratory, in order to reduce the resistances of the chemical substances and the material of the 1/9 scale model laboratory, the 1/9 scale model laboratory was made of PVC board (hard type).

In addition, in order to imitate the air exchange environment in a real laboratory, the inlet and outlet of FH is connected by 2 pipes to the ventilation fan motors (MDS420-24, Oriental motor[70]) outside the 1/9 scale model laboratory.

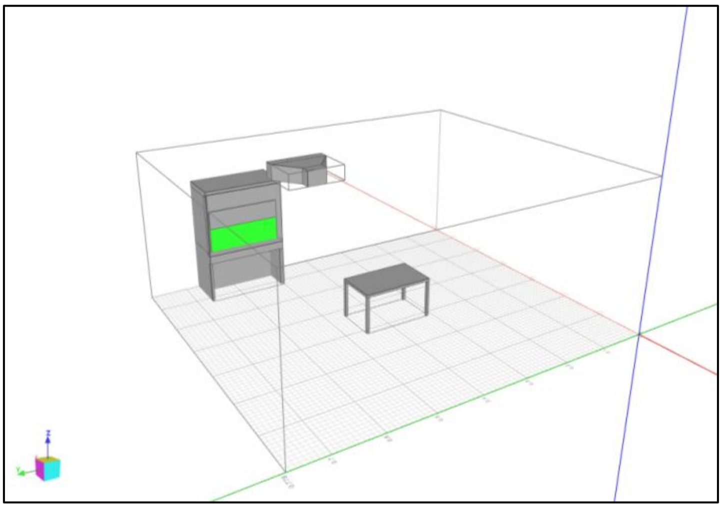


Fig. 2- 3 The geometric creation of full-scale model laboratory in CFD pre-processing environment.

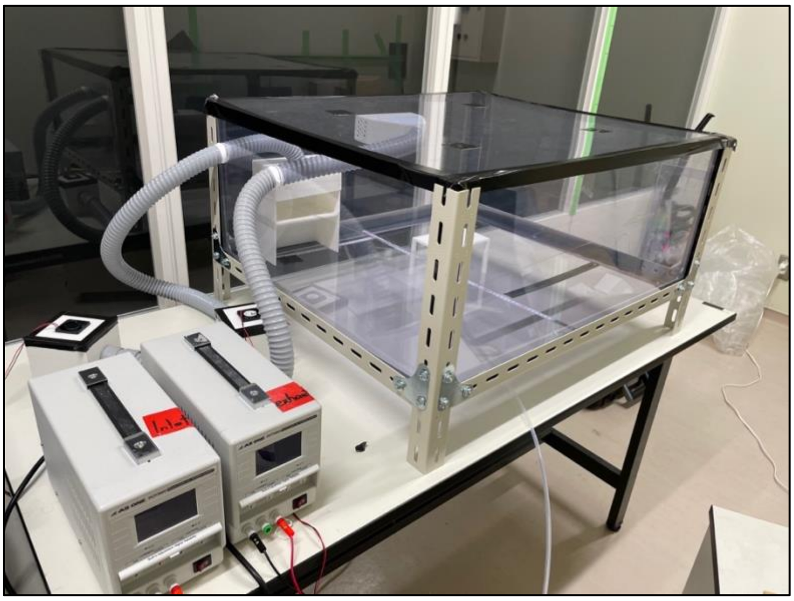


Fig. 2- 4 The 1/9 scale model laboratory made of PVC board.

2. 3. 3 Similarity laws for indoor airflow in shrinkage models

In general, in model experiments, if there's no geometric changes with only the length scale changed, then it's necessary to consider how to comply with the similarity laws between 2 objectives, a dimensionless number should be fit in order to obtain the same airflow characteristics as those of the full-scale model. In the range of indoor airflow, Archimedean number, Reynolds number, Prandtl number, Turbulent Reynolds number, and Turbulent Prandtl number have been routinely discussed[71].

Archimedean number:

$$Ar = \frac{g\beta\Delta T_0 L_0}{{U_0}^2}\left(= \frac{Gr}{Re^2}\right) \qquad (2-4)$$

Reynolds number:

$$Re = \frac{U_0 L_0}{\nu} \qquad (2-5)$$

Prandtl number:

$$Pr = \frac{\nu}{\alpha} \qquad (2-6)$$

Turbulent Reynolds number:

$$Ret = \frac{U_0 L_0}{\nu_t} \qquad (2-7)$$

Turbulent Prandtl number:

$$Prt = \frac{\nu_t}{\alpha_t} \qquad (2-8)$$

In the retrospective studies, a research which using 1/10 scale model to prove the similarity between 1/10 scale model laboratory and full-scale laboratory[3], it used Froude number to determine the wind speed in the shrinkage model by fitting that the Froude numbers of the full-scale laboratory and the 1/10 scale model laboratory. In the thesis, the calculation will be conducted with Froude number as the same.

Froude number:

$$Fn = \frac{U^2}{Lg} \qquad (2-9)$$

The following equation shows the agreement between shrinkage model and full-scale model:

$$\left(\frac{U^2}{Lg}\right)_{model} = \left(\frac{U^2}{Lg}\right)_{prototype} \qquad (2-10)$$

In equation 2-10, *L* represents the height of the room, *U* represents the inlet wind speed, assuming that use n_u、n_l to represent the shrinkage ratio to the real model of *L* and *U*, then following equation can be obtained:

$$\frac{{n_u}^2}{n_l} = 1 \qquad (2-11)$$

In this thesis, a 1/9 scale model was used, so the n_l would be 1/9. Assuming there's no change with g , the following equation can be obtained:

$$n_u = \frac{1}{\sqrt{9}} \qquad (2-12)$$

Besides that, assigning u_1 represents the reference speed of full-scale laboratory, and u_2 represents the reference aped of 1/9 scale model laboratory relatively, the following equation can be obtained based on the similarity laws:

$$u_2 = \frac{u_1}{\sqrt{9}} \qquad (2-13$$

Nomenclature

U_0	Representative wind speed (average wind speed)	m / s
L_0	Representative length	m
ν	Coefficient of molecular kinematic viscosity	m^2/s
ν_t	Coefficient of vortex viscosity	m^2/s
g	Gravitational acceleration	m^2/s
γ	Density (air)	Kg/m^3
u	Fluctuation wind speed	
ΔT_0	Representative temperature difference (Difference between blowout average temperature and room average temperature)	℃
α	Coefficient of Molecular thermal diffusivity	m^2/s
α_t	Coefficient of vortex thermal diffusivity	m^2/s
β	Coefficient of thermal expansion (air)	1/℃

In this study, the wind speed of full-scale laboratory used the actual wind speed of a laboratory in the University of Tokyo (room 425, environmental studies building, GSFS). The wind speed was measured by an anemometer(CLIMOMASTER 6501-00, KANOMAX[72]). Based on the equation 2-13, the wind speed in 1/9 scale model laboratory can be calculated relatively.

		full-scale model laboratory	1/9 scale model laboratory
	the dimensions of model laboratory	6 m x 7 m x 3 m	0.67 m x 0.78 m x 0.33 m
FH	wind speed	1.59 m/s (1.25 m x 0.3 m)	0.53 m/s (0.14 m x 0.03 m)
inlet	quantity of flow	35.7 m^3/min	1.32 x 10^{-1} m^3/min
FH	wind speed	0.5 m/s (1.4 m x 0.85 m)	0.17 m/s (0.16 m x 0.09 m)
outlet	quantity of flow	35.7 m^3/min	1.32 x 10^{-1} m^3/min

Table 2- 4 The calculated wind speed of 2 model laboratories.

Chapter 3 Relationship between chemical substance concentration distribution and airflow in the laboratory

3. 1 Experiment description

This experiment was conducted to study the concentration diffusion and distribution condition of chemical substance in the laboratory through the indoor airflow. In other words, to study the role of indoor airflow played in the chemical distribution. It can be considered that the distribution of chemical substance concentration in the laboratory is different depending on the location and capacity of the ventilation system.

This experiment was conducted in the 1/9 scale model laboratory mentioned in Chapter 2.

Gas sensor: 4 small passive gas sensors(XV-389, COSMOS[73]) were used in the experiment. 2 gas sensors log the measurement value with 15-second average, the other 2 sensors log the measurement value with 1-minute average.

Measurement method: fix 3 gas sensors at each point A to C (Fig. 3- 1), sensor B and sensor C were 1-minute average type, and sensor A was 15-second average type. The other 15-second average sensor was moved to spot 1~5 in turn to measure the chemical concentrations at different place.

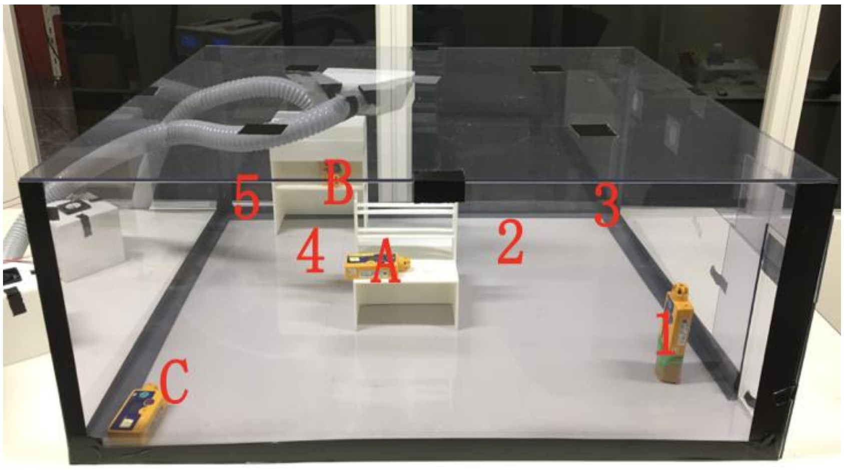


Fig. 3- 1 1/9 scale model laboratory.

Fig. 3- 2 small passive gas sensor.

Chemical substance: Hexane (CAS: 110-54-3, 500 mL, FUJIFILM[74]). During the experiment, hexane was poured into a tiny container with 8 mm x 8 mm x 6 mm size, and this container was placed on the laboratory bench in the center of the 1/9 scale model laboratory, allowing the hexane evaporate into the indoor air. The air conditioner in the laboratory was not turned on, the temperature was the current room temperature.

Time per measurement: the measurement time of each experiment is 25 minutes, and FH, the local ventilation device, was in the open state throughout the 25 minutes. In order to stabilize the airflow in the 1/9 scale model laboratory, hexane cannot be put into the model laboratory for 0-3 minutes. After 3 minutes, the container containing hexane was manually put into the laboratory, and the hexane evaporated to 10 minute, then the container was taken out manually again, leaving the remaining 15 minutes for the FH to discharge the hexane in the model laboratory.

3. 2 Experiment results

The following shows the measurement result of gas sensor A, B, C and another gas sensor in spot 5.

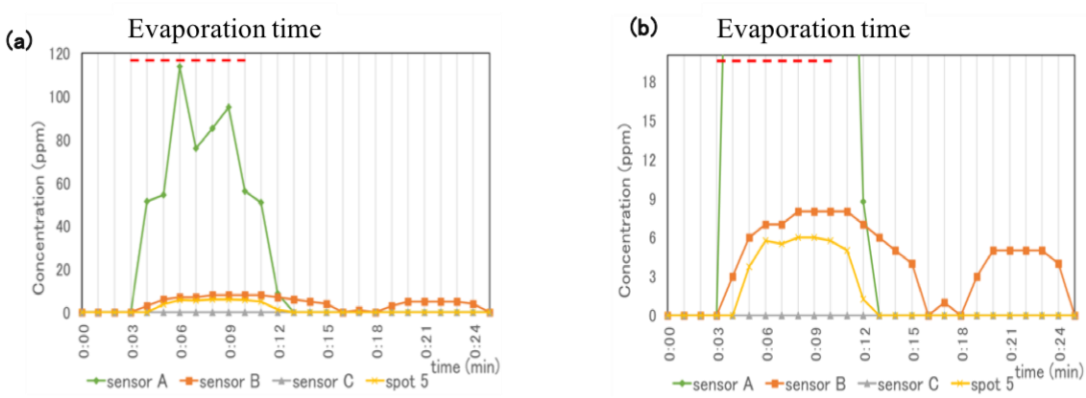


Fig. 3- 3 (a) Temporal variation of concentrations at gas sensor A to C and spot 5; (b) magnified view.

The following results can be obtained from Fig. 3- 3:

- Gas sensors detected different chemical concentration values in different locations, suggesting that there is a large concentration distribution in the 1/9 scale model laboratory;

- There is a great difference in indoor concentration distribution with the changing of time and location;

- The effect of human action on the airflow when manually putting in and taking out the container, as well as the size of the gas sensor itself, which is too large within the 1/9 scale model laboratory and may become an obstacle to the diffusion of chemicals, were found to be factors that may affect the results, making it necessary to improve the experimental methods and conditions in the future.

3. 3 Summary about chemical concentration measurement

In the experiments for measuring the concentration distribution of chemical substances, it was found in the initial experiments that it was not only impossible to control and grasp the amount of evaporation of chemical substances if the solvents were put directly into the 1/9 scale model laboratory, but also the impact of human action on the airflow could not be ignored because the container was put in and taken out manually.

At a later stage, the amount, temperature and time of chemical flow into the 1/9 scale model laboratory were controlled by using a PERMEATER (パーミエーター, PD-1B, GASTEC[75]) externally, it avoided the effects of manually inserting and removing solvent evaporation container. However, due to the accuracy and sensitivity of the gas sensors, the gas sensors could not detect the concentration of chemical substances flowing through the PERMEATER well, and the concentration values reflected on the gas sensors were far from the concentration value set by the PERMEATER, so the later series of experiments on the factors (ventilation systems, experimental devices, chemical substances, etc.) that affecting the concentration distribution of chemical substances in the laboratory did not go on well.

Given that the accuracy and sensitivity of measuring instruments will become better and better, it can be expected that experiments on the factors influencing the concentration distribution of chemical substances can be continued if suitable gas sensors are used and the experimental method are further improved.

3. 4 Case-study: a COVID-19 "cluster" infection in a university

As mentioned earlier, in general, the air environment of the laboratory can be considered that is affected by the ventilation devices, the operation of FH (Fume Hood), the experimental device that generates heat, the amount, time, and location of volatile chemical substances, and the movement of the experimenter, which caused the laboratory has it's unique and complicated air environment influencing factors, limited by the accuracy and sensitivity of gas sensors, the chemical substance distribution when the place of chemical generated changed did not be discussed, but as discussed in chapter 1.5, the chemicals are always used and spread in a same place. The following discussed droplets transmission condition which the generating place of droplets have not changed, and the indoor air environment affected by the airflow.

Background:

At PHMDC, **cluster** is defined as two or more infection cases associated with the same location, group, or event around the same time[76]. The cluster discussed in this study was occurred among a group of teachers and staff, it happened in 2020.

There were 26 people in the same meeting room, an older person was first to be found infected with the Coronavirus after the meeting, followed by 7 other PCR-positive infections, and the first person to be diagnosed later died.

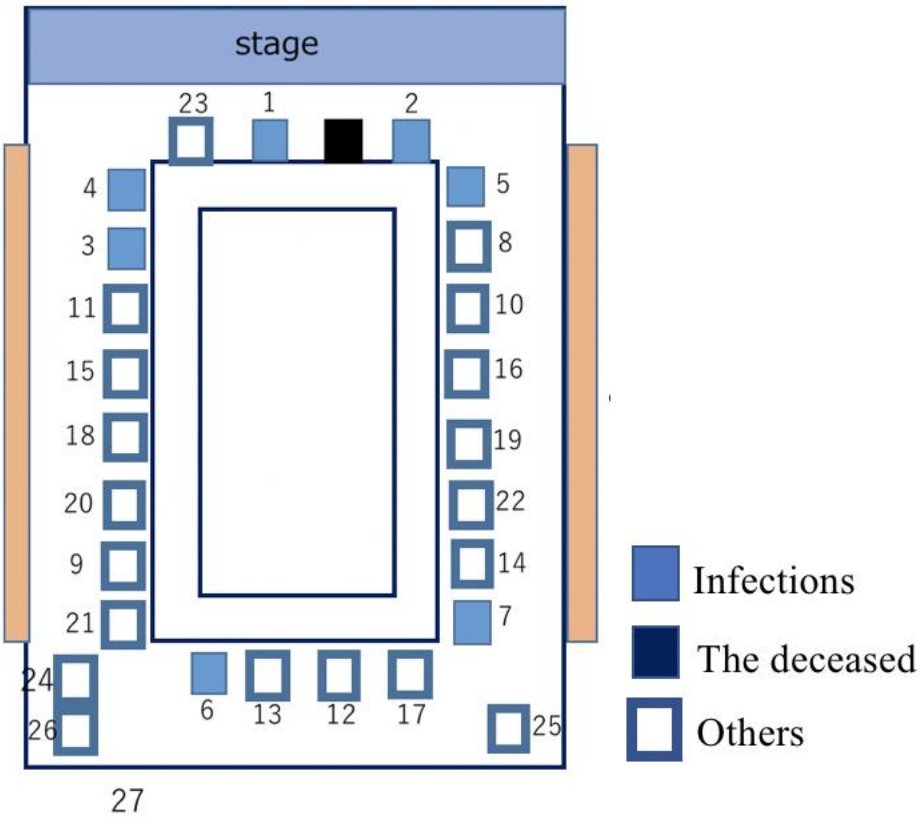


Fig. 3- 4 Schematic diagram of the meeting room and the seating plan of attendees.

Other factors that may affect the probability of infection, such as age, health conditions, etc., are ignored in this study, and only the effect of indoor airflow on the droplet transmission is considered.

Simulation in CFD:

The indoor air environment and the transmission of droplets under the influence of airflow were simulated by CFD.

Through actual measurement and investigation, the geometric dimensions of that meeting room are 13.5 m x 7.1 m x 3.0 m, the air exchange in the meeting room that day was mainly completed by an air conditioner, the actual measurement to the inlet airflow is 2.353 m^3/min, and the outlet airflow is 2.282 m^3/min, since the airflow did not reach the flow balance, the rest flow was considered that outflowed from the small opening on the door. There were 4 inlet ports within the air conditioner, and the actual measured air flow of the 4 inlet ports were 0.612 m^3/min, 0.612 m^3/min, 0.574 m^3/min and 0.555 m^3/min.

The following recorded other boundary conditions in CFD pre-processing environment.

Boundary conditions

room size	13.5×7.1×3.0 m
temperature	26 ℃
relative humidity	60%
turbulence model	k-ε model
fluid type	air
number of mesh	≒ 100000
surface temperature of the human head	36.5 ℃
Height of human mouth	1.2 m

The CFD simulation was conducted by steady state solution and non-steady state solution. The definition of steady state solution is to calculate the change in airflow and temperature in a flow field until it reaches a certain level (balanced state) and does not change any more. The definition of non-steady state solution is to calculate the change over time at each incremental time.

Based on the obtained information, a geometric model was created in CFD pre-processing environment.

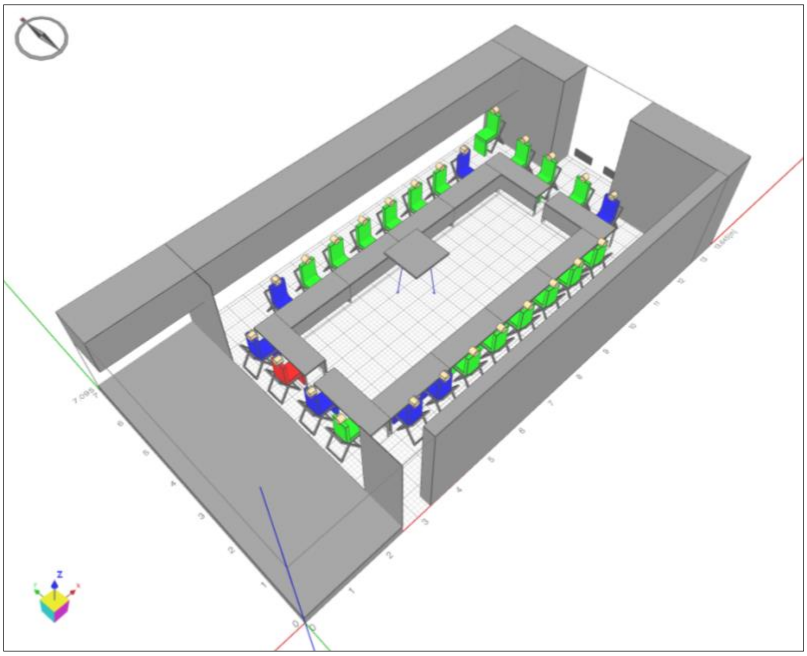


Fig. 3- 5 Geometric model of the meeting room.

In this CFD model, the dummy in red color indicates the dead attendee, blue color indicates the 7 PCR-positive infections, the rest of green color represent the other attendees.

The above boundary conditions are mainly used in the steady state solution. In addition, on the other hand, in order to simulate the transmission state of the droplets in the meeting room after they are ejected by human mouth, this study also conducted non-steady state solution according to the meeting duration, which is 1 hour. Based on the research conducted by Institution of Physical and Chemical Research (RIKEN) with super computer FUGAKU[77], in this study, the human sprayed droplets with a size of 10 µm and 500 droplets per minute, while in order to simulate a real meeting scenario in which participants speak, the index person was specified to spray droplets only in the time period of 4-9 minutes from 0-60 minutes.

Simulation results:

1) Air environment:

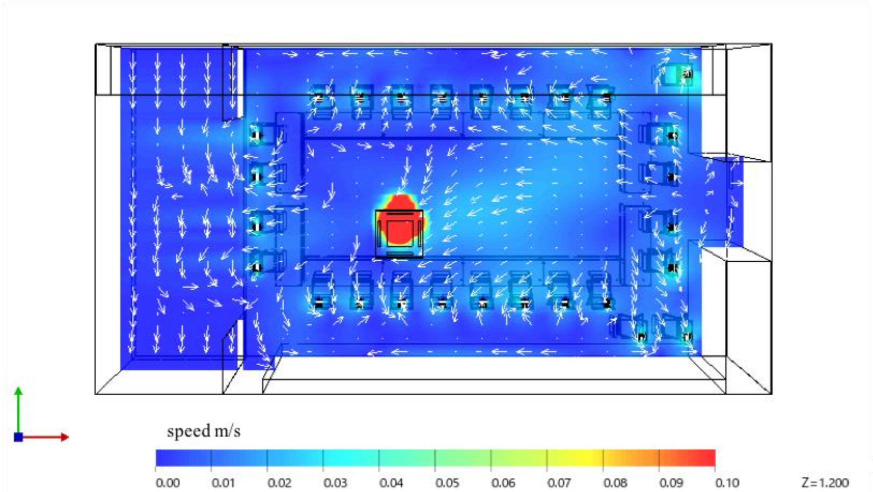


Fig. 3- 6 The airflow rate distribution of the meeting room.

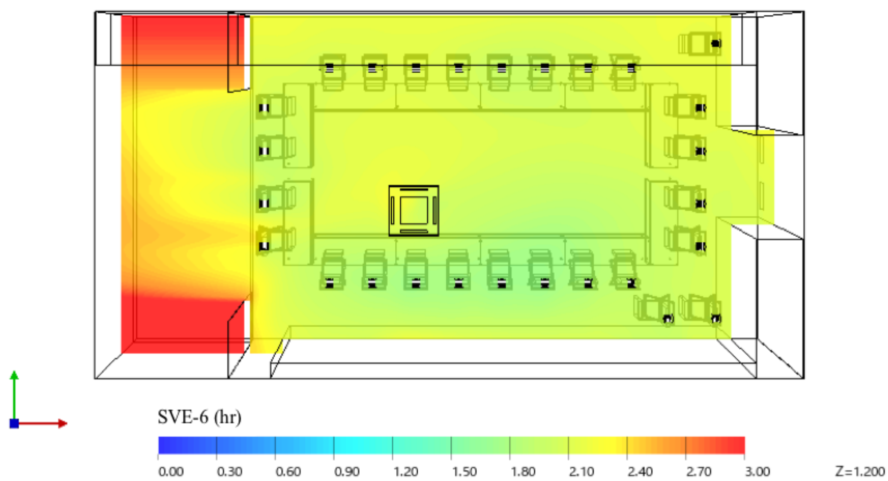


Fig. 3- 7 The SVE-6 (hr) of the meeting room.

As showed in Fig. 3- 6, in the section of the human breathing field at a height of 1.2 meters, the airflow rate in the meeting room is at a relatively low level, except for the place below the air conditioner, where the air been exchanged, the airflow rate below the air conditioner is significantly higher than the rest of the meeting room. In general, it can be considered that the faster the airflow rate in the room, the higher the airflow performance, and as a result, the better the indoor air environment.

As a result of the low airflow rate in the meeting room, the SVE-6 of the meeting room remained a high level conversely (Fig. 3- 7). In the SVE-6 expressed in time unit, the SVE-6 (hr) of most places in this meeting room remained at 2, which means the air in these places may linger in the room for about 2 hours. Both sides of the stage due to the blockage of the wall panel, the air stagnation condition is more serious.

It is known that the inflow of air in this meeting room is 2.353 m^3/min, which is 141.18 m^3/h, and the necessary air exchange in the room is 30 m^3/h/person according to the Building Standards Act[78], while there were 26 people in that meeting room at that time, which means that the air exchange volume for each person in the room at that time was 5.43 m^3/h/person, which is far below the necessary air exchange volume. It cannot be said that the meeting room lacked of adequate ventilation and maintained a good indoor air environment at that time.

2) Droplets transmission:

Droplets transmission pathways were simulated for the deceased and all the PCR-positive infections.

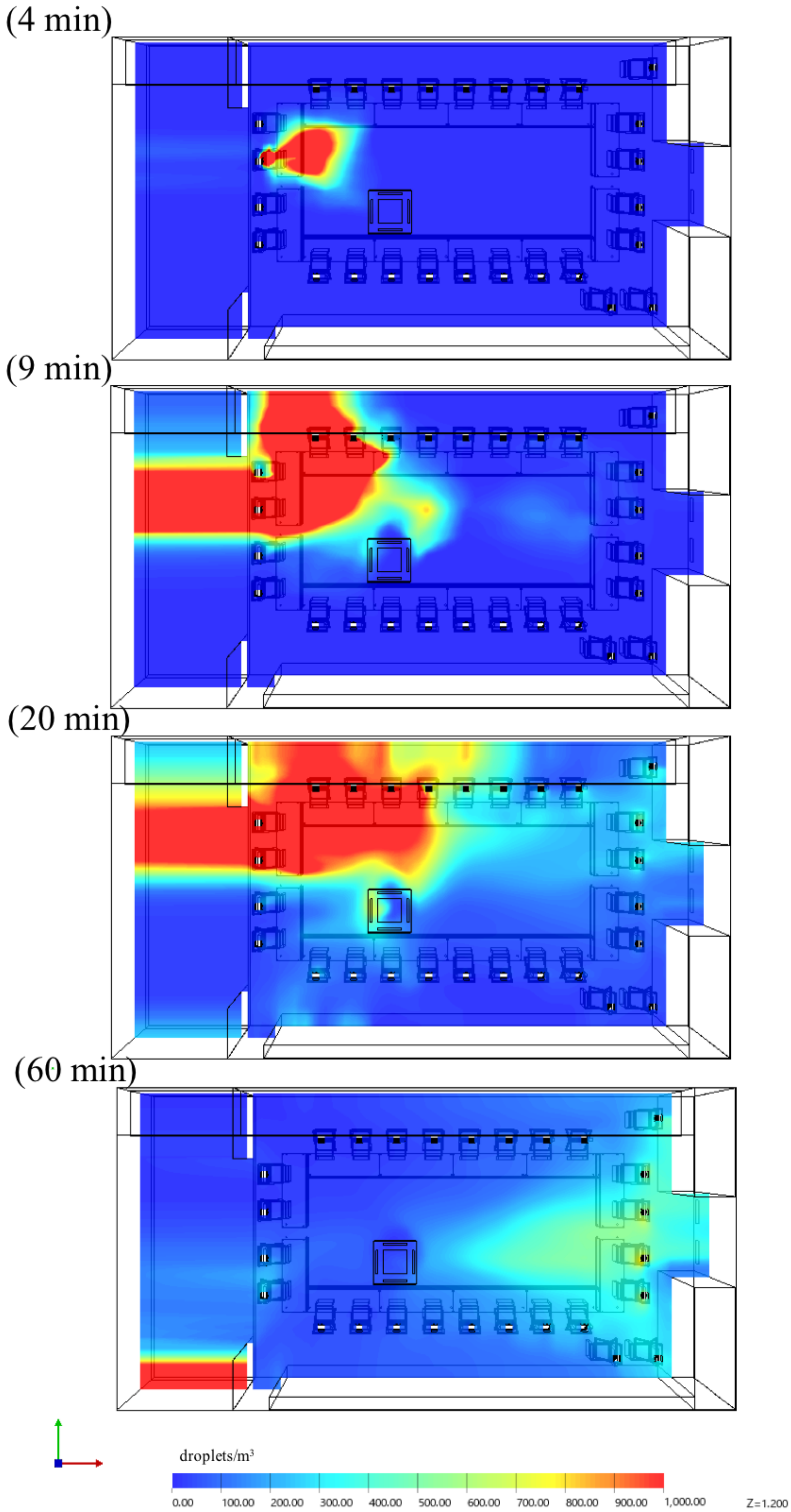


Fig. 3- 8 The droplets transmission state of the deceased in 1 hour.

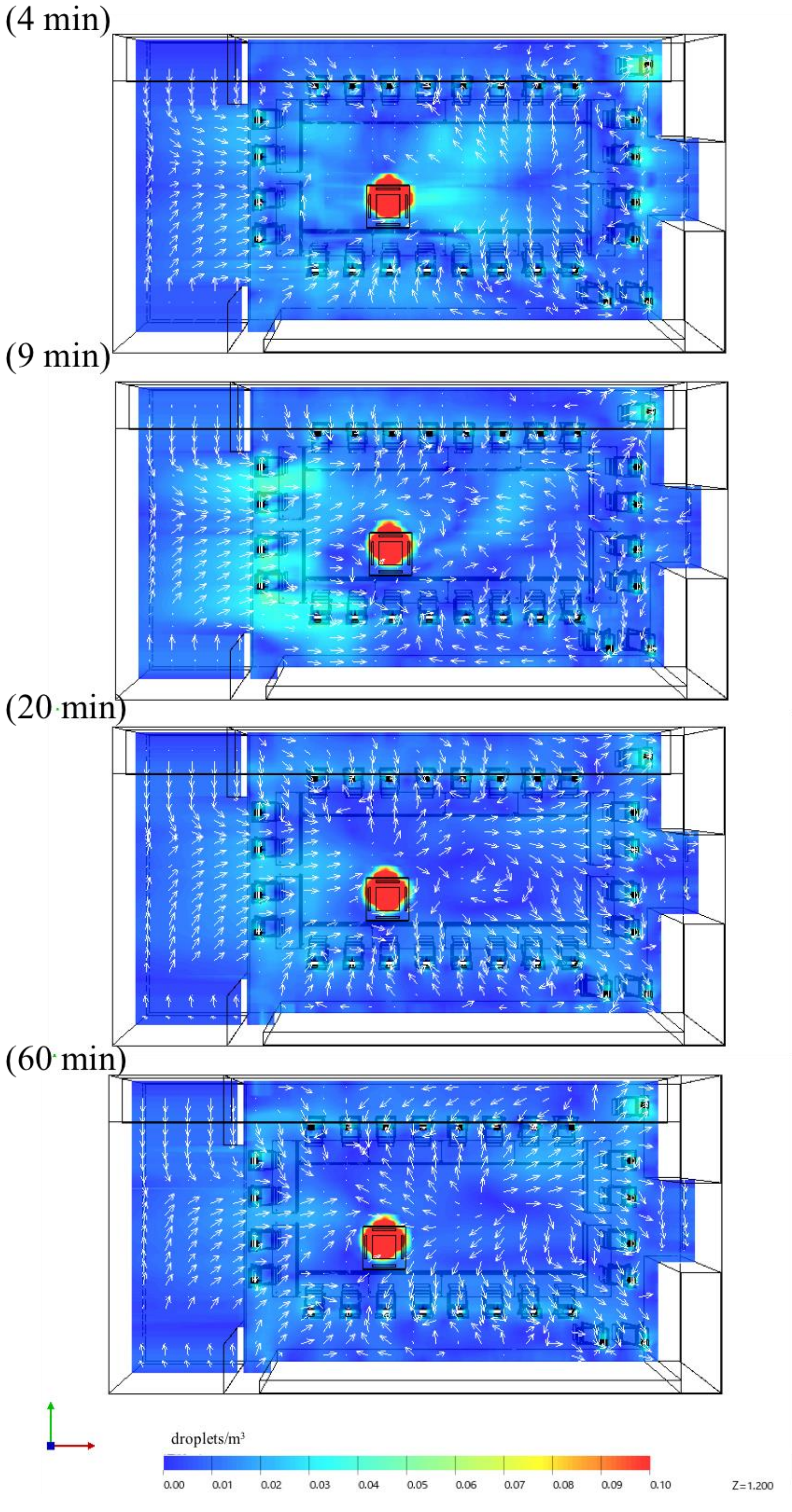


Fig. 3- 9 The changes of indoor airflow rate in 1 hour.

Since the index person was first tested positive for Coronavirus and died after infection, it is considered likely to be the source of this cluster infection. As a result, this thesis will focus on the pathways of droplets transmission for the deceased and refer to the appendix for the remaining 7 PCR-positive infections.

In Fig. 3- 8, the time set for droplets to be expelled was at the 4 minute, the droplets expelled by the deceased at the 4 minute spread to the surrounding area in a small domain, and the spread of the droplets grew in the following 5 minutes as the droplets kept being expelled. The droplets stopped being expelled at the 9 minute, but the droplets continued to spread during the 9-20minute period. The concentration of droplets around the deceased decreased, but the range of spread increased, and a small amount of droplets still remained in the room after 40 minutes, besides that, a high concentration of droplets remained behind the stage at the same time.

The reasons for the transmission pathways of droplets in Fig. 3- 8 can be explained by Fig. 3- 9. In Fig. 3- 9, the airflow rate in the room is similar to the airflow rate calculated by steady state solution (Fig. 3- 6), which are both in a slow airflow rate, it made the droplets are spreading slowly around the deceased who was set up to emit out the droplets in that period of time. Due to the ventilation effect of air conditioner, indoor airflow flowing with the inlet airflow and outlet airflow of the air conditioner. In the ventilation process of air conditioner droplets which are not discharged gradually flowing to the door, since there are 2 natural vents on the door. As for the droplets behind the stage, because the air is difficult to reach and discharge around the behind part of stage, once the droplets are spread to the behind of stage, they will stop over there for a long time relatively.

In summary, the reason why droplets stay in the meeting room for a long time and caused such a severe cluster infection can be attributed to the lack of adequate ventilation and there were too many people in there. It indicates that the importance of adequate ventilation for increasing airflow rate to avoid indoor air stopped in a place for a long time.

3) Location differences of indoor air environment:

Differences in the air environment in the meeting room are illustrated by the total number of droplets present in the room after people emitting droplets in different seats.

Same as the non-steady state solution of deceased, other 7 non-steady state solution conducted on the 7 PCR-positive infections. The simulation time, size and amount of droplets, the time of infections emit droplets, etc. are totally same with the deceased. Besides that, calculated the total amount of droplets present in the room by using the "**Domain Specification**" tool of CFD.

The "Domain Specification" tool is used by dividing the indoor space into small fields, them calculating the average value of droplets in each small field. In this study, the middle part of meeting room where participants been are divided into 6 x 10 small domains with the geometric dimension of 1 m x 1 m x 1 m, and the height of these small domains are set to 0.7 – 1.7 m depending on the height of 1.2 m, which is the height of people's mouth (respiratory area) when people remaining a sitting gesture.

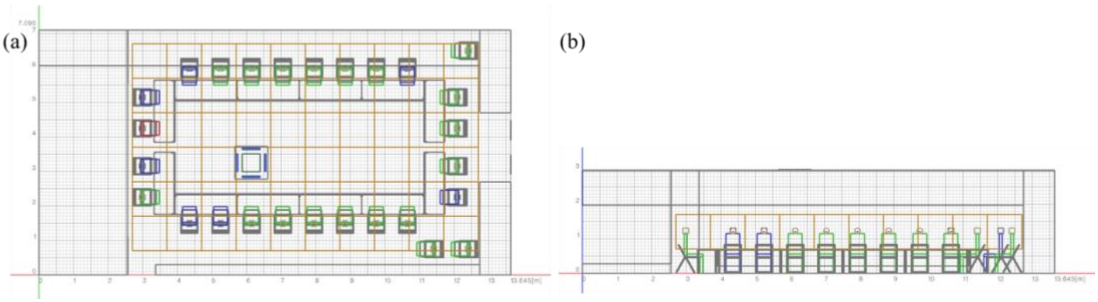


Fig. 3- 10 The schematic diagrams of "Domain Specification": (a) X-Y indication, (b) X-Z indication.

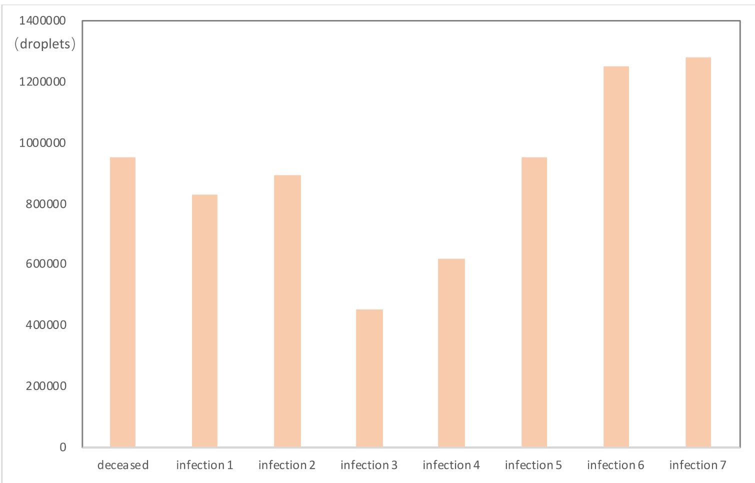


Fig. 3- 11 The total number of droplets expelled by infections at different seats.

Fig. 3- 11 indicated the differences among the total number of droplets expelled by infections at different seats. Combined with Fig. 3-4, infection 1, 2 and 5 shared adjacent area of the meeting room, in sight of the low airflow rate of the room, so it is not difficult to imagine that they have the similar droplets transmission amounts. On the other hand, infection 3 and infection 4 in the opposite direction to infection5, the total number of droplets expelled by infection 3 and 4 are clearly lower than infection 5 and other adjacent infections, it shows that the air environment in this area is better than the opposite side, probably because the seats of infection 3 and infection 4 are closer to the air conditioner, and Fig. 3- 6 also show that the airflow rate in this area is faster and the SVE-6 (hr) is shorter (Fig. 3- 7). The same results happen to the area of infection 6 and infection 7, and the air environment in this area is even worse.

Because of the lack of adequate ventilation, and the airflow brings virus-containing droplets to everywhere of the room slowly, even if there is only the deceased emitting the virus-containing droplets, his droplets could reach every place in the room and not be completely discharged after 50 minutes. The influence of air environment difference also indicated the importance of ventilation performance and indoor airflow to the droplet transmission.

Chapter 4 Analysis of the actual condition of the indoor air environment and development of a local ventilation system for the purpose of preventing virus spread in the lecture room

In the beginning of the pandemic, to mitigate the risk of Coronavirus infection, universities in Japan were closed for a period of time, students had no choice but taking online classes at home. Continuous online education certainly would have a minus impact on the teaching quality and students' physical and mental health, not to mention some field investigation and experimental courses cannot be conducted online, and students cannot do other activities which are normal before COVID-19.

To reduce the impact of pandemic on educational activities, Japanese universities also were obligated to reopen campus after the end of the state of emergency, returning educational activities to normalcy. To reduce the risk of infection, the universities has taken measures such as adopting "hybrid class" to compromise online class and face-to-face traditional class, splitting students to small groups, wearing mask, washing hands regularly, and reporting health status before coming to campus, etc.

Reopening universities is an exciting progress in light of pandemic, but at this time when epidemic is still recurring and vaccines are not yet widely available, face to face class is still very risky. Although it's possible to reduce the frequency of students discussing in class, the teacher cannot avoid talking in class. If the teacher was infected with coronavirus unfortunately, as the teacher speaks loudly in class, virus-containing droplets will also spread to the classroom through airborne transmission and aerosol transmission, which will greatly increase the probability of students infecting the coronavirus.

Based on a real lecture room in GSFS, The University of Tokyo, this study investigated the transmission pathways of droplets expelled by teach during class and proposed a low-cost solution to block the spread of droplets from teacher side to student side, hoping to reduce the risk of coronavirus infection during face-to-face class.

4. 1 Target room for analysis

The target room is a lecture room which located in 4F, Environmental studies building, GSFS, The University of Tokyo. The following is the overview information about this lecture room.

Geometric size	7.95 m x 14.4 m x 3 m
Doors	2
Windows	3, but only one of them can be opened
Ventilation	16 inlets: 1.5 m x 0.02 m x 16
	8 outlets: 0.2 m x 0.2 m x 8
Ventilation speed	inlet: 1.85 m/s
	outlet: 2.78 m/s
Accommodation	before pandemic: 42 students + teachers
	after pandemic: 21 students + teachers

Table 4- 1 Overview of the lecture room.

The ventilation system in the lecture room included 2 total heat exchangers (550 m^3/h) and 2 air conditioners (1602 m^3/h), the wind speed of inlets and outlets are calculated by the performance of the total heat exchangers and air conditioners.

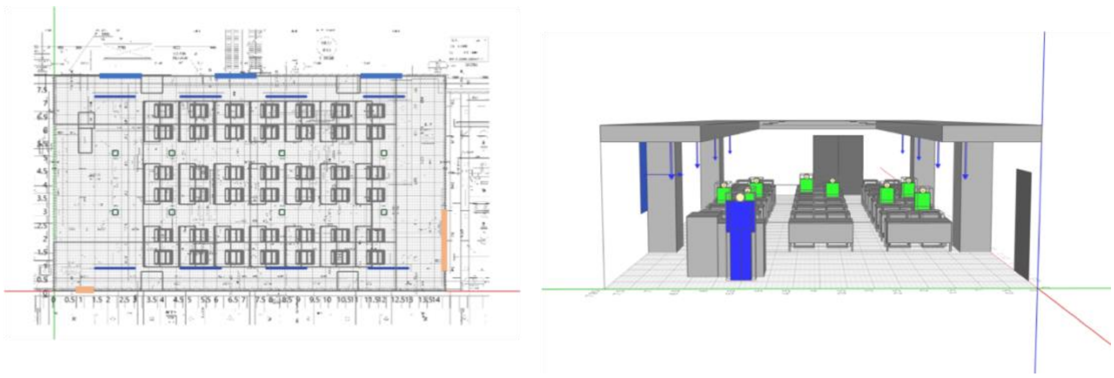


Fig. 4- 1 The schematic diagram of the lecture room.

4. 2 Air environment analysis of the lecture room

At present, the index of CO_2 concentration under 1000 ppm is being widely discussed. This is because the Building Standard Law regulated the indoor CO_2 concentration should be less than 1000 ppm, to meet this standard, the requirement of 30 m^3/h/person is supposed to be met. It does not mean that once the CO_2 concentration less than 1000 ppm, the infection risk disappeared. But it would not be a "poorly ventilated enclosed space" at least if the current standard of 1000 ppm CO_2 is met[79].

To confirm the CO_2 concentration in the lecture room, this study conducted CO_2 concentration measurements by using CO_2 densitometers.

CO_2 concentration measurements were conducted on May 25th, 2021. Measurements were taken twice during the second class in the morning and the third class in the afternoon, each time for 1 hour and 45 minutes consecutively, according to the university's teaching schedule. No one was in the lecture room in that morning, face-to-face class conducted there in the afternoon, 1 professor and 8 students were present. The positions of students are indicated in Fig. 4-1, number 1~5 and door indicates the position of CO_2 densitometers.

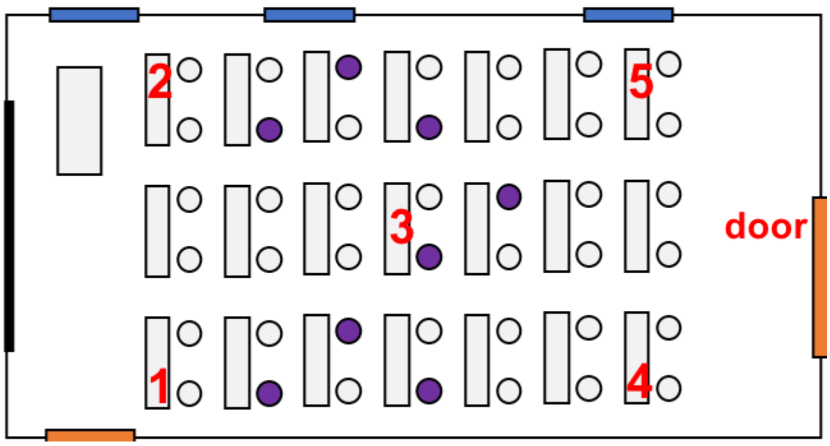


Fig. 4- 2 The positions of students and CO_2 densitometers.

The ventilation conditions in the lecture room were consistent for these 2 measurements: the ventilation equipment was on, the air conditioning was on and kept at 26 °C, and the window and doors were open. The differences about outdoor temperature and wind speed in the morning and afternoon were ignored.

Fig. 4- 3 CO2 densitometers: (a) type 1, (b) type 2.

2 types of CO_2 densitometers were used in this study. Densitometers used at position 1~5 were type 1 (Logtta CO2 センサー, *SATOTECH*[80]), the densitometer used at position “door” was type 2 (HJ-CO2-SD, *SATOTECH*[81]), the CO_2 sensor in both of 2 types adopt Non-dispersive Infrared (NDIR)[82].

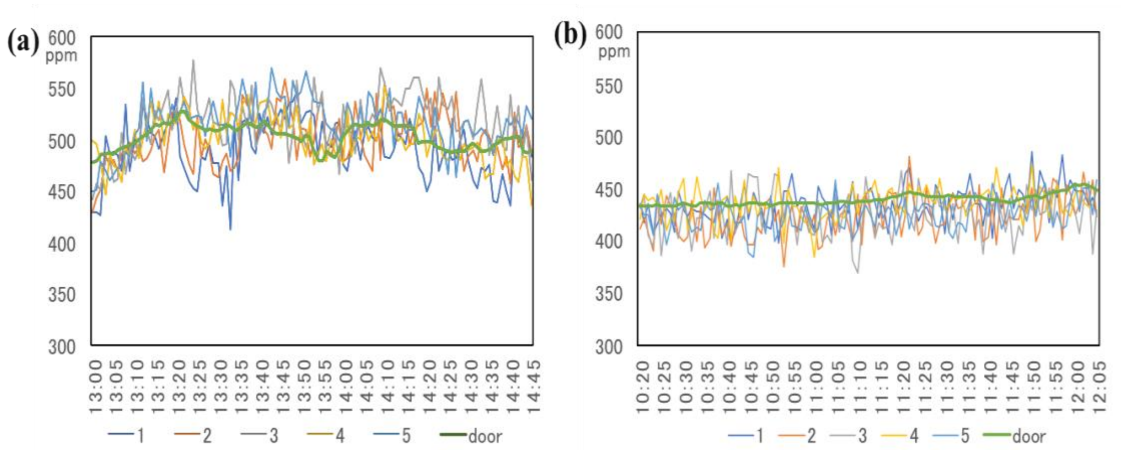


Fig. 4- 4 Monitoring results of CO_2 concentration: (a) 3rd class, (b) 2nd class.

Since there was no one in the lecture room during 2nd class, and the window, doors and ventilation were open, the adequate ventilation made the CO_2 concentration in the lecture room been kept a low level and had no significant changes during the monitoring time, besides that, the CO_2 concentration was basically consistent with the outdoor atmospheric CO_2 concentration, indicated a good air environment during that period of time (Fig. 4- 4 (b)).

On the other hand, due to there were students attended in the 3rd class, the CO_2 concentration in the room kept increasing in the initial period of the class as students and professor kept exhaling CO_2, but contributes to the good ventilation performance of the lecture room, the CO_2 concentration in the room basically stabilized after about 20 minutes and remained at a low level of 500 ppm.

These measurements prove that even in a face-to-face classing environment, the lecture room can still maintain a low level of CO_2 concentration if adequate ventilation is guaranteed. Meanwhile, the concentration changes of densitometers type 1 and type 2 monitored also indicate that it is necessary to pay attention to the meter's accuracy when buying a CO_2 densitometer.

However, there were only 9 persons in the lecture room at that time, so it's not possible to prove whether the CO_2 concentration was still below 1000 ppm when the number of people in the room increased, and it was not clear whether it would have an effect on CO_2 concentration changes if the doors and window should be closed to keep quiet.

To investigate the effect of the number of people on CO_2 concentration change in the lecture room, this study conducted several simulations by using CFD.

	simulation 1	simulation 2	simulation 3
Number of people	10 students + 1 teacher	1 students + 15 teachers	42 students + 1 teacher
Temperature	26 ℃	26 ℃	26 ℃
Relative humidity	60%	60%	60%
Turbulence model	k-εmodel	k-εmodel	k-εmodel
Fluid type	air	air	air
Number of mesh	≒100000	≒100000	≒100000
Surface temperature of the human head	36.5 ℃	36.5 ℃	36.5 ℃
Height of human mouth	1.2 m	1.2 m	1.2 m
CO2 exhauled by human	40 g/h	40 g/h	40 g/h
Initial concentration of co2	540 ppm	540 ppm	540 ppm
Windows	open	close	close
Wind speed			
Doors	open	close	close
Ventilation speed	inlet: 1.85 m/s	inlet: 1.85 m/s	inlet: 1.85 m/s
	outlet: 2.78 m/s	outlet: 2.78 m/s	outlet: 2.78 m/s
Outflow	53.376 m3/min	53.376 m3/min	53.376 m3/min
Inflow	145.08 m3/min	53.28 m3/min	53.28 m3/min
Natural outflow	91.704 m2/min	0.096 m3/min	0.096 m3/min

Boundary conditions

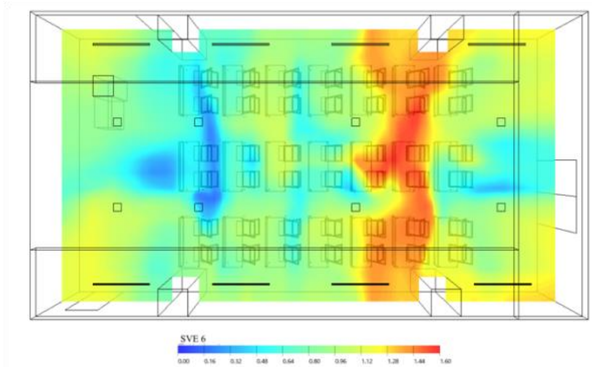


Fig. 4- 5 The SVE 6 distribution in the lecture room

As mentioned in Chapter 2, the SVE 6 is used to indicate the status of indoor ventilation, and the shorter residual lifetime of air, the faster the polluted air is discharged. Figure 4-5 shows the calculation results with prerequisites that the windows and doors closed. This is the result of cutting at 1.2m on the Z side of the lecture room. The left side is the blackboard in front of the room, and the right side is the back of the room on the doorway side. The result shows that the SVE 6 in the room is not uniform, with some areas on the rear side of the room that are difficult to exhaust and some areas that are easily exhausted in the front.

To verify whether the air in the back of this room was really stagnant, CO_2 concentration simulations were conducted referred to the calculation conditions.

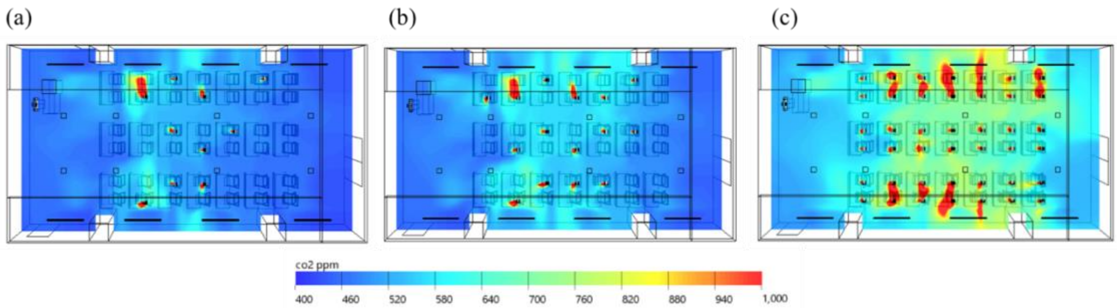


Fig. 4- 6 Dependence of CO_2 concentration on the number of people: (a) simulation 1; (b) simulation 2; (c) simulation 3.

Fig. 4- 6 shows that as the number of people in the lecture room increases, the carbon dioxide concentration in the room gradually rises as well, the distribution of CO_2 concentration is highly dependent on the number of people.

Combine the distribution of SVE 6 and the CO_2 concentration simulation, it can be considered that the analysis results of indoor air environment can provide a guide information when people are considering where the CO_2 sensors should be placed and where is more suitable for students to seat.

4. 3 The development of a local ventilation device

In face-to-face classes, if someone in the room exhales virus-containing droplets, it is possible that these droplets are spread to the others through airborne or aerosol transmission, it may increase the risk of “cluster” infection.

In this study, it is assumed that the teacher who has the most opportunity to speak in class is the one who generated droplets. In order to minimize the chance of droplets spreading into the lecture room, this study proposed several prevention measurements at the start.

4. 3. 1 By acrylic panel

The use of acrylic panels to stop the spread of droplets is very common in pandemics, especially in restaurants, cafeterias and other places where people need to take off their masks. Because it is easy to install and does not require to renovate the room, the first thought was whether acrylic panels could be installed around the lectern to stop the droplets expelled by teacher from spreading to the students with the indoor airflow.

Therefore, it was assumed that an acrylic panel with a height of 1 meter was installed around the edge of the lectern (Fig.4-7), and the blocking effect of the acrylic panel on droplet transmission was simulated by CFD.

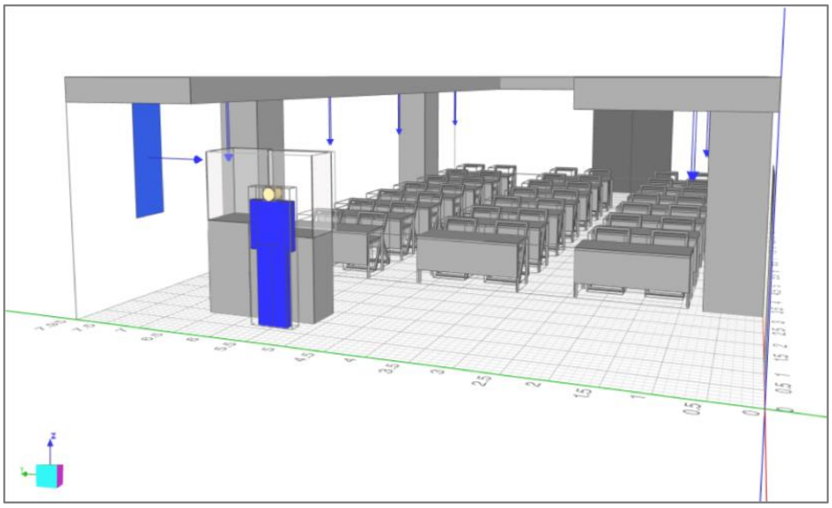


Fig. 4- 7 The schematic diagram of the acrylic panel.

Simulation results:

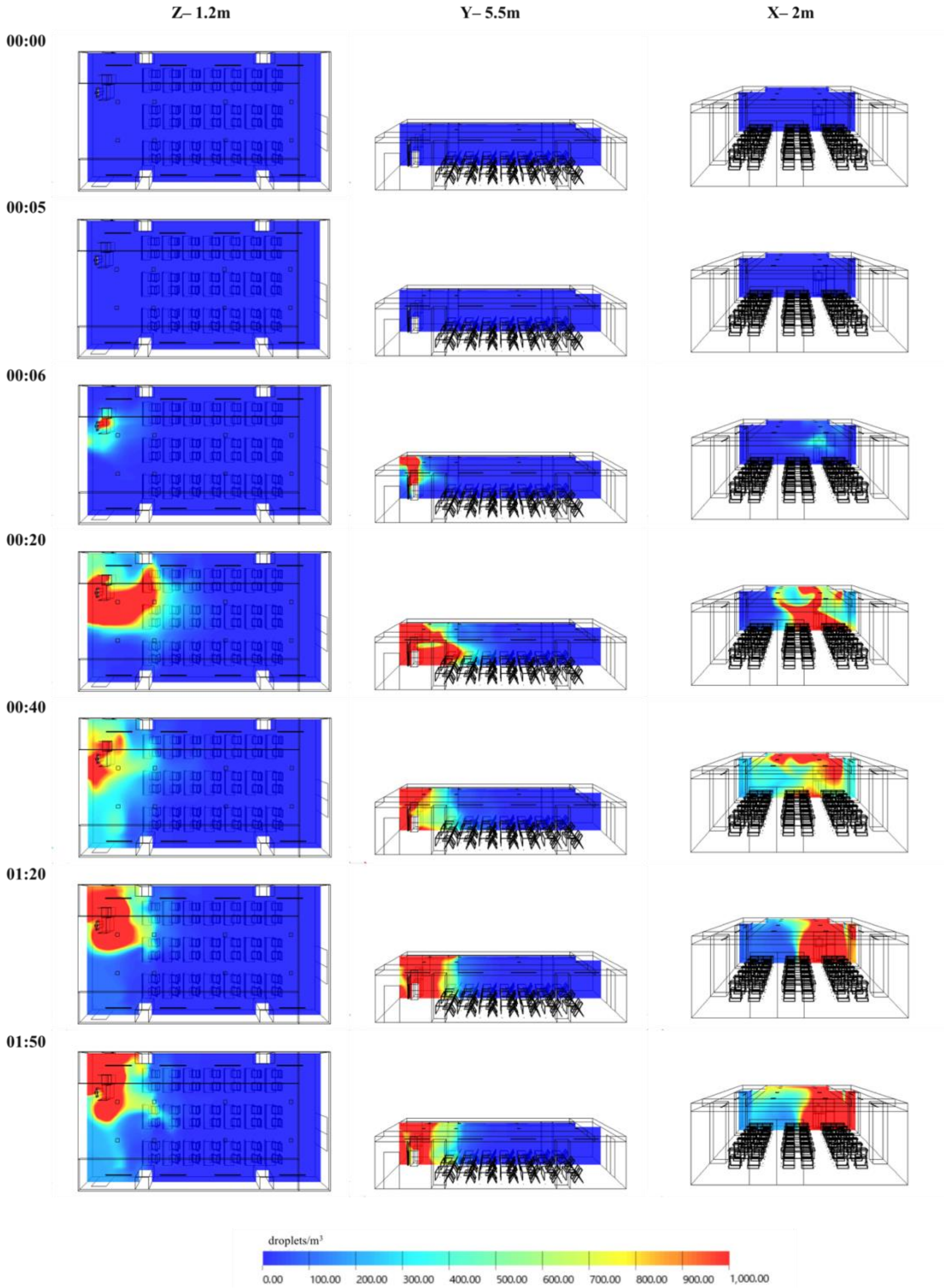


Fig. 4- 8 Droplets diffusion changes in 1h50min with acrylic panel.

According to the simulation results, it must be admitted that the acrylic panel plays a blocking effect on the droplets diffusion is not obvious in this lecture room. There is a high concentration of droplets around the outside of the panel.

The reason for this may be related to the original size of the droplets and the airflow in the lecture room. As can be seen in Fig. 4- 8 (Y-5.5m, 00:06), during the first minute when the droplets were indeed blocked by the acrylic panels, but due to there are exhaust ports above the lectern, the small droplets were expelled or diffused into the room with indoor airflow more than they were blocked by the acrylic panel. During a real conversation, the droplets with larger sizes expelled, these droplets will be blocked by the acrylic panels or due to their own gravity to settle below, only the water-evaporated droplet nuclei, will be floating in the air with the indoor airflow for a long time. It can be explained in the simulation results that after the droplets were expelled by the professor, they spread upward firstly and then spread around.

4. 3. 2 By air-curtain

Since acrylic panels do not play a good role in blocking the spread of droplets in this lecture room, it was suggested whether the spread of droplets could be blocked by air curtain. The air curtain is a fan-powered device that creates an invisible air barrier over the doorway to separate efficiently two different environments, without limiting the access of the people or vehicles[83]. Air curtains are commonly found in department stores and factories, where people come and go so frequently that the doors remain open all the times, the role of air curtain is to provide a thick layer of air to avoid outside dust and the outside air temperature and humidity influencing on the inside air environment.

There have been studies proved the effect of air curtains on reducing the amount of smoke leaking from the smoking area to the non-smoking area in the restaurant[84], and a model laboratory was used to verify that air curtain is effective in reducing the risk of aerial infection[85]. Moreover, there has been a research that studied on the performance of shut-off of outdoor air invasion by the side-blow air curtain system[86]. These retrospective studies provided a profound reference for this study.

Common uses of air curtains are: (a) hanging from the ceiling and blowing airflow from above to form an air barrier, (b) placed horizontally on a flat surface and blowing airflow from below to form an air barrier, and (c) two fans blowing airflow to each other's direction to form an invisible air barrier.

This study also proposed several ways of using air curtain in the lecture room based on the actual use of air curtain, hoping that the air curtain will not affect the normal class experience but also block the spread of droplets in the lecture room.

The effect validation of the air curtain was conducted by simulation in CFD. Based on the fan that can be bought in the market as a prototype, a similar fan model was created in CFD. The air volume of the fan was calculated according to the commodity information, and the effect of the fan was firstly verified in CFD with a wind speed of 4 m/s.

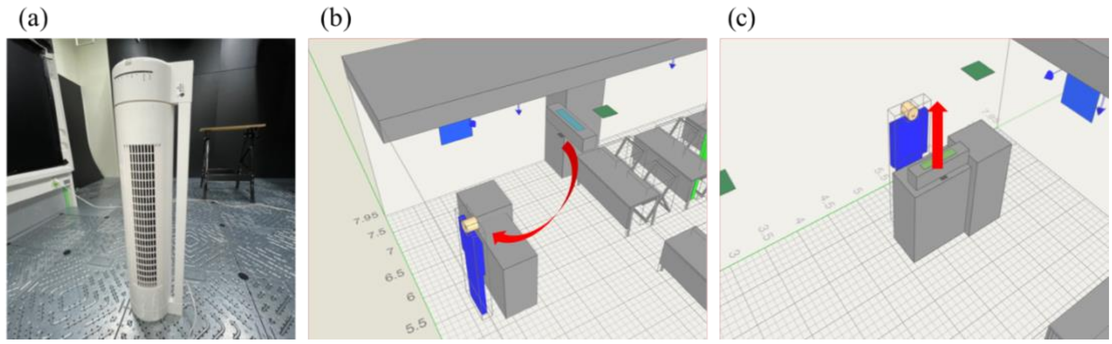


Fig. 4- 9 Air curtain: (a), prototype fan; (b), the fan blowing airflow from above; (c), the below-blow air curtain.

The following show the simulation results for the velocity of the airflow represented by the streamlines:

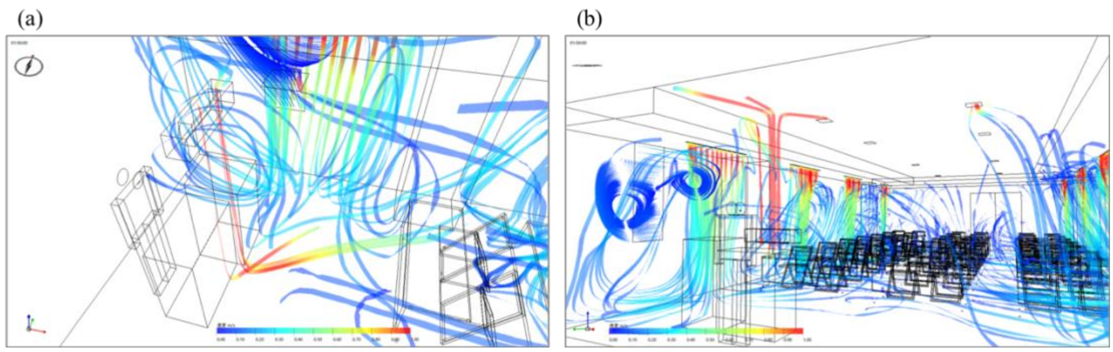


Fig. 4- 10 The velocity streamlines of the air curtains' airflow: (a) above-blow; (b) below-blow.

Fig. 4-10 (a) shows that the airflow from the fan hanging from the ceiling can form an air barrier in front of the dolls, but the velocity streamlines show that the airflow starts to flow toward the middle of the lecture room after hitting the floor, in which case the risk of infection in the lecture room may be greatly increased if the airflow contains virus-containing droplets. The same situation appears on Fig.4-10 (b), the airflow blowing from the below to the top is divided into two directions when it reached the ceiling, and part of the airflow also flowed into the lecture room.

The simulation results proved that neither top-down nor bottom-up the airflow control methods are suitable for lecture room use. Therefore, this study proposes a way to form an air barrier by placing two fans in front of the podium (Fig. 4- 11 (a)).

The specific design concept is the droplets expelled by teacher inhaled into the first fan firstly, or blocked by the air barrier, then the droplets flow into the second fan with the airflow blowing out by the first fan, the air outlet in the second fan installed a high-performance HEPA filter, exhausting the inhaled air back into the lecture room after filtering (Fig. 4- 11 (b)).

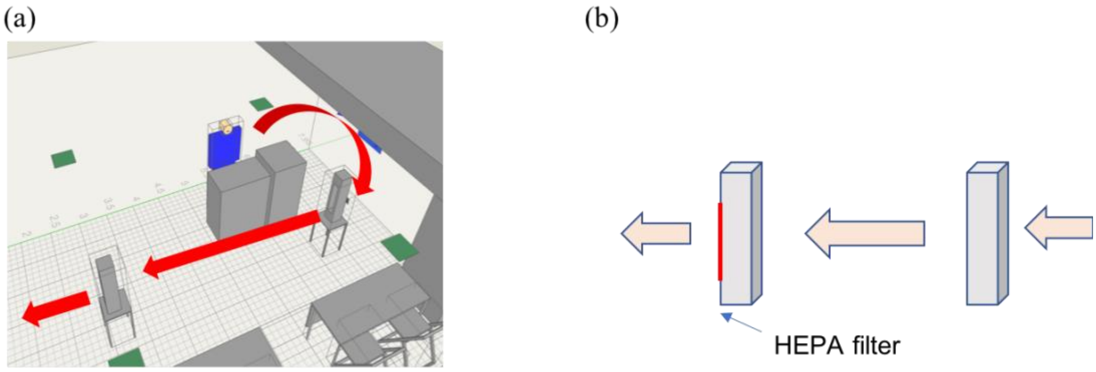


Fig. 4- 11 The schematic diagrams of air curtain with HEPA filter.

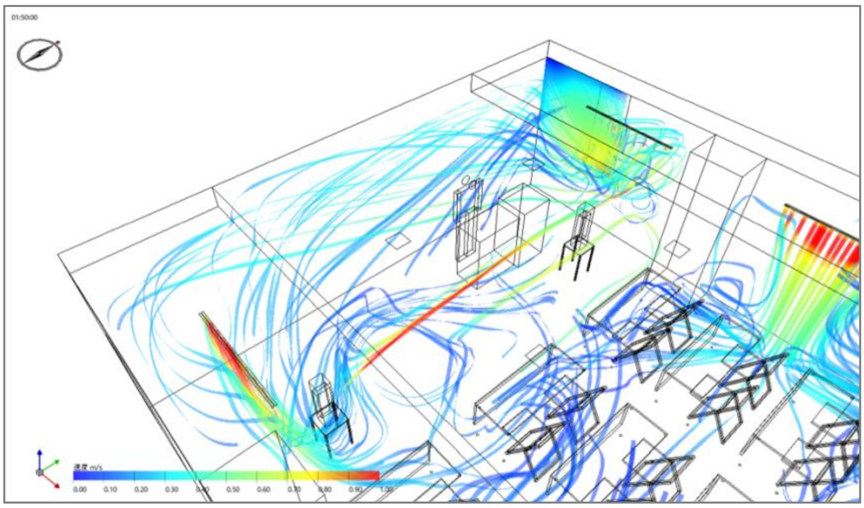


Fig. 4- 12 The velocity streamlines of the air curtain with HEPA filter.

Fig. 4- 12 shows that there is a velocity streamline is formed between the two fans, which can be thought of as there is an invisible air barrier there. The results of the simulation appear that this placement of fans may play a role on blocking the spread of droplets. Therefore, the effect of the air curtain with HEPA filter was further investigated based on this placement.

The following table shows the fan information in initial simulations:

Initial boundary condition of fans

NO.1	
Size	0.185m x 0.185m x 0.818m
Size of outlet	0.1m x 0.5m
Size of inlet	0.1m x 0.5m
Aperture ratio of outlet	75%
HEPA filter	aperture ratio: 21.26%
	capture ratio: 99%
Velocity	4 m/s
The height from the floor	1 m
The distance between 2 fans	5 m
The distance from the teacher	1.4 m

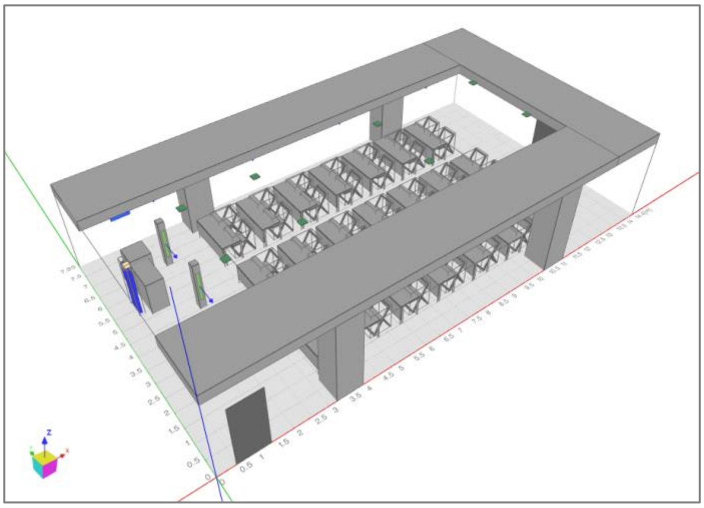


Fig. 4- 13 Schematic diagrams of air curtain in the lecture room.

4. 4 The effect and optimization of air curtain

4. 4. 1 Original diffusion state of droplets in the lecture room

An important starting point when investigating the propagation pathways of human expired aerosols in the transmission of disease is to gain a comprehensive knowledge of the expired aerosol generation process, which included the sizes distribution and numbers of aerosol, initial velocity when speaking or coughing, and the respiratory tract, etc.[64]. Much of researches focus in infection control have been investigating the entire range of droplet sizes and numbers distribution over past decades[87][88][89][90][91]. However, due to the differences in the methods and mathematical models used by each researcher, the estimations of the droplet size and number distribution from these studies vary greatly in terms of results. There is no doubt that the size of the droplets expelled when a person speaks, coughs or sneezes is between 1 μm to hundreds μm, but there is still a great deal of disagreement about which parts of the droplet size are majority and the number of droplets among each same size. Meanwhile, based on the research of the effects of mask conducted by Institution of Physical and Chemical Research (RIKEN) [77], which indicates that non-woven masks can stop almost all droplets over 5 μm from being sprayed out of the mask, but the capture rate for aerosols of 0.3 ~ 5 μm is only 50%. Apart from these, the physical data such as the initial velocity and the angle of the exhaled airflow, even the gender difference also play a key role in analyzing the pathway of droplets transmission[38]. Based on the above studies and considering the limitations of the CFD software used in this study, the dynamic of the droplets is ignored, meanwhile, the size of the droplets is set to 3 μm which cannot be captured by mask, and the speed of droplets generation is set to 191 droplets/s refer to a droplet size distribution research conducted by The Hong Kong University of Science and Technology[63].

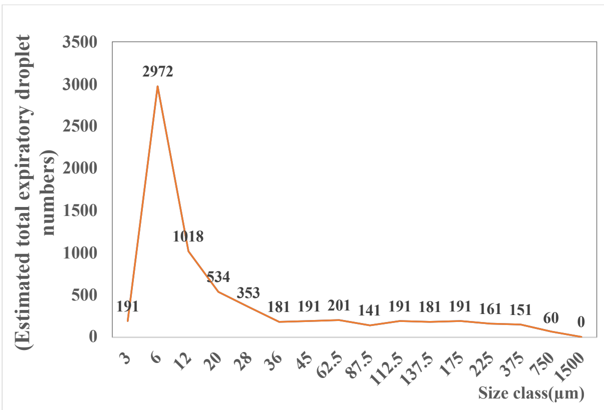


Fig. 4- 14 The distribution of droplets numbers refers to Chao (2009)[63].

The following indicates other boundary conditions in simulations.

Boundary conditions

Number of people	1 professor
Temperature	26 ℃
Relative humidity	60%
Turbulence model	k-ε model
Fluid type	air
Number of mesh	≒ 1000000
Surface temperature of the human head	36.5 ℃
Height of human mouth	1.6 m
The size of droplets	3 μm
The generation speed of droplets	191 droplets/s
The generation time of droplets	0-5 min: 0 droplets/s
	6-110 min: 191 droplets
CO_2 exhaled by human	40 g/h
Windows	close
Doors	close
Ventilation speed	inlet: 1.85 m/s
	outlet: 2.78 m/s
Outflow	53.376 m3/min
Inflow	53.28 m3/min
Natural outflow	0.096 m3/min

In the CFD calculations of this study, the initial velocity of droplets as they are emitted from the mouth was ignored.

Simulation results:

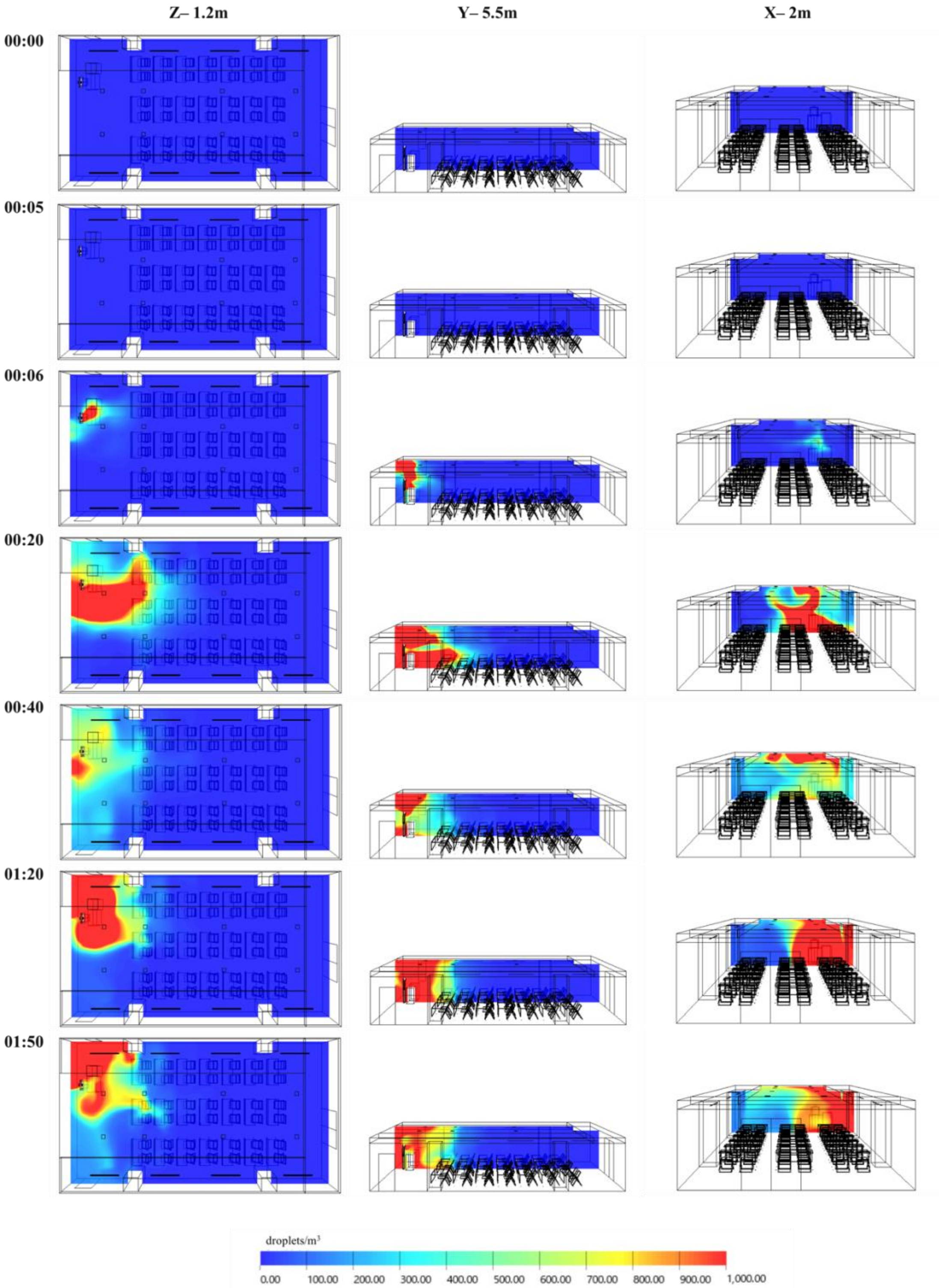


Fig. 4- 15 Droplets diffusion changes in 1h50min.

As shown in Fig. 4- 15, from the 6 minute when the droplets started to be generated, the spread range of droplets in the lecture room gradually expanded around the teacher's position, but as mentioned before, there is enough air exchange in this lecture room so that although the droplets keep being generated, the spread is still limited to the vicinity of the lectern according to Fig. 4- 15, and only a small portion of the droplets spread beyond the first row of seats because there are 2 exhaust ports above the lectern, which can suck up the droplets containing air.

Moreover, using “Domain Specification” tool divide the lecture room into 6 x 12 small domains with the geometric dimension of 1 m x 1 m x 1 m, the height of these small domains is set to 0.7-1.7 m and 1-2 m, depending on the height of human mouth, 1.2 m and 1.6 m relatively (Fig. 4- 16), and calculated the total number of droplets in each small domain (Fig. 4- 17). It should be noted that the total number of droplets in each small field is obtained by adding up the number of droplets present in the field at each temporary time (1 minute) within 1 hour and 50 minutes, so if the droplets present in the previous temporary time are not completely discharged, those droplets may be double counted in the next temporary time.

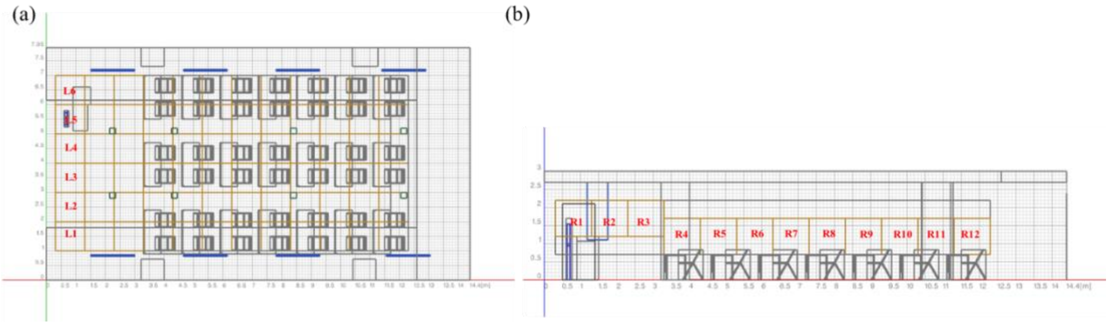


Fig. 4- 16 The schematic diagrams of “Domain Specification”: (a) X-Y indication, (b) X-Z indication.

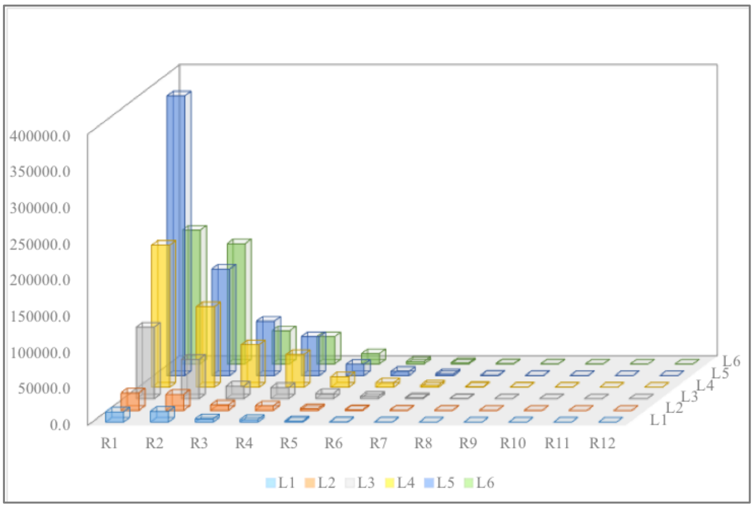


Fig. 4- 17 The droplets number of each domain when there is no air curtain in the room.

In Fig. 4- 15, the spread of droplets occurred almost exclusively in the vicinity of the lectern, but as can be seen in Fig. 4- 17, some droplets escaped the control of the exhaust airflow and spread in the middle of the lecture room, although it was only a small portion compared to the total number of the droplets. However, it should be clarified that this is only the droplets that exist in the divided domains, it is not difficult to imagine that there are droplets still exist in other parts of the lecture room outside of the divided domains. As a result, it is necessary to add other measures to the existing ventilation system if there is a need to minimize the risk of virus infection.

4. 4. 2 Effect of air curtain

First of all, in order to prove whether the air curtain really has a blocking effect on droplets, a PIV experiment was carried out.

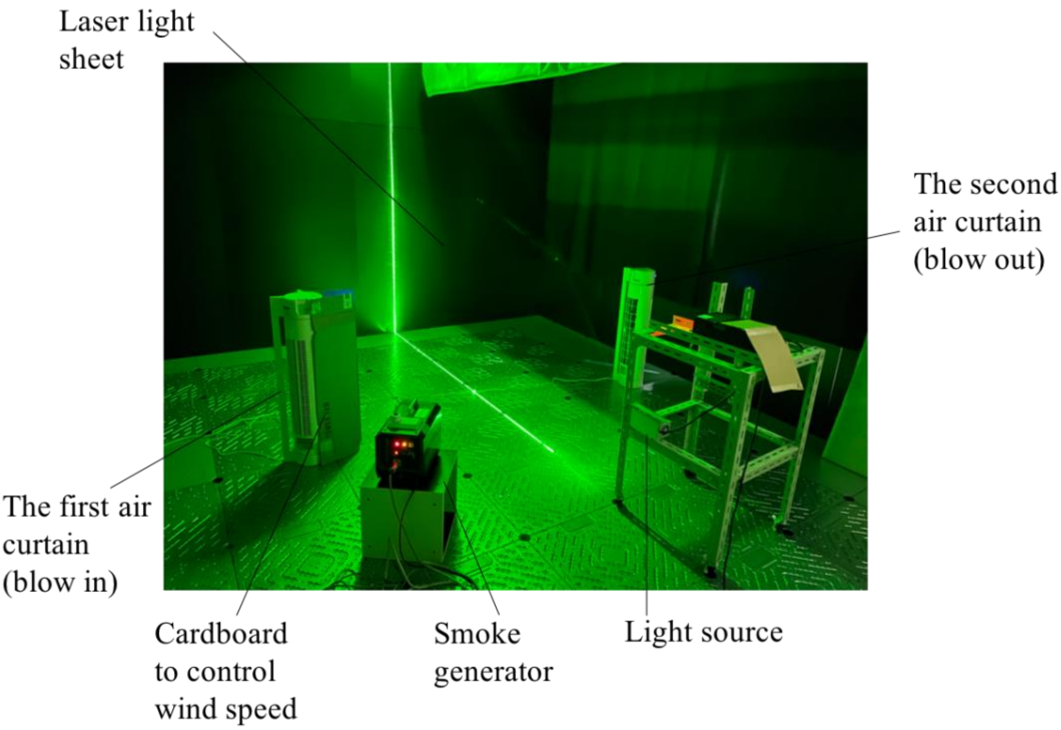


Fig. 4- 18 Overview diagram of PIV experiment.

In PIV experiment, in order to control the direction of air flow from the first fan, two pieces of cardboard were installed at the first fan so that the air flow from the first curtain is flow into the second fan directly. Moreover, in order not to increase the air velocity of the air outlet because the area of air outlet is reduced, a gap is left between the cardboard and the first fan.

The laser light source was placed 1 meter away from the center of the two fans at a height of 46 cm. the laser light sheet illuminated by the laser light source can form a plane in horizontal or vertical direction by adjusting the direction of the laser light source.

Considering the size of 3 μm droplets were used in CFD simulations, in order to be as similar as possible to the simulations, a smoke generator was used to emit smoke which the size is about 10 μm to instead of the droplets expelled by human being. The placement of the smoke generator was set to 1.5 m from the air curtain and close to the laser light source. the height is the same as the laser light source. In each experiment, the smoke occurred for 3 seconds.

The fans can be adjusted for the following wind speeds: low level (5 m/s), middle level (7 m/s), high level (10 m/s). when the wind speed of the fan is set to a high level (10 m/s), the wind speed at the suction port is 2.4 m/s, this wind speed was always used for the second fan in the experiment.

The room ventilation was closed during the experiment, and the ventilation equipment was turned on after each experiment to ensure that each PIV observation would not be affected by the residual smoke from the previous experiment.

In the experiment, a smart phone (iPhone 12) was used to videotape the diffusion of smoke.

Experiment results:

(1) The blocking effect of air curtain:

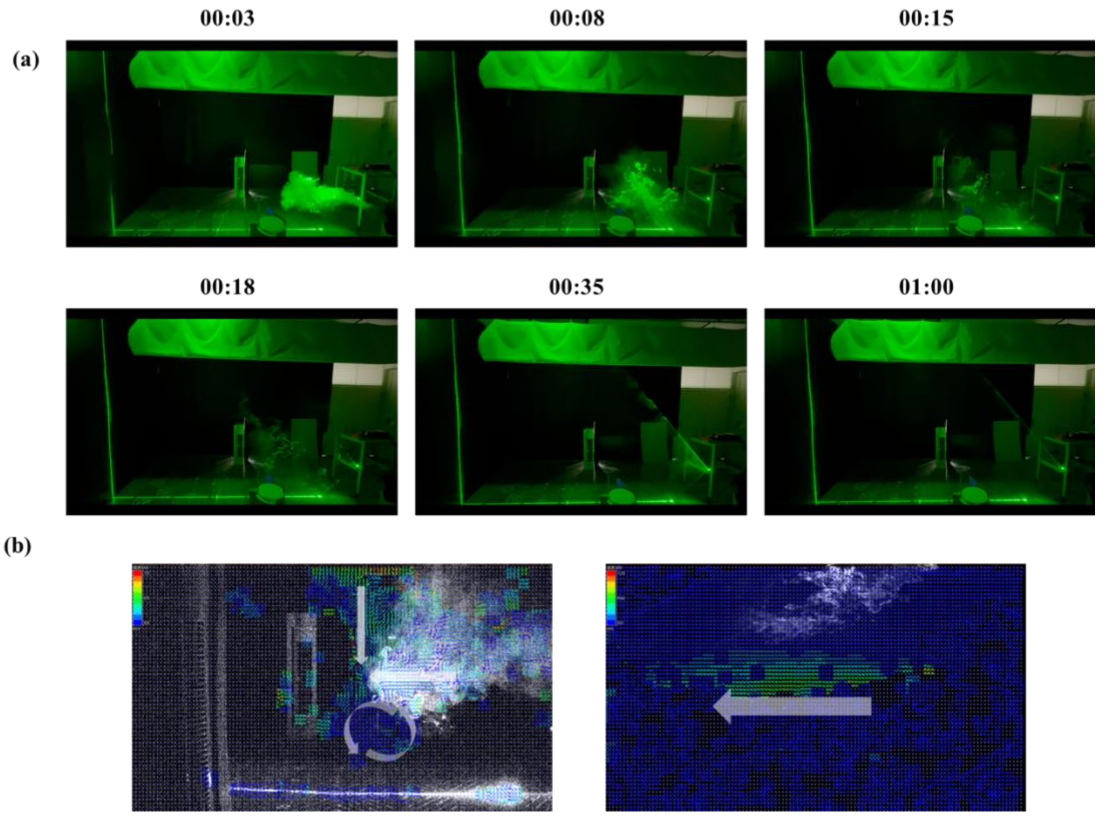


Fig. 4- 19 The blocking effect of air curtain in a low-level speed: (a) the smoke diffusion changes during 1 min; (b) smoke movements in vertical and horizontal direction.

As shown in Fig. 4- 19, the emitted smoke is blocked by the air barrier between the two fans when it reaches the air barrier formed by fans (00:08); the blocked smoke moves upward with the airflow from the first fan, and most of the smoke moves backward and formed a vortex on the side of the smoke-generating source, but a small portion of the smoke moves upward and beyond the control range of the air barrier and flows to the other side (00:15, 00:18). As the air curtain promotes the indoor airflow rate in the room, it makes the smoke flow back to the laser light sheet in a several minutes after flowing quickly to other places (00:35), together with the gravitational settling of the smoke itself, the smoke can basically settle to the floor within a minute under the action of the air flow generated by the fans (01:00).

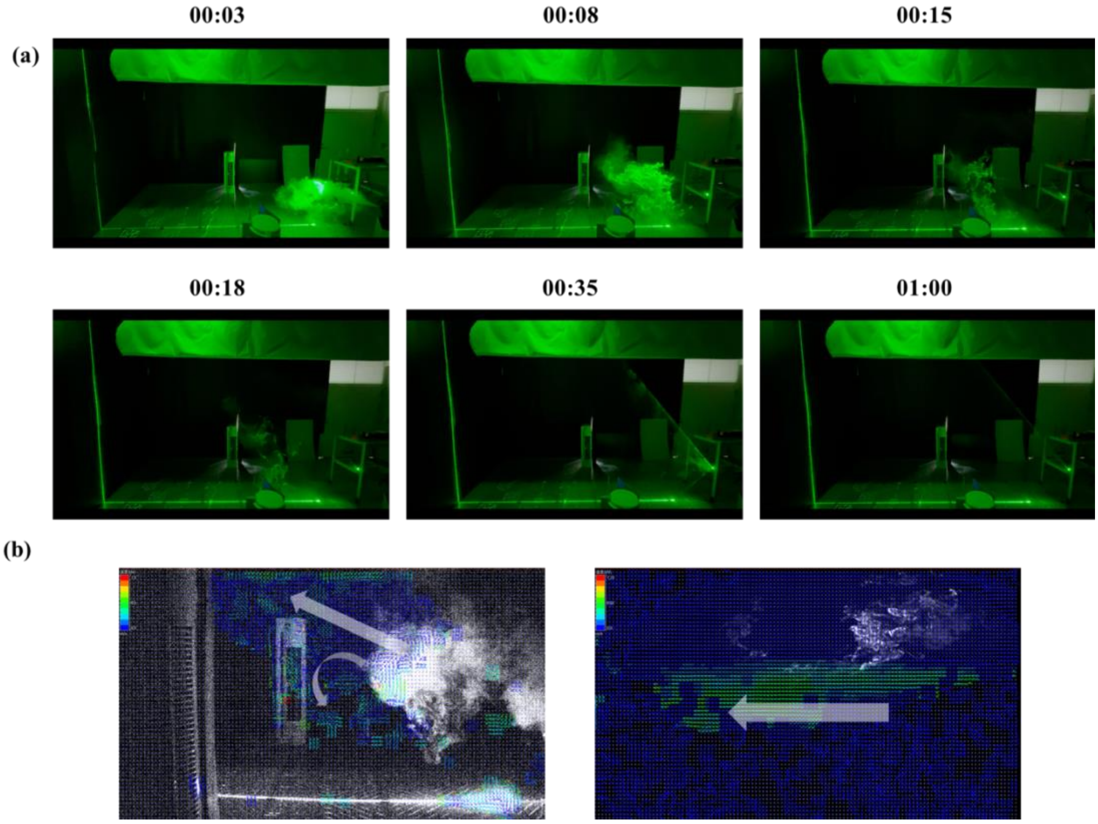


Fig. 4- 20 The blocking effect of air curtain in a middle-level speed: (a) the smoke diffusion changes during 1 min; (b) smoke movements in vertical and horizontal direction.

The same situation happened when the air curtain was set to a middle-level wind speed, and a faster flow of smoke was observed in the experiment.

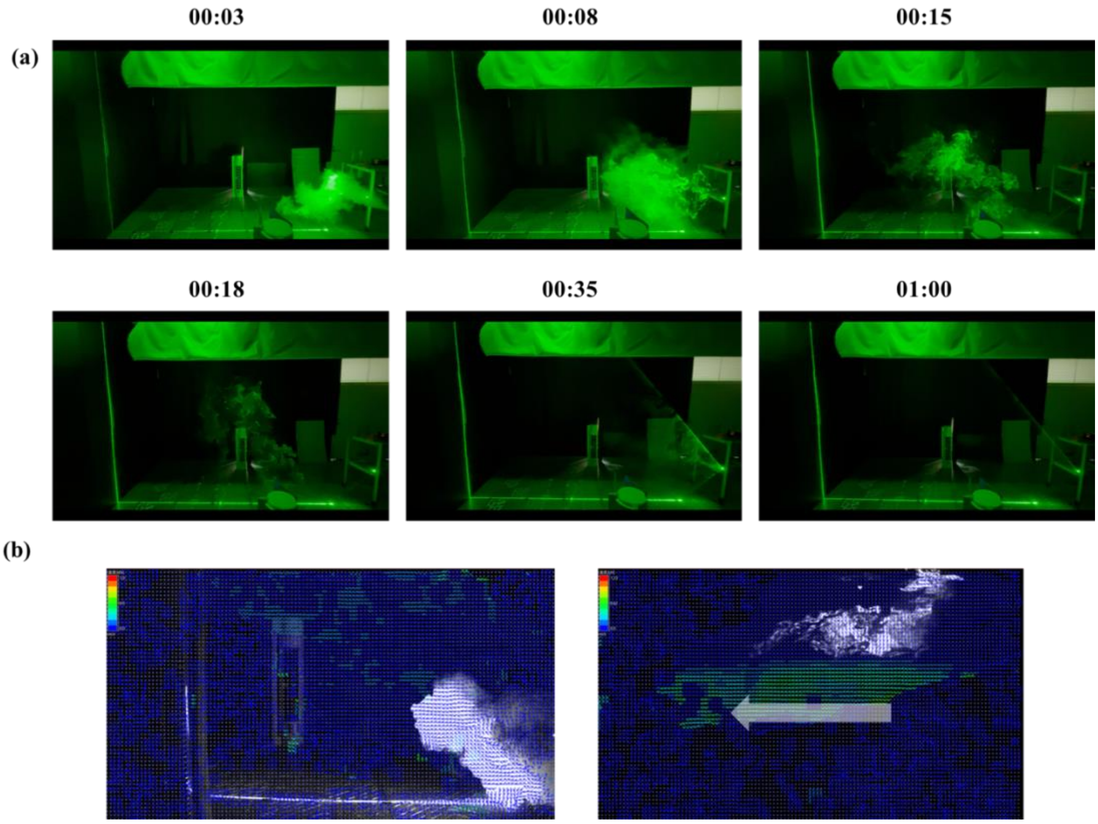


Fig. 4- 21 The blocking effect of air curtain in a high-level speed: (a) the smoke diffusion changes during 1 min; (b) smoke movements in vertical and horizontal direction.

When the wind speed was accelerated to 10 m/s, it appeared that more smoke was carried by the fast airflow to the other side, which indicates that the faster the wind speed the better the blocking effect is not in the context of blocking small size and light weight aerosols by air barriers.

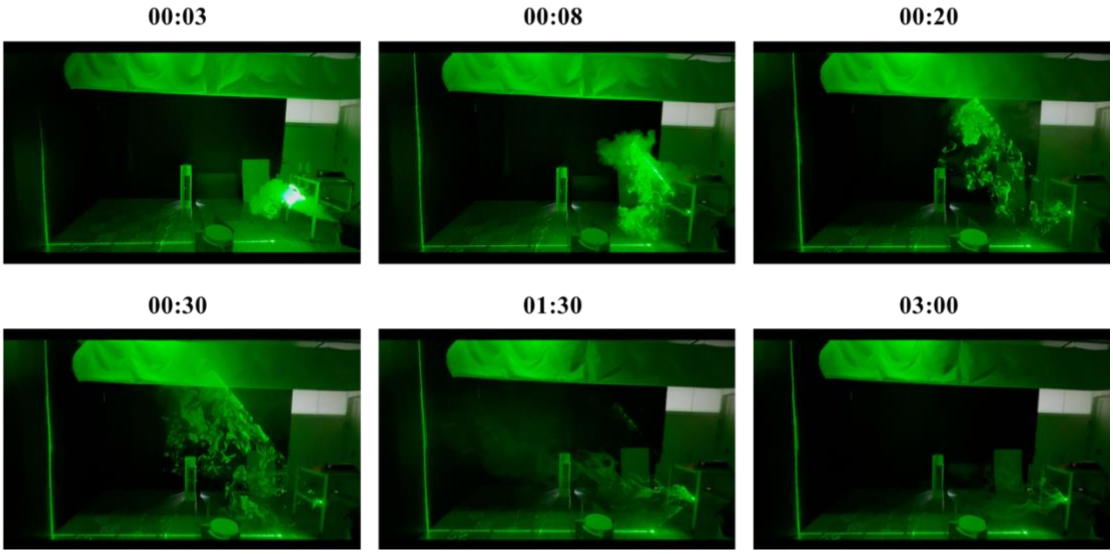


Fig. 4- 22 The smoke diffusion changes when the fans were turned off.

Compared to the experiments that the fans were turned on, when the fans were not open, the flow rate of smoke was significantly slower, reached the position of air curtain at 20 second (00:20); spread more widely in the room (00:30, 01:30) and stayed in the indoor air for a longer period of time, with the smoke still floating in the air after 3 minutes (03:00).

By comparing the PIV observations with or without the fans open, it indicates that the air barrier formed by fans is effective in blocking the diffusion of droplets of about 10 μm.

(2) The effect of suction capacity:

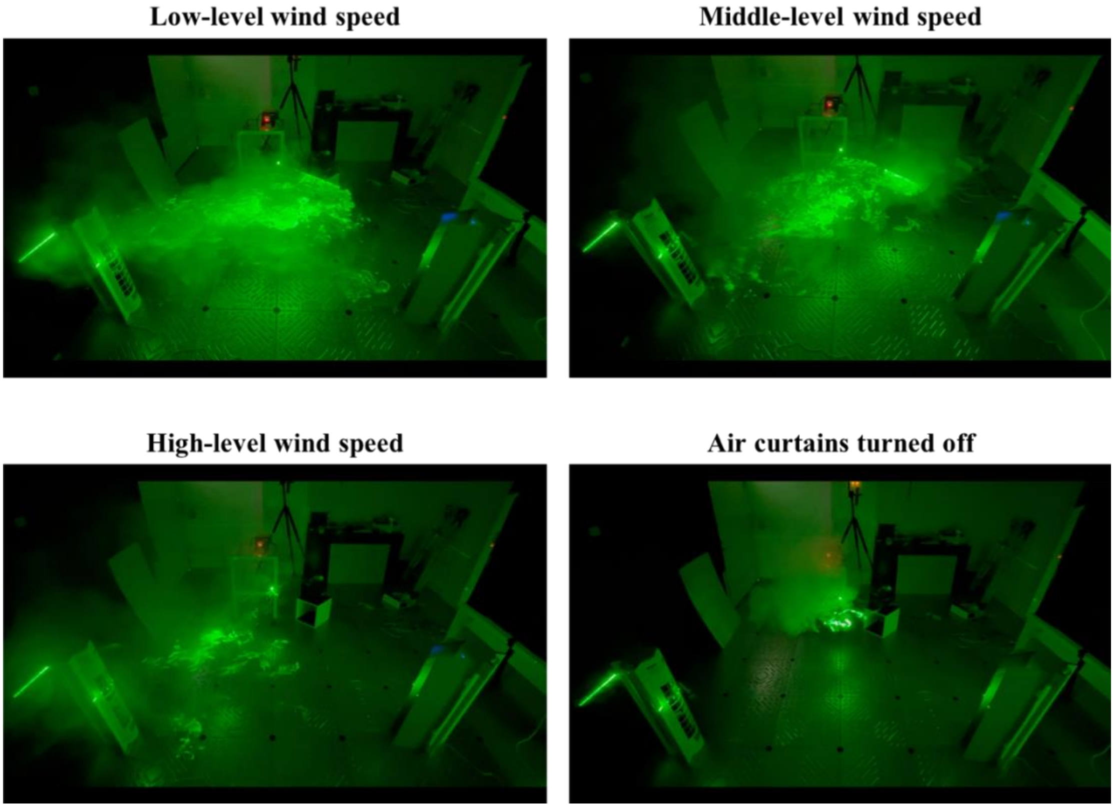


Fig. 4- 23 The flow direction of smoke at 00:08.

As can be seen in Fig. 4- 23, when the air curtain was set at low, middle and high-level wind speeds, and invisible air barrier was formed between these two fans. And due to the lack of inhalation capacity of the second fan, a large amount of smoke was blown around the second fan by the airflow emitted from the first fan, especially when the first fan was at high wind speed, the performance of air curtain to control the smoke diffusion was the worst.

At the same time, it was also observed that the smoke spreads to both sides of the air barrier when the smoke moves with the airflow between the two fans, which is same to the CFD simulations.

Fig. 4- 24 in other observation direction also shows that the flow of smoke is mainly controlled by the airflow emitted from the first fan due to the lack of suction capacity of the second fan. And due to the height restriction of the fan, it is limited from sucking smoke from high places.

Therefore, it is foreseeable that in the process of preventing the spread of droplets, it is necessary to increase the suction capacity and the area of the suction port of the fan that is responsible for the suction function.

Fig. 4- 24 The smoke diffusion at 4 second when the wind speed of first fan was low-level.

(3) simulated in CFD:

The fans used in the PIV experiment were imported into CFD, and simulated the diffusion path of the droplets exhaled by the teacher when the wind speeds of the first fan was set up to low-level. Different from the simulations in **Chapter 4. 3**, the second fan here does not have a HEPA filter installed. The rest of the boundary conditions remained unchanged.

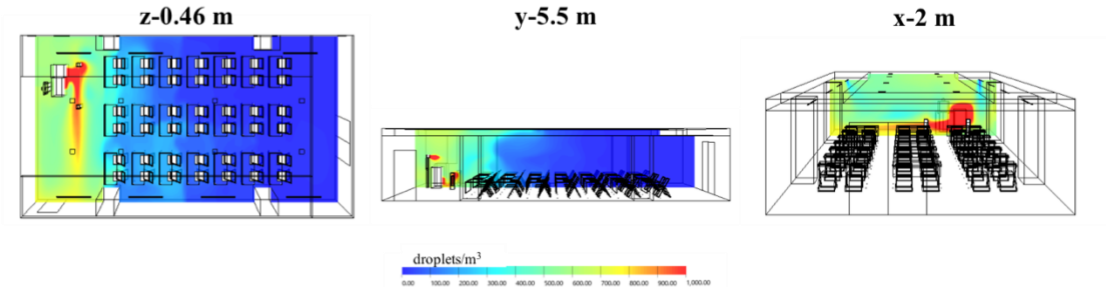


Fig. 4- 25 Simulation result of air curtain in a low-level wind speed.

Similar to the observation results in the PIV experiment, such two fans can guide the flow direction of droplets to some extent, but due to the restrictions of the suction capacity and the height of the suction port, they cannot well prevent the droplets from spreading into the classroom.

In order to find the reason for the poor performance of the droplet blocking effect in this case, the following simulations also were conducted in CFD:

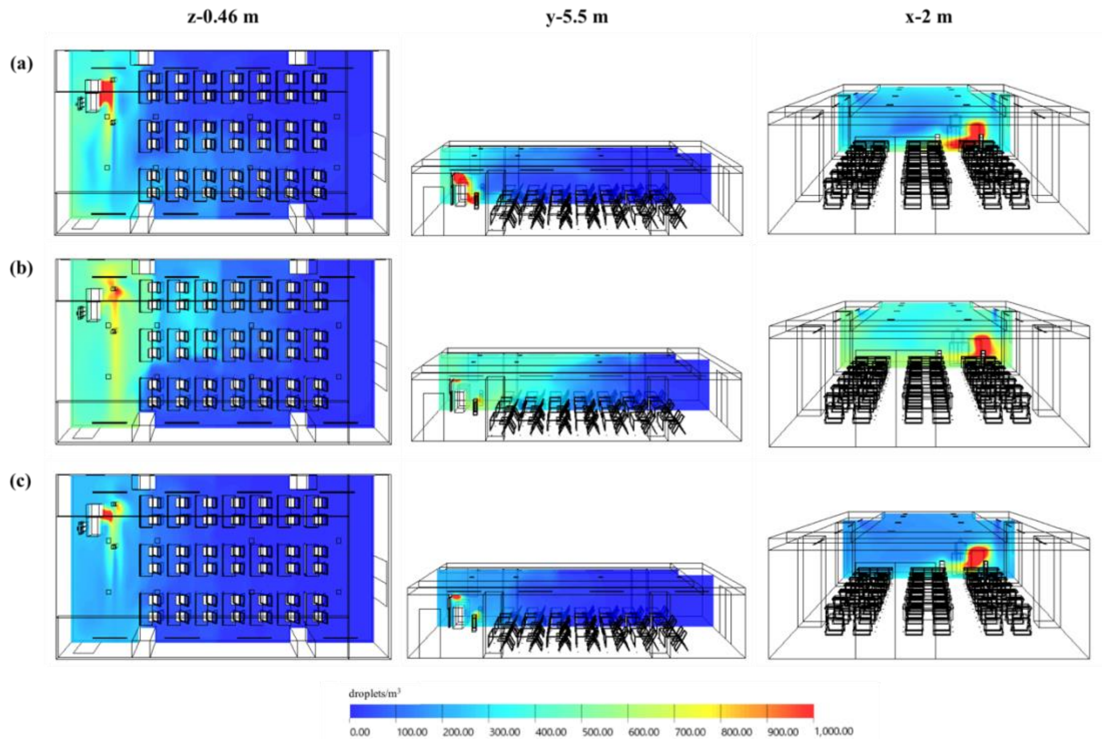


Fig. 4- 26 Simulation results of air curtain: (a) added HEPA filter in the second fan; (b) enhanced the wind speed of the second fan to 5 m/s; (c) added HEPA filter and enhanced the wind speed to the second fan at the same time.

When the suction capacity of the second fan differs greatly with the first AC, which is responsible for blowing out fast air flow, adding a HAPA filter can only filter the droplets that is sucked into the second fan, it is disable to catch more droplets (Fig. 4- 26 (a)). On the other hand, if it is only to improve the suction capacity of the second fan, the inhaled droplets will still return to the room if it is left untreated (Fig. 4- 26 (b)). However, if the two improvement measures are combined, it will be found that the air curtain can well guide the flow of the droplets and reduce the spread of droplets (Fig. 4- 26 (c)).

Summary:

Through the use of real fans which are similar to those in the simulations, visualized the blocking effect of air curtain on droplets in PIV experiments.

The following conclusions can be summarized:

1) All of the low, middle and high-level wind speeds of the fans purchased in this study can form an air barrier between the two fans to prevent excessive smoke from spreading to the other side of the smoke generated. However, under the premise that the suction capacity of the second fan is insufficient, if the first fan emits a too fast airflow, it will cause more smoke to spread to the other side of the air barrier;

2) according to the CFD simulation results, the two fans used in the PIV experiments are not enough to block the droplet spreading during class, but combined with the simulation results, enhancing the suction capacity of the second fan, increasing the inhalable height of the second fan, and the use of the HEPA filter may improve the performance of the air curtain to block the spread of droplets.

4. 4. 3 Optimization of air curtain

In order to find out the most suitable way to use air curtain for this lecture room, many forms of fan usage were simulated in CFD. And by using "Domain Specification" tool, the total amount of droplets was calculated for each form of air curtain. The domains are divided in the same way as the simulations that there were no fans were placed.

The effect of the fan – fan distance:

According to the initial boundary conditions, all the conditions remain the same, except that the distance between 2 fans is changed to 3 m and 2 m.

	NO. 1	NO. 2	NO. 3
The distance between 2 fans	5m	3m	2m
droplets amount	1309381	1136478	1010554

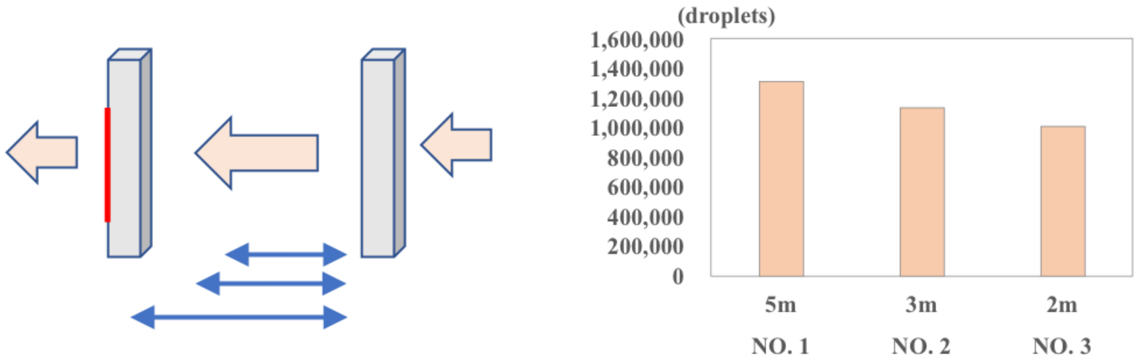


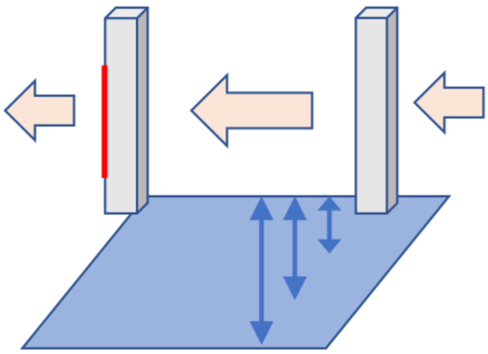
Fig. 4- 27 The amount comparison of droplets by the fan-fan distance.

Statistical results show that under the condition the wind speed is 4 m/s, the total droplets amount tend to lower when the distance between 2 fans is gradually reduced. Although the 2-meter air barrier do not completely cover the whole area of the podium, it did have the best effect on blocking droplets.

The effect of fans – floor distance:

Based on the simulation result about the effect of the distance between 2 fans, the discussion continues to the effect of fans' height from the floor with the distance between 2 fans is 2 meters. All the conditions remain the same, except that the height of the fan is changed to 0.5 m and 0 m respectively, which means the fans are placed on the floor directly, to carry out the simulation.

	NO. 3	NO. 4	NO. 5
The height from the floor	1m	0.5m	0m
droplets amount	1010554	1068821	1405807



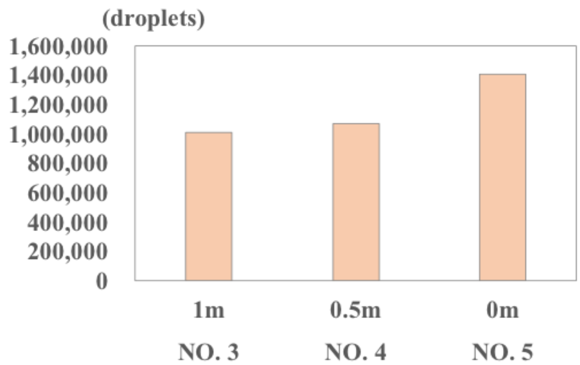


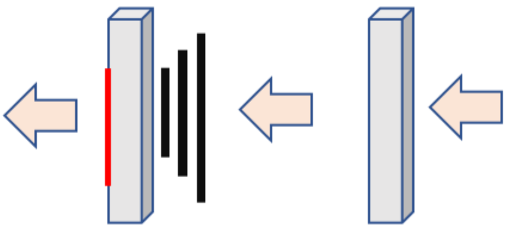
Fig. 4- 28 The amount comparison of droplets by fans - floor distance.

Statistical results show that the lower the placement height of the fan, the less effective on blocking droplets when the size of the fan is about 0.8 meters. Combined with the simulation results show that the blocking effect looks good when 0.8 meters of fans placed at 1 meter above the floor, and the central part of the outlet is about the same to the height of the doll's mouth.

The effect of fans' length:

On the basis of the distance between 2 fans is set to 2 m, the height of fans from the floor is set to 1m, the discussion continues to the effect of fans' length. 4 cases are considered in this study, namely 0.4 m, 1.6 m, 2.4 m and 0.8 m, the initial boundary condition in the simulations. Among them, the 1.6 m and 2.4 m fans have to be placed at a height of 0 m because they are too long. In practice, it is also more convenient to place directly on the floor.

	NO. 6	NO. 3	NO. 7	NO. 8
The length of fans	0.4m	0.8m	1.6m	2.4m
The geometric size of outlets	0.1 x 0.24 m	0.1 x 0.5 m	0.1 x 0.98 m	0.1 x 1.47 m
droplets amount	1405807	1010554	751753	518076



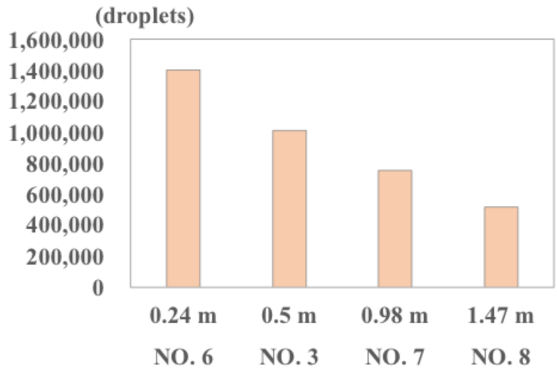


Fig. 4- 29 The amount comparison of droplets by fans' length.

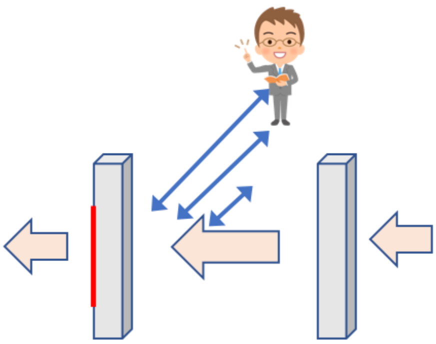
Obviously, the longer the length of fans, the more effective it is in blocking droplets. Because the larger the size of the fan, the area of blowing outlet will be correspondingly larger, and the amount of flowing-out airflow will be increased as well. The rapid airflow blows the droplets-containing air to the second fan, filtered by the HEPA filter and then discharge to the lecture room, which plays an impressive role in reducing droplet amount in the lecture room.

On the other hand, although the fan with a length of 2.4 m has the best effect of blocking the spread of droplets, but imagine that there are 2 obstacles in the classroom almost as high as the ceiling will definitely affect the attention of students and teachers, and affect the teaching. Therefore, this study believes that the length of 1.6 m is more appropriate.

The effect of air curtain – teacher distance:

Based on the simulation conditions of NO. 8 (the distance between 2 fans is 2 meters, the height from floor is 0 m, the length of fans is 1.6 m), the discussion continues to the effect of the distance between fans and teacher, it means how far away from the teacher should the fans be placed. 3 cases are considered in this study: 0.9 m, 2.4 m and 1.4 m, the initial distance between fans and teacher.

	NO. 9	NO. 7	NO. 10
The distance between fans and teacher	0.9m	1.4m	2.4m
droplets amount	760058	751753	1060063



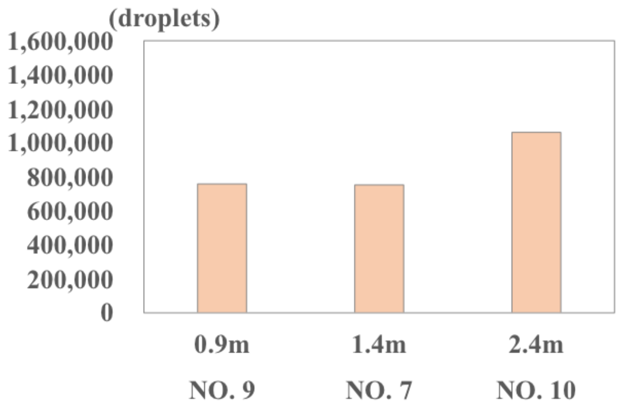


Fig. 4- 30 The amount comparison of droplets by air curtain - teacher distance.

In the CFD model, the 2.4 m distance from the teacher to fans, the fans almost meet the first row of students' seats, so it can be assumed that the simulation NO. 11 has a higher total amount of droplets is because the close distance between fans and student seats making part of the droplets escape from the airflow streamline between the two fans and spread to the side of the students during the airflow is carrying the droplets from the first fan to the second fan. Fig. 4- 31 shows that at 1 hour 50 min, the part of droplets blew out by the first fan did not be sucked into the second fan, instead, they are spread to the sides of the fans.

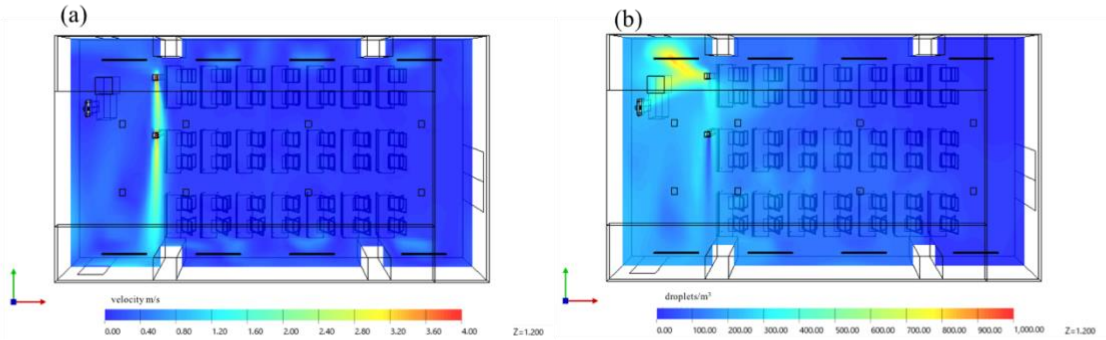


Fig. 4- 31 Simulations of NO. 11: (a), the velocity of airflow blew by fans at 01: 50; (b), the droplets distribution at 01:50.

The statistical results show that there is rarely difference between the distance of 0.9 m and 1.4 m, but considering the situation that the droplets may escape from the airflow streamline during the airflow carrying the droplets from the first fan to the second fan. To reduce the large number of droplets escaping, it may be better to a distance from the fans to the teacher. Therefore, this study believes that the distance of 1.4 m between fan and teacher is more appropriate.

The effect of fans' wind speed:

A wind speed of 4 m/s has been used to fans to block droplet diffusion throughout all the simulations. In order to understand the effect of fans' wind speed on forming an air barrier to block droplet diffusion, this study also supplemented the simulations of air curtain's performance at different wind speeds. In addition to the 4 m/s, wind speed of 2 m/s, 6 m/s and 8 m/s were also simulated. The other boundary conditions are the same as simulation NO.7.

	NO. 11	NO. 7	NO. 12	NO. 13
wind speed	2 m/s	4 m/s	6 m/s	8 m/s
droplets amount	1213353	751753	571635	467020

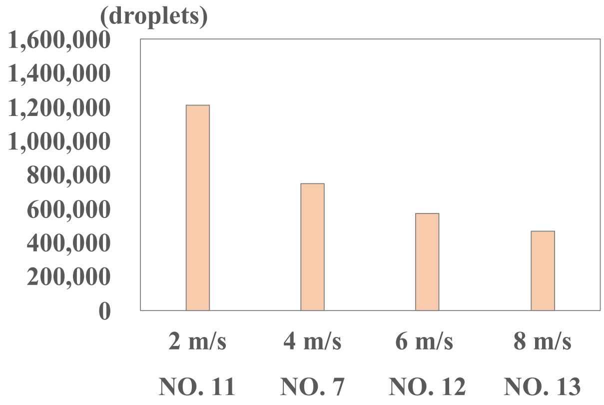


Fig. 4- 32 The amount comparison of droplets by air curtains' wind speed.

From the statistic (Fig. 4- 32), there is no doubt that the faster the wind speed is, the smaller droplets amount spreading to the student side, which means that the air barrier formed between 2 fans is more effective in blocking the spreading of droplets.

Summary of air curtain optimization:

Divide the number of particles diffused to the student side by the total amount of generated particles, the droplet capture of each air curtain can be calculated.

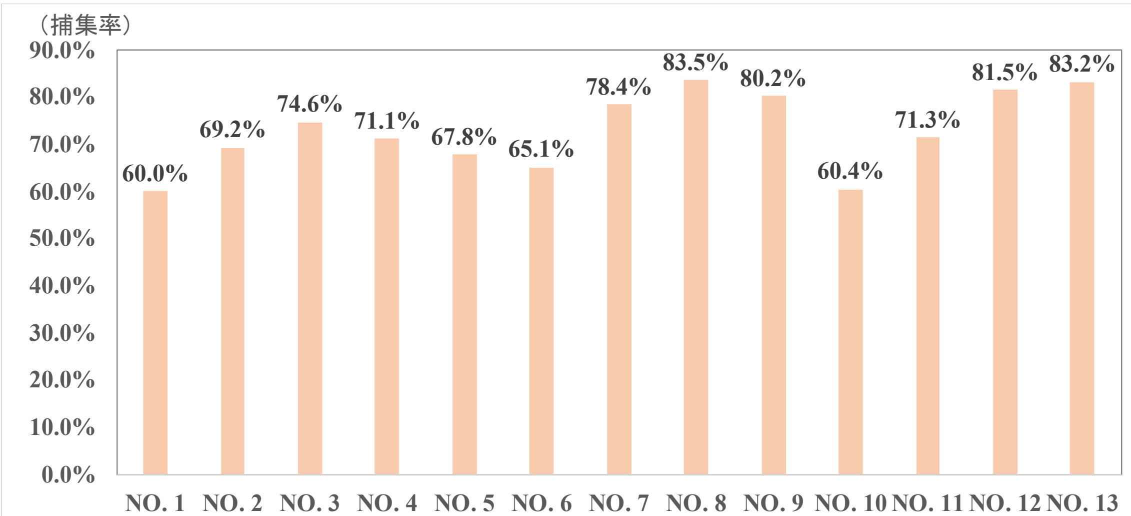


Fig. 4- 33 The droplet capture rate of each air curtain.

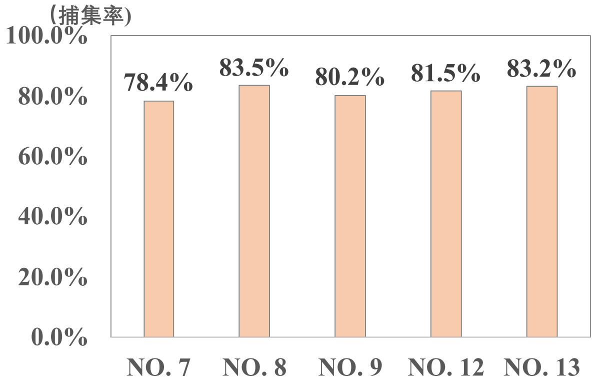


Fig. 4- 34 Air curtains with good droplet capture performance.

Fig. 4- 33 shows the whole droplet capture performance of each air curtain, and among them, No. 7, NO. 8, NO. 9, NO. 12 and No. 13 performed better, their capture rate was about 80%.

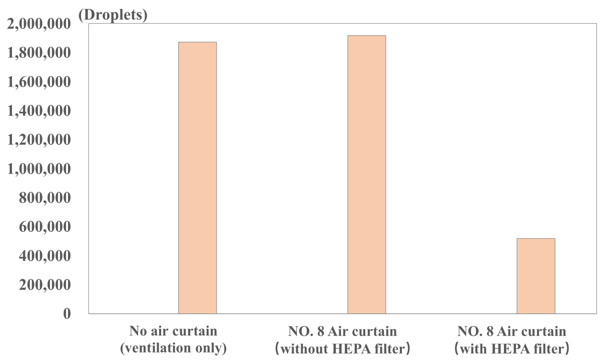


Fig. 4- 35 The comparation between ventilation and NO. 8 air curtain.

Comparing the number of droplets in the No. 8 air curtain with the highest capture rate with the number of droplets in the lecture room when only mechanical ventilation is in operation, it can be found that the number of droplets in the lecture room seems to be almost the same when there is no air curtain and when there is an air curtain (NO. 8), or it can be said even higher. The reason for this is that without a HEPA filter, the air curtain draws in the surrounding air with droplets and then blows the air into the room, and the rapid airflow of the air curtain expands the spread of droplets. However, when there is a HEPA filter inside the air curtain, the situation that the air curtain accelerates the spread of droplets is much reduced, and the number of droplets in the room also drops sharply.

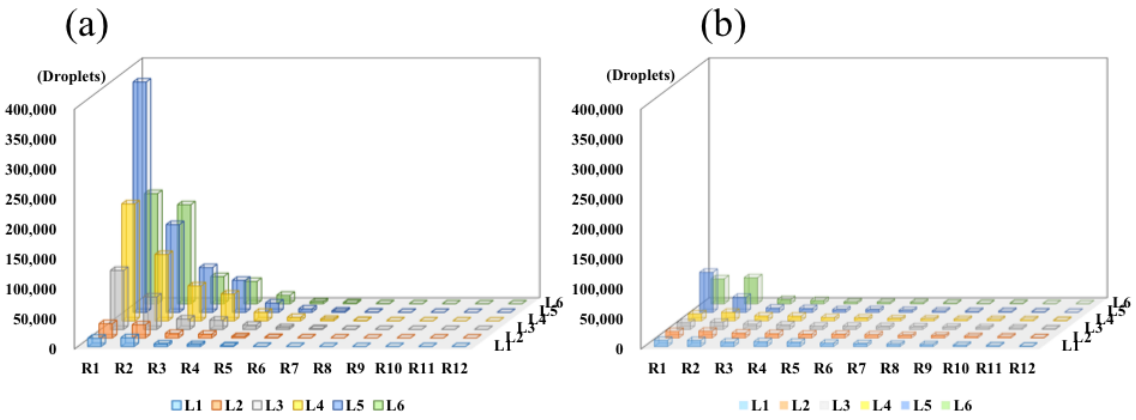


Fig. 4- 36 The droplets number of each domain: (a) no air curtain (Fig. 4-16); (b) NO. 8 air curtain with HEPA filter.

Obviously, when the No. 8 air curtain is in operation, the distribution of droplets in the room has changed astonishingly compared with the room with only mechanical ventilation. Especially in the area where R4 and L5 intersects (the actual position is shown in Figure 4- 37), this place has the closest linear distance to the teacher. When the air curtain is activated, the number of droplets at this position has significant reduction.

Fig. 4- 37 The position where domain R4 and L5 intersects.

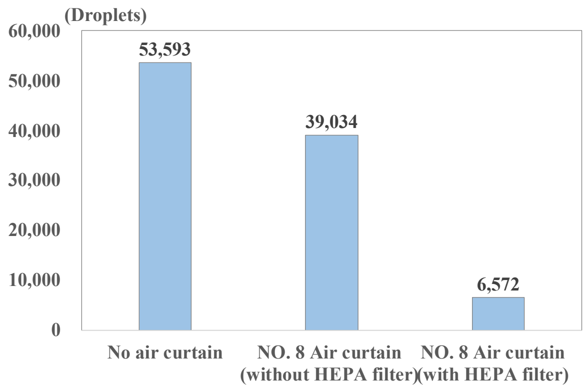


Fig. 4- 38 The droplets amount comparation among No air curtain and NO. 8 air curtain with or without HEPA filter at the position where domain R4 and L5 intersects.

Furthermore, comparing the droplets amount of no air curtain and NO. 8 air curtain with or without air curtain (Fig. 4- 38), it demonstrated that in the place closest to the teacher, the air curtain can prevent a part of the droplets from crossing the air barrier, and if the droplet removal effect of the filter is added, the performance of the air curtain to block the spread of droplets will be further enhanced. At the same location, compared with no air curtain, the No. 8 air curtain with a filter reduces the amount of droplets in the place by 87.7%.

The following table (table 4- 2) shows the statistics of the number of droplets diffused to the students' side for each air curtain setting condition in 13 + 1 simulations.

	Size	Fan - fan distance	Fans - floor distance	Length	Size of outlet	Air curtain - teacher distance	Wind speed
NO. 1	0.185 x 0.185 x 0.818 m	5 m	1 m	0.818 m	0.1 x 0.5 m	1.4 m	4 m/s
NO. 2	0.185 x 0.185 x 0.818 m	3 m	1 m	0.818 m	0.1 x 0.5 m	1.4 m	4 m/s
NO. 3	0.185 x 0.185 x 0.818 m	2 m	1 m	0.818 m	0.1 x 0.5 m	1.4 m	4 m/s
NO. 4	0.185 x 0.185 x 0.818 m	2 m	0.5 m	0.818 m	0.1 x 0.5 m	1.4 m	4 m/s
NO. 5	0.185 x 0.185 x 0.818 m	2 m	0 m	0.818 m	0.1 x 0.5 m	1.4 m	4 m/s
NO. 6	0.185 x 0.185 x 0.4 m	2 m	1.4 m	0.4 m	0.1 x 0.24 m	1.4 m	4 m/s
NO. 7	0.185 x 0.185 x 1.6 m	2 m	0 m	1.6 m	0.1 x 0.98 m	1.4 m	4 m/s
NO. 8	0.185 x 0.185 x 2.4 m	2 m	0 m	2.4 m	0.1 x 1.47 m	1.4 m	4 m/s
NO. 9	0.185 x 0.185 x 1.6 m	2 m	0 m	1.6 m	0.1 x 0.98 m	0.9 m	4 m/s
NO. 10	0.185 x 0.185 x 1.6 m	2 m	0 m	1.6 m	0.1 x 0.98 m	2.4 m	4 m/s
NO. 11	0.185 x 0.185 x 1.6 m	2 m	0 m	1.6 m	0.1 x 0.98 m	1.4 m	2 m/s
NO. 12	0.185 x 0.185 x 1.6 m	2 m	0 m	1.6 m	0.1 x 0.98 m	1.4 m	6 m/s
NO. 13	0.185 x 0.185 x 1.6 m	2 m	0 m	1.6 m	0.1 x 0.98 m	1.4 m	8 m/s
NO. 8 (no HEPA filter)	0.185 x 0.185 x 1.6 m	2 m	0 m	2.4 m	0.1 x 1.47 m	1.4 m	4 m/s

Table 4- 2 Summary of setting conditions of each air curtain.

4. 5 Summary

Under the pandemic, in order to provide a safe indoor air environment for teachers and students during face-to-face lectures, this research investigated the air environment of a real classroom, and tried to propose a low-cost, easy-to-install and move local ventilation system.

The air environment of the target room indicated that the SVE 6 in the room is not uniform and the distribution of CO_2 concentration is highly dependent on the number of people, which are expected to play a role when people are considering where the CO_2 sensor should be placed.

Compared with installing acrylic panels on the podium to block the spread of droplets, this research proposed a more flexible and low-cost solution - air curtains.

PIV experiments have actually proved that an air barrier can be formed between two side-blow fans, which were able to have a blocking effect on smoke. PIV experiments found that the greater the wind speed, the fans can form a winder air barrier, but under the situation that the second fan has insufficient suction capacity, its droplet blocking effect will not be enhanced, instead to accelerate the spread of droplets. It shows the importance of enhancing the suction capacity of the second fan, increasing the inhalable height of the second fan, and the use of the HEPA filter may improve the performance of the air curtain to block the spread of droplets.

At the same time, through CFD calculation, different styles of air curtains were simulated to find an air curtain with good droplet blocking effect and removal effect in the classroom. Ultimately, the setting mode of the fans are 2 meters apart, the length of fans is 2.4 meters, and the distance of teacher – air curtain kept in 0.9 ~1.4 meters, which would have a relatively good blocking effect. Similar to the PIV experiment, the CFD calculations also showed that in order to better block the spread of droplets, using a HEPA filter to capture the droplets restricted by the air curtain will make the air curtain show a better performance.

Chapter 5 Conclusion

5. 1 Conclusions

In this study, the airflow environment in laboratories and lecture rooms were investigated, which are shared by multiple people in universities, through calculations and experiments. In lecture rooms where countermeasures against Covid-19 are required, this study clarified the necessity of quantitative understanding the distribution of air contamination, and the effectiveness of installing local air barriers as a measure to prevent the virus spread. Thus, the study of ventilation was shown to be an important and effective methodology that contributes to environmental safety in university research environments, in that it can quantitatively visualize invisible risks such as air quality and help to understand the current situation and take countermeasures. From these results, the study on ventilation was shown to be an important and effective methodology to contribute to environmental safety in university research environments which can quantitatively visualize invisible risks such as air quality and help to understand the current situation and take countermeasures.

5. 2 Future developments

This study took the university indoor air environment as the precondition, selected representative university laboratory and university lecture room as the research objects, studied the influence of indoor airflow on the diffusion of chemical substances in the university laboratory and the influence of indoor airflow on the droplet diffusion in the university lecture room. In sight of that there are still some shortcomings in this study, if the following can be improved in the future, it is foreseeable that it will improve knowledge of the indoor environment safety of universities and fully fulfill the education and research function of universities under the condition that the pandemic could last long-term.

Firstly, this study only measured the impact of local air ventilation on the diffusion of chemical substances in the laboratory. It is expected that future research can break through the constraints of experimental equipment, quantitatively study influence of overall air exchange, the amount of chemicals generated, the time of chemicals generated, the waste liquid tank, and the exothermic equipment on the diffusion of chemical substances.

Secondly, this study proposed a feasible fan setting method in CFD simulation, it is expected that the future research can truly reproduce the same fans as in the CFD simulation and verify its droplet blocking effect in the real lecture room.

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Appendix

(1) The droplets transmission state of the other 7 PCR-positive infections;

(2) The droplets diffusion changes of each air curtain in optimization simulations.

(1) The droplets transmission state of the other 7 PCR-positive infections:

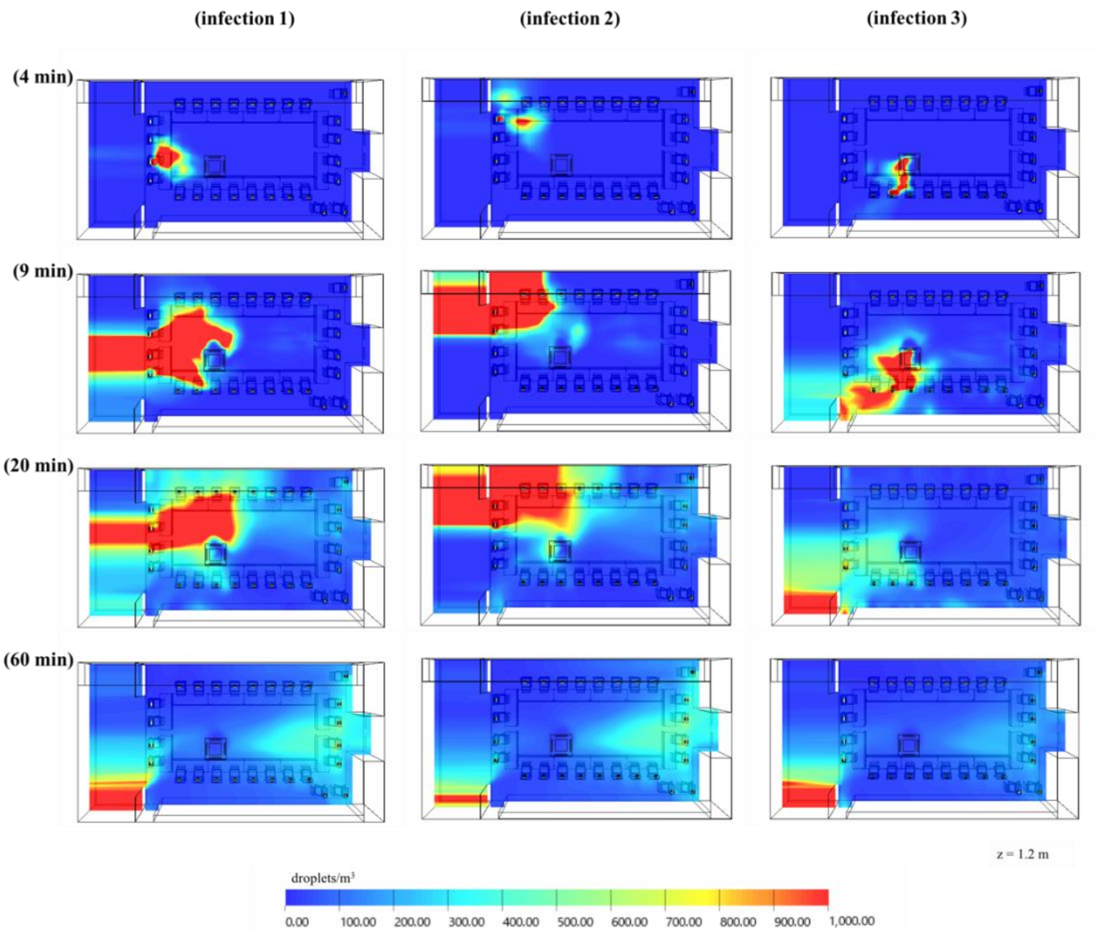

Fig. A- 1 The droplets transmission state of infection 1, infection 2 and infection 3.

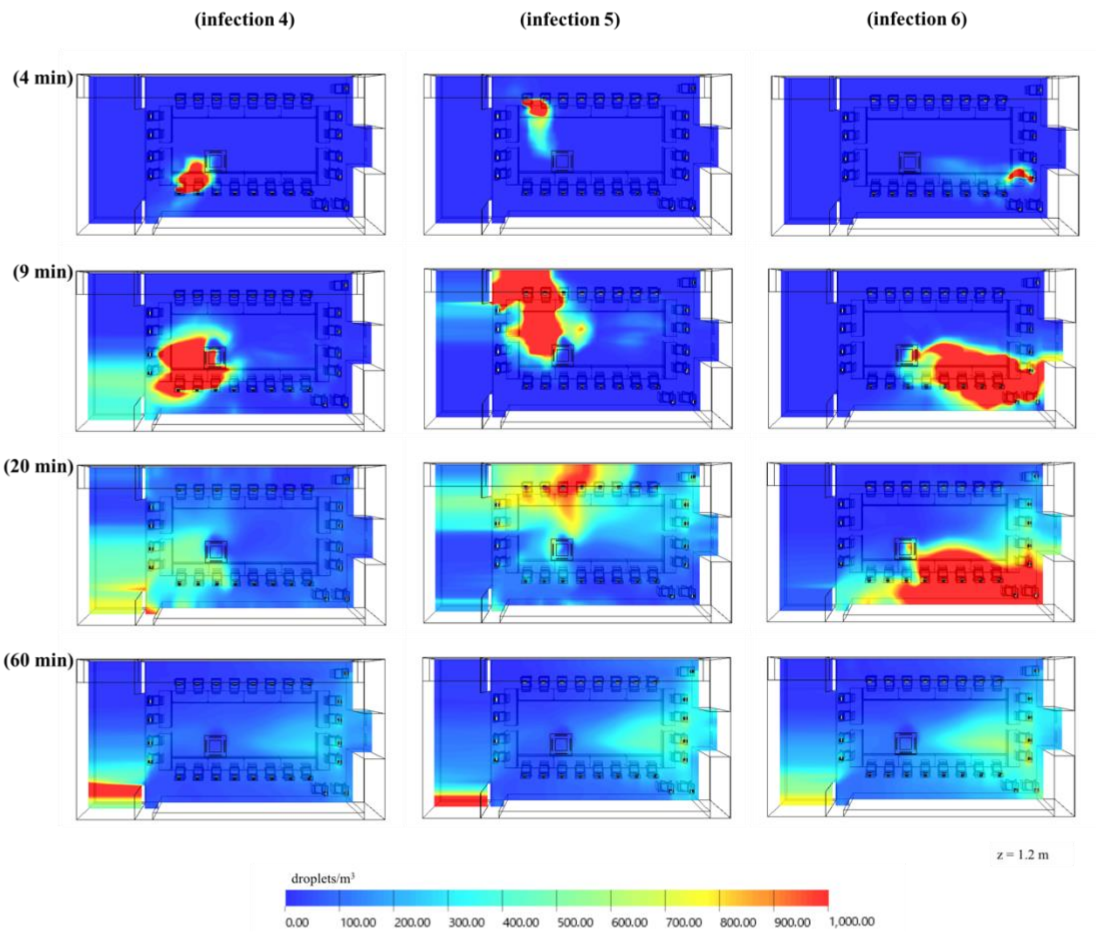

Fig. A- 2 The droplets transmission state of infection 4, infection 5 and infection 6.

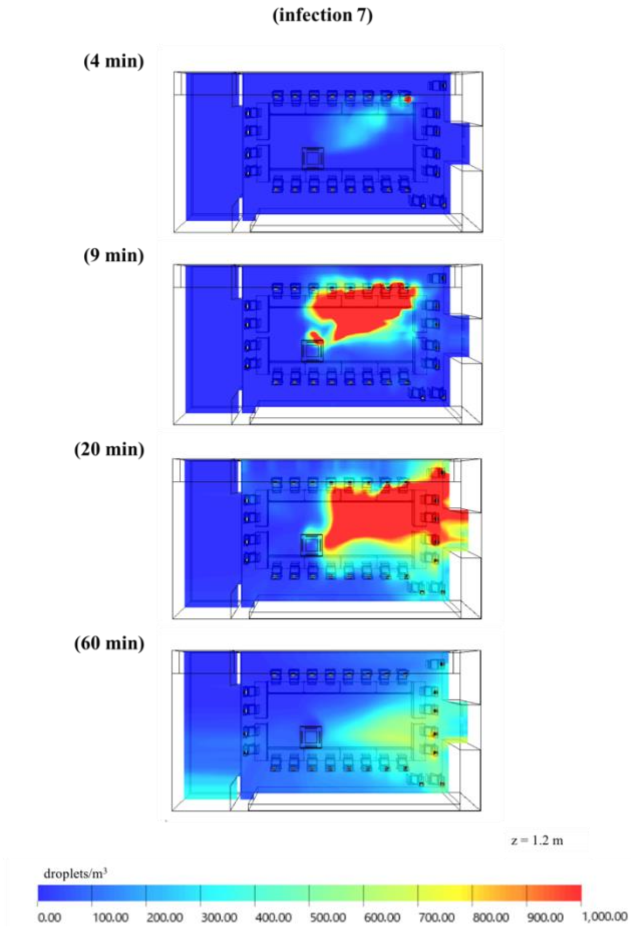

Fig. A- 3 The droplets transmission state of infection 7.

(2) **The droplets diffusion changes of each air curtain in optimization simulations:**

The specific boundary conditions refer to page 78.

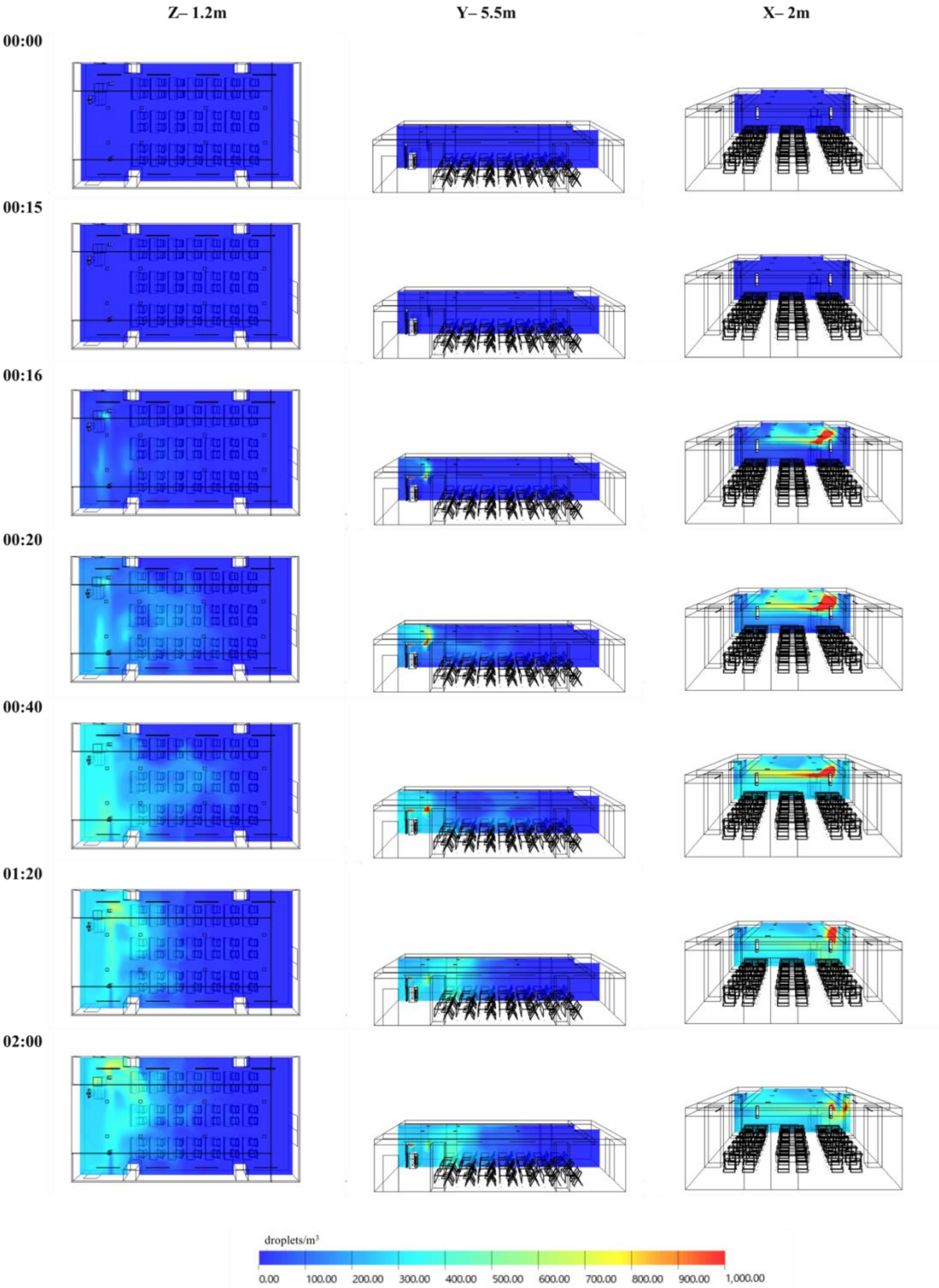

Fig. A- 4 Simulation NO. 1.

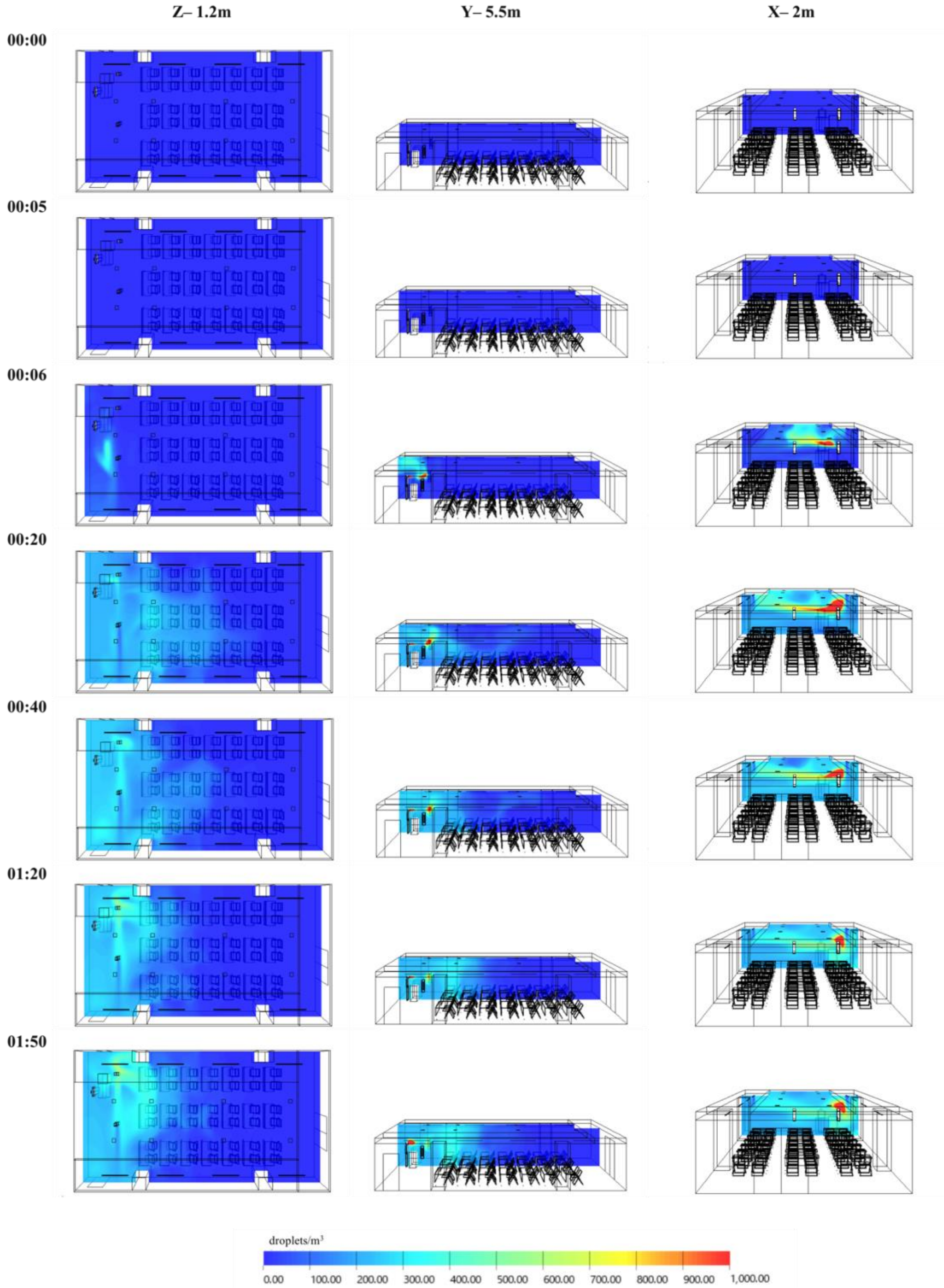

Fig. A- 5 Simulation NO. 2.

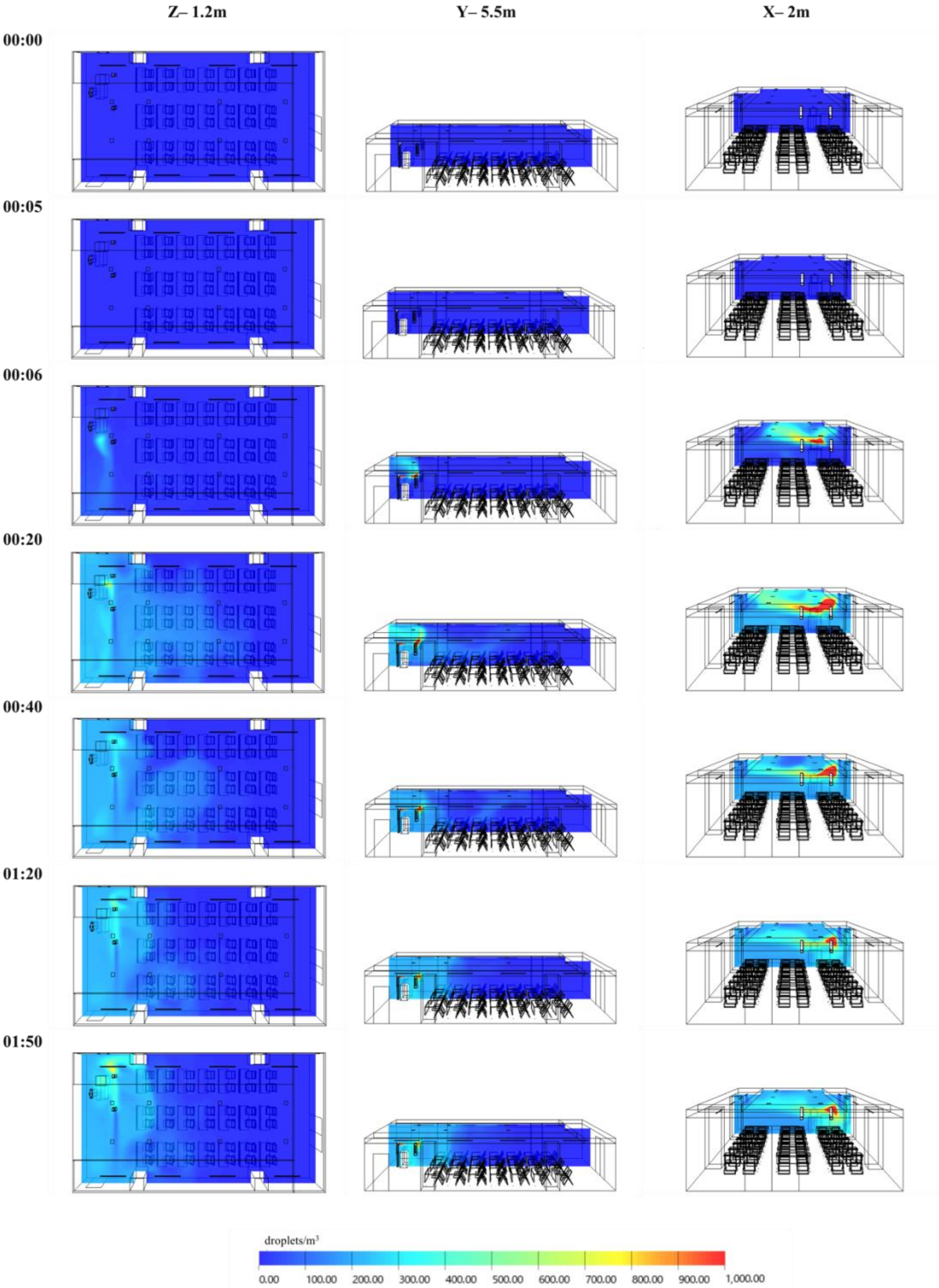

Fig. A- 6 Simulation NO. 3.

The fan - fan distance of simulation NO. 1, NO. 2 and NO. 3 is 5 m, 3 m, and 2 m respectively, from the perspective of the diffusion range, the diffusion range of the air curtain at a fan - fan distance of 2 m is smaller.

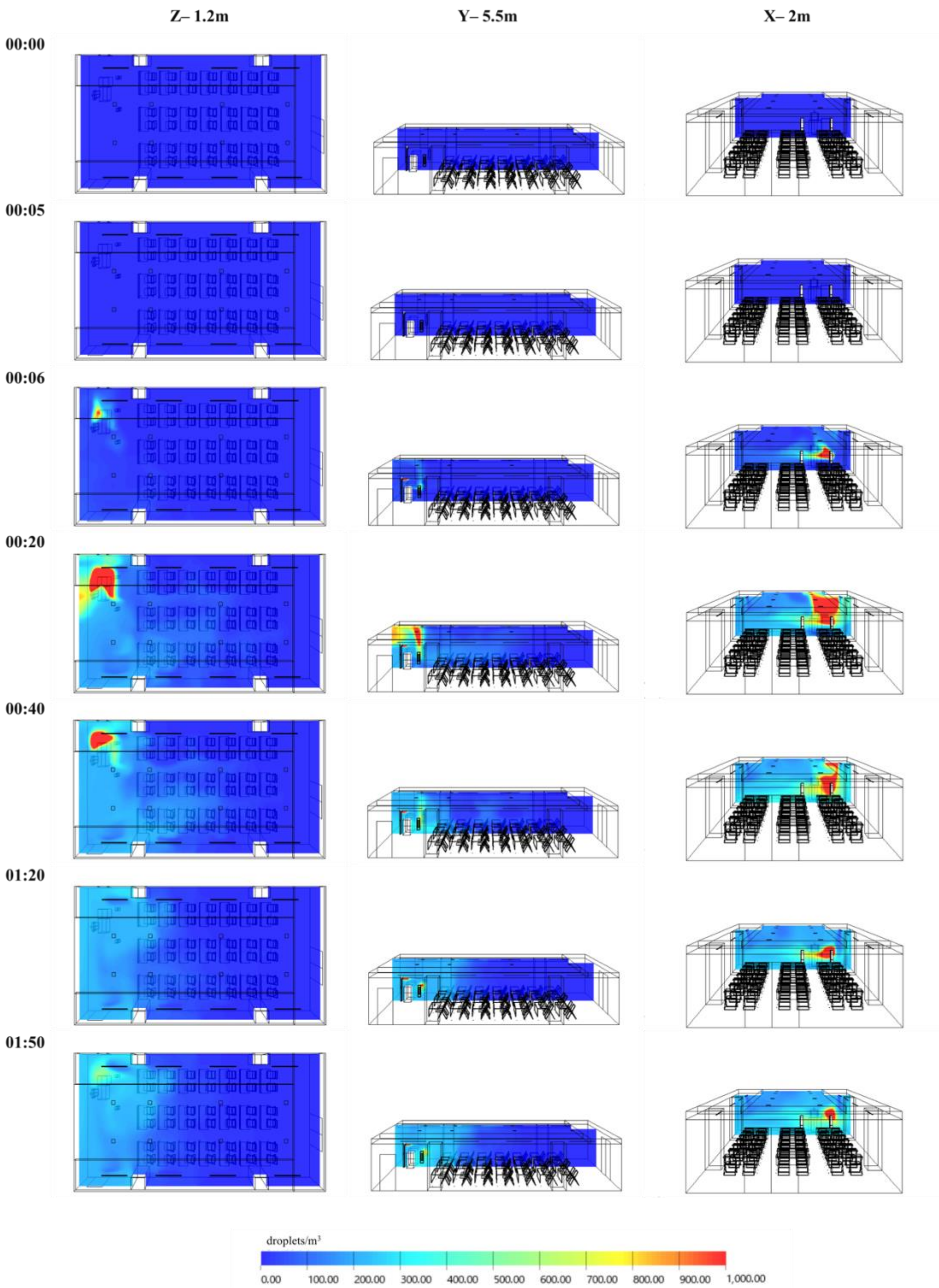

Fig. A- 7 Simulation NO. 4.

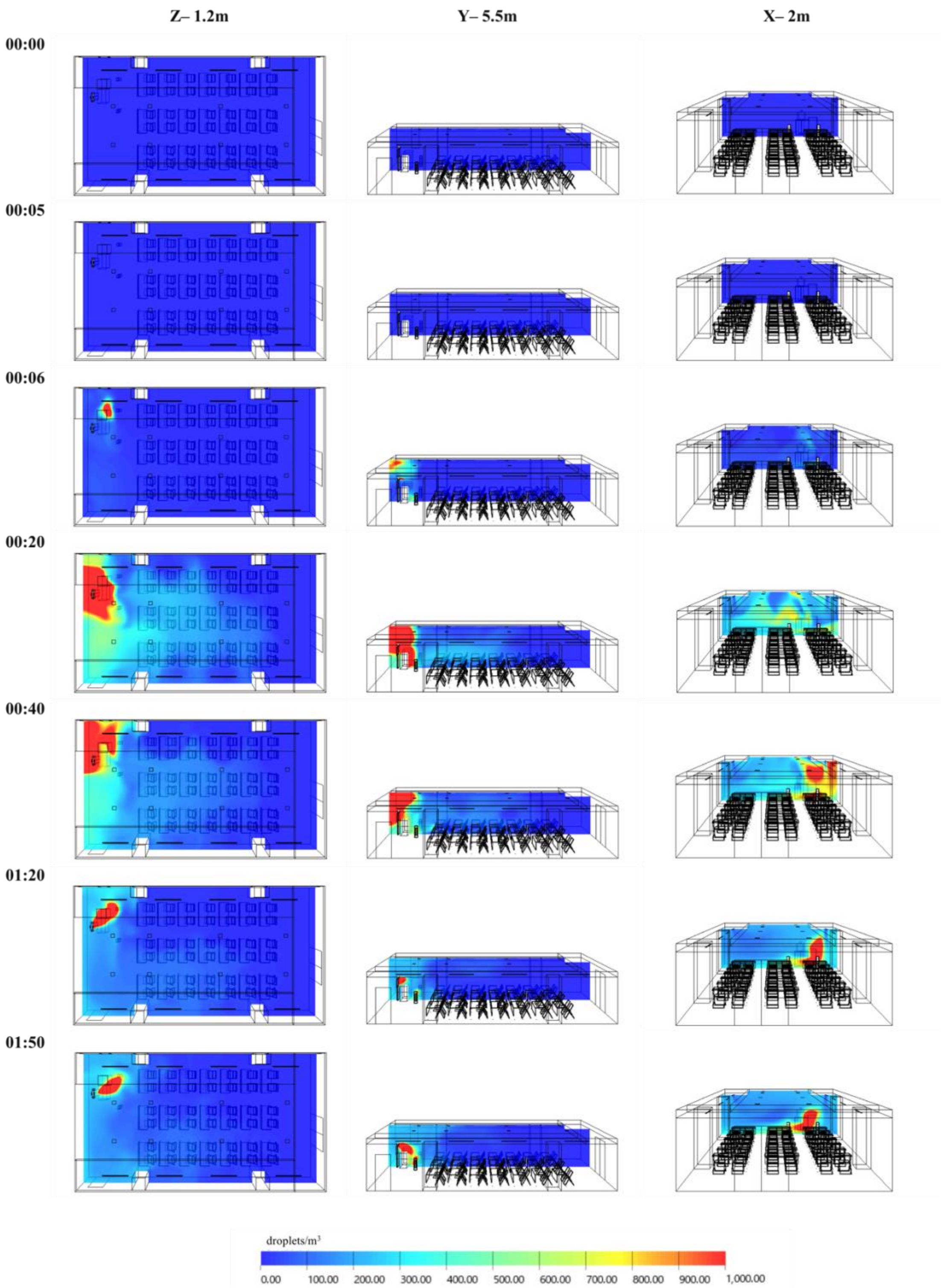

Fig. A- 8 Simulation NO. 5.

The fans - floor distance of simulation NO. 3, NO. 4 and NO. 5 is 1 m, 0.5 m, and 0-m respectively, it can be seen that the air curtain No. 3 whose outlet height is closest to the height of a person's mouth has the best blocking effect.

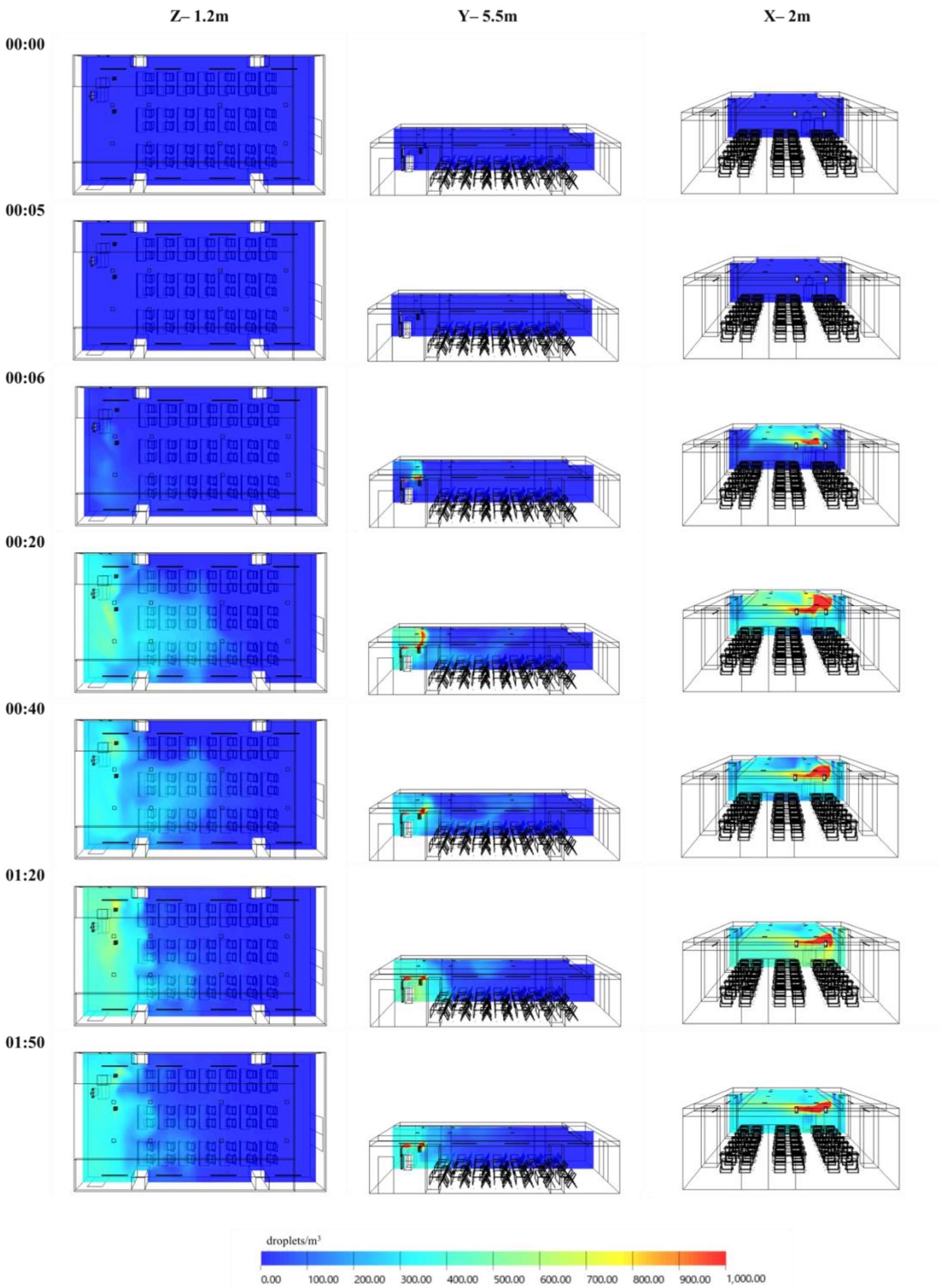

Fig. A- 9 Simulation NO. 6.

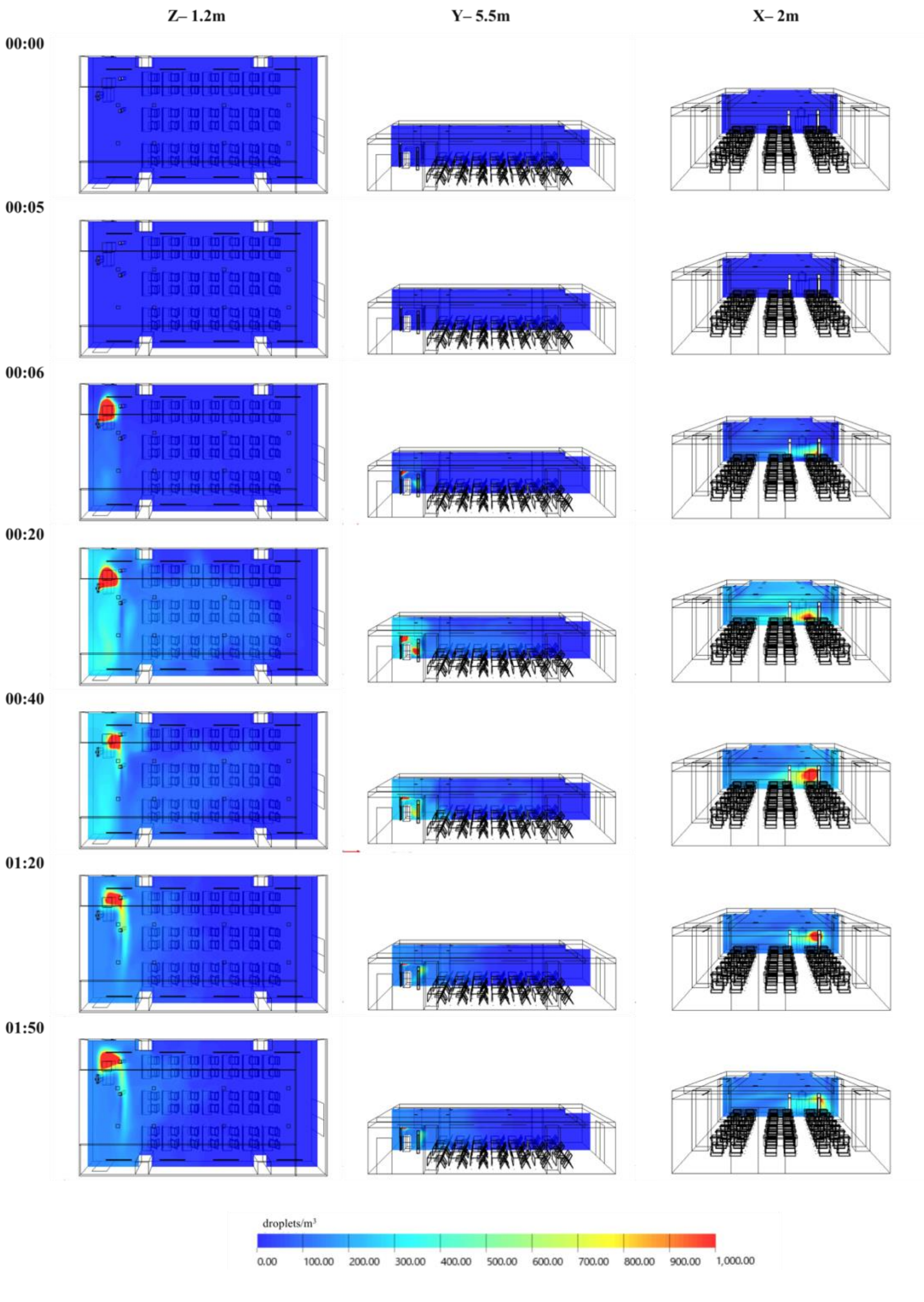

Fig. A- 10 Simulation NO. 7.

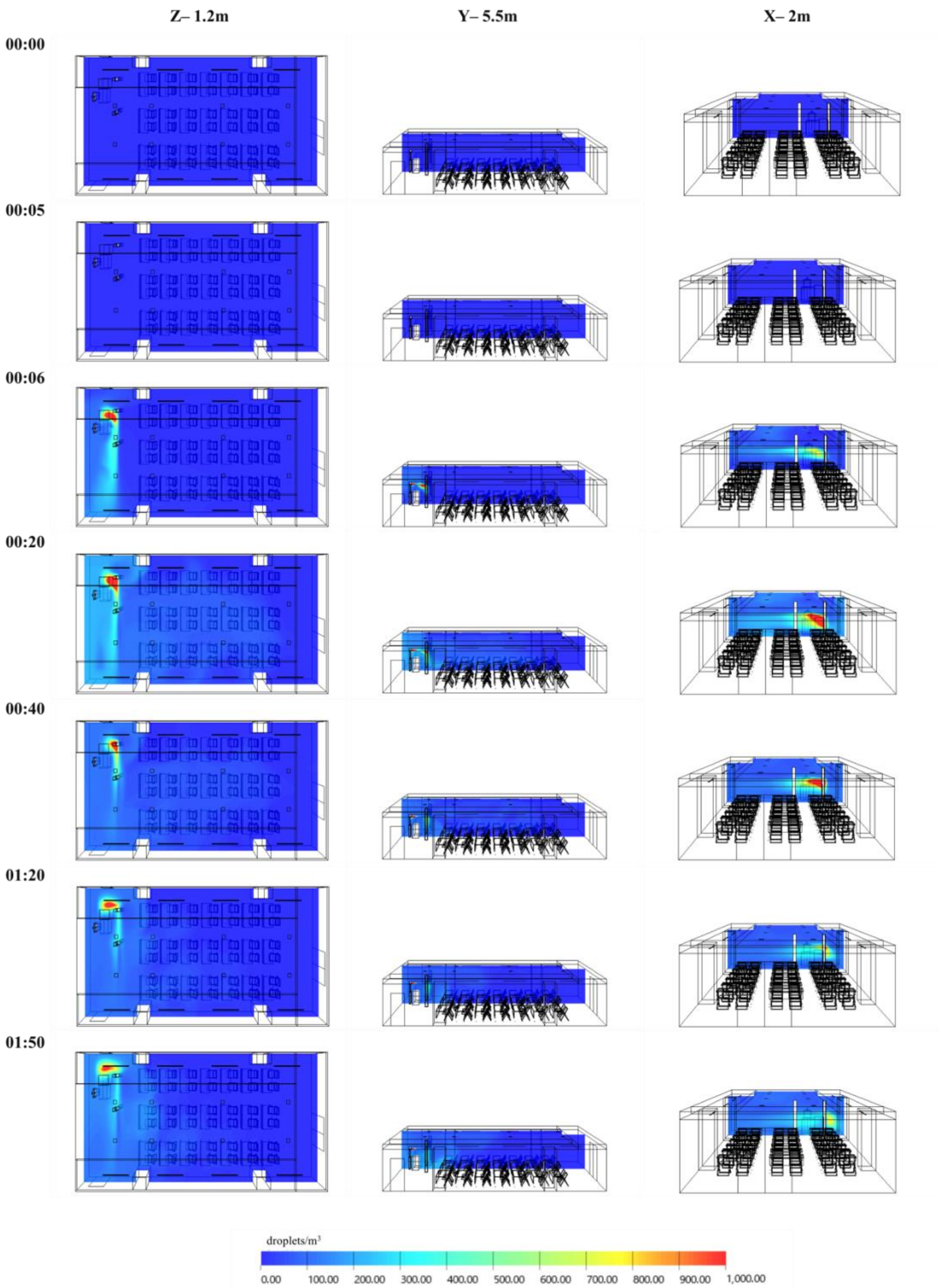

Fig. A- 11 Simulation NO. 8.

The outlet length of air curtain in simulation NO. 6, NO. 3, NO. 7 and NO. 8 is 0.24 m, 0.5 m, 0.98 - m and 1.47 m respectively, under the condition of a certain width, the longer the outlet length of fans, the more air volume blown out, and the stronger the effect of the air barrier.

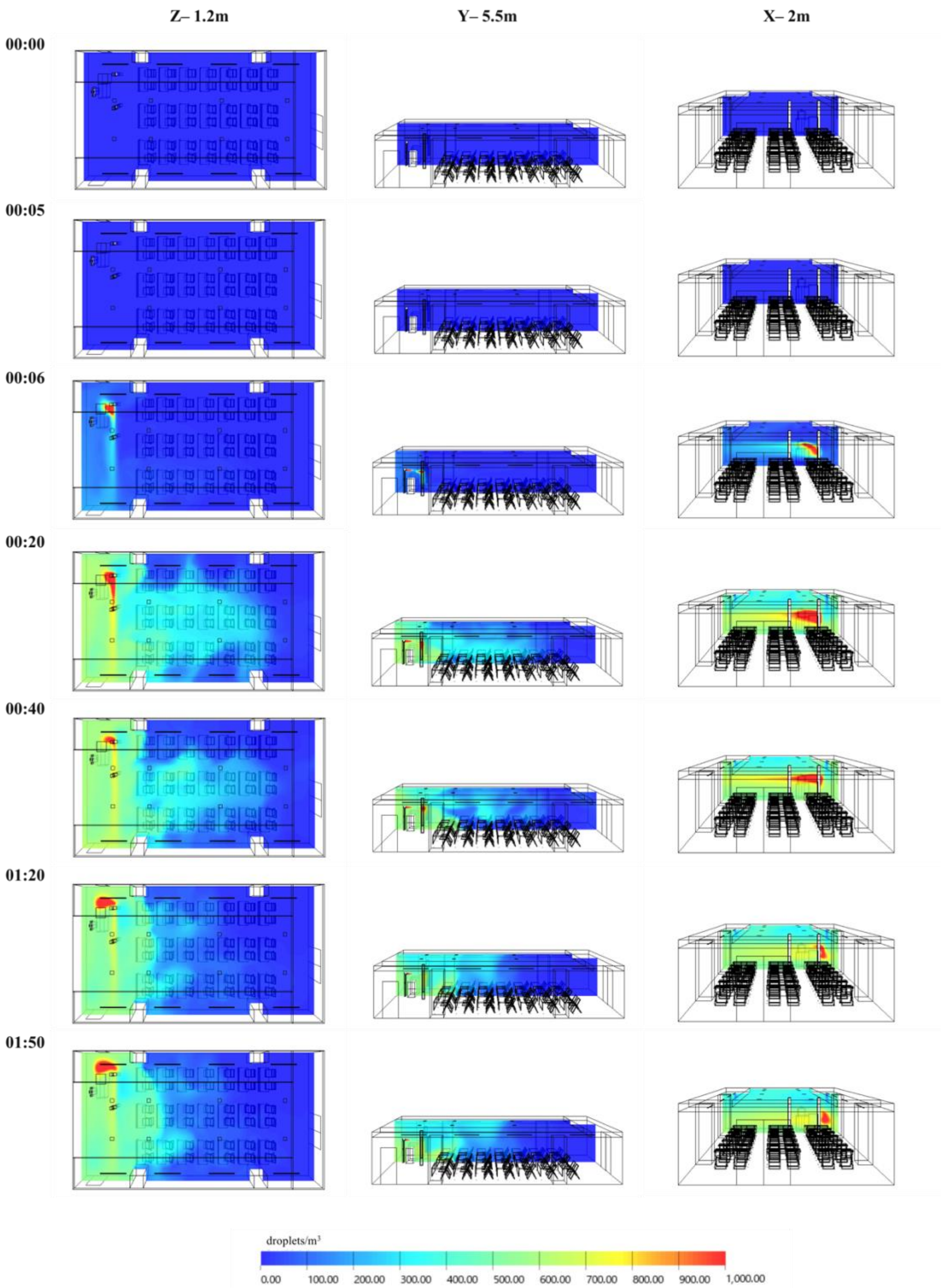

Fig. A- 12 Simulation NO. 8 (no HEPA filter).

If there is no HEPA filter to catch the droplets restricted by the airflow of the fans, the airflow blown out by the fans will expand the spreading range of the droplets instead.

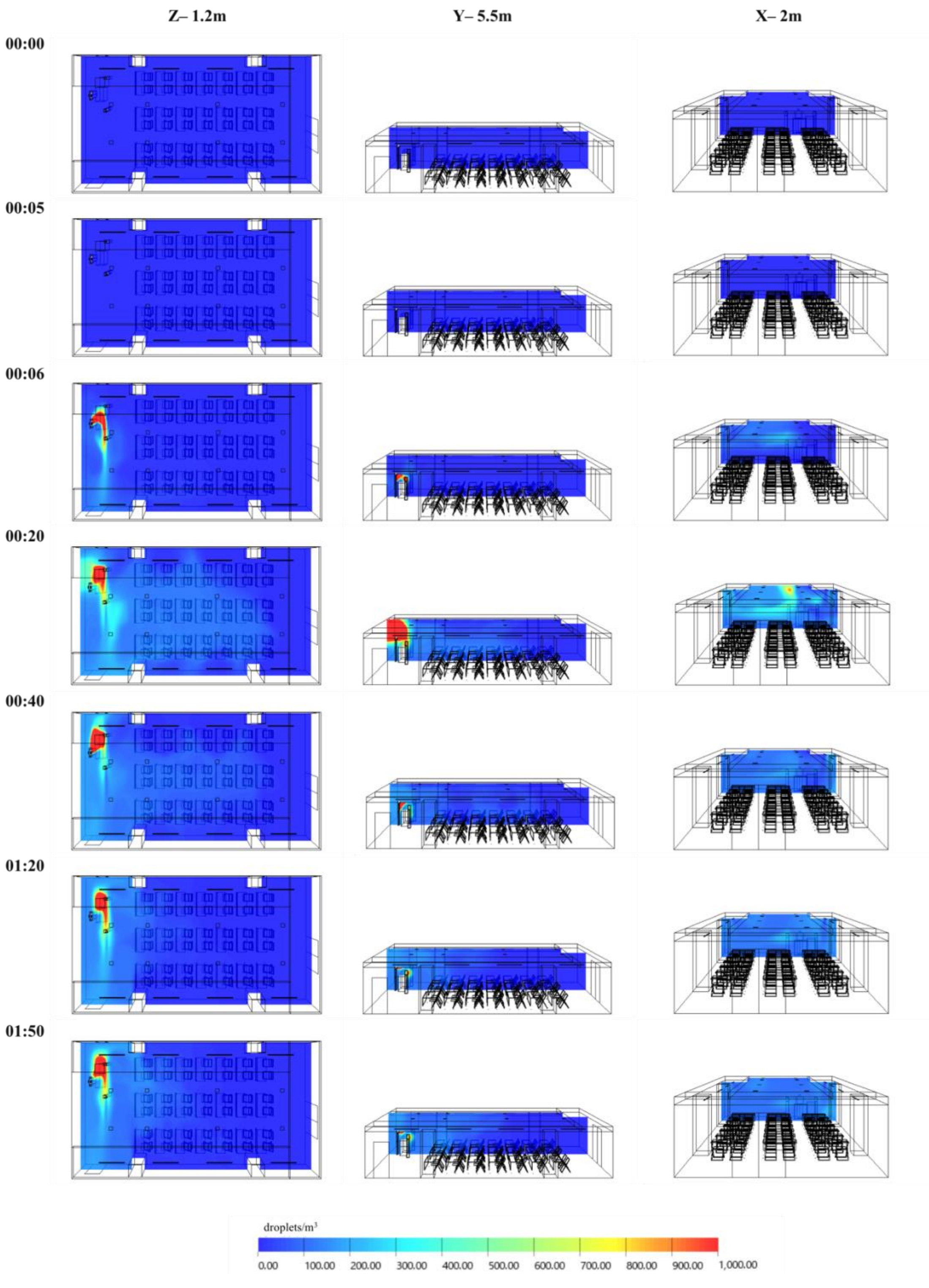

Fig. A- 13 Simulation NO. 9.

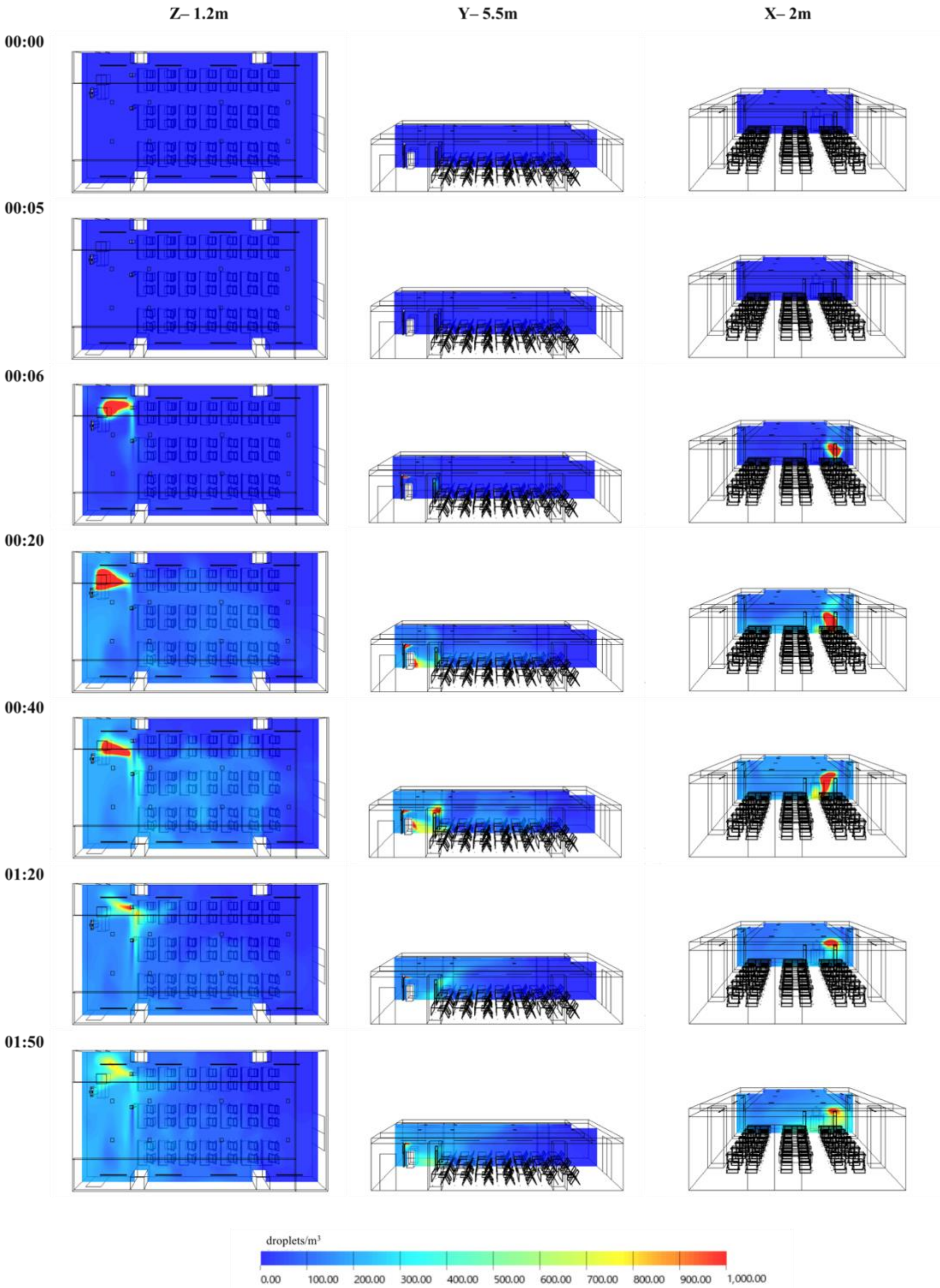

Fig. A- 14 Simulation NO. 10.

The air curtain - teacher distance of simulation NO. 9, NO. 7, and NO. 10 is 0.9 m, 1.4 m, 2.4 -m respectively, when the air curtain is too far away from the droplets-generated source, a part of the droplets will float to the top of the classroom and spread into the classroom before being controlled by the air curtain.

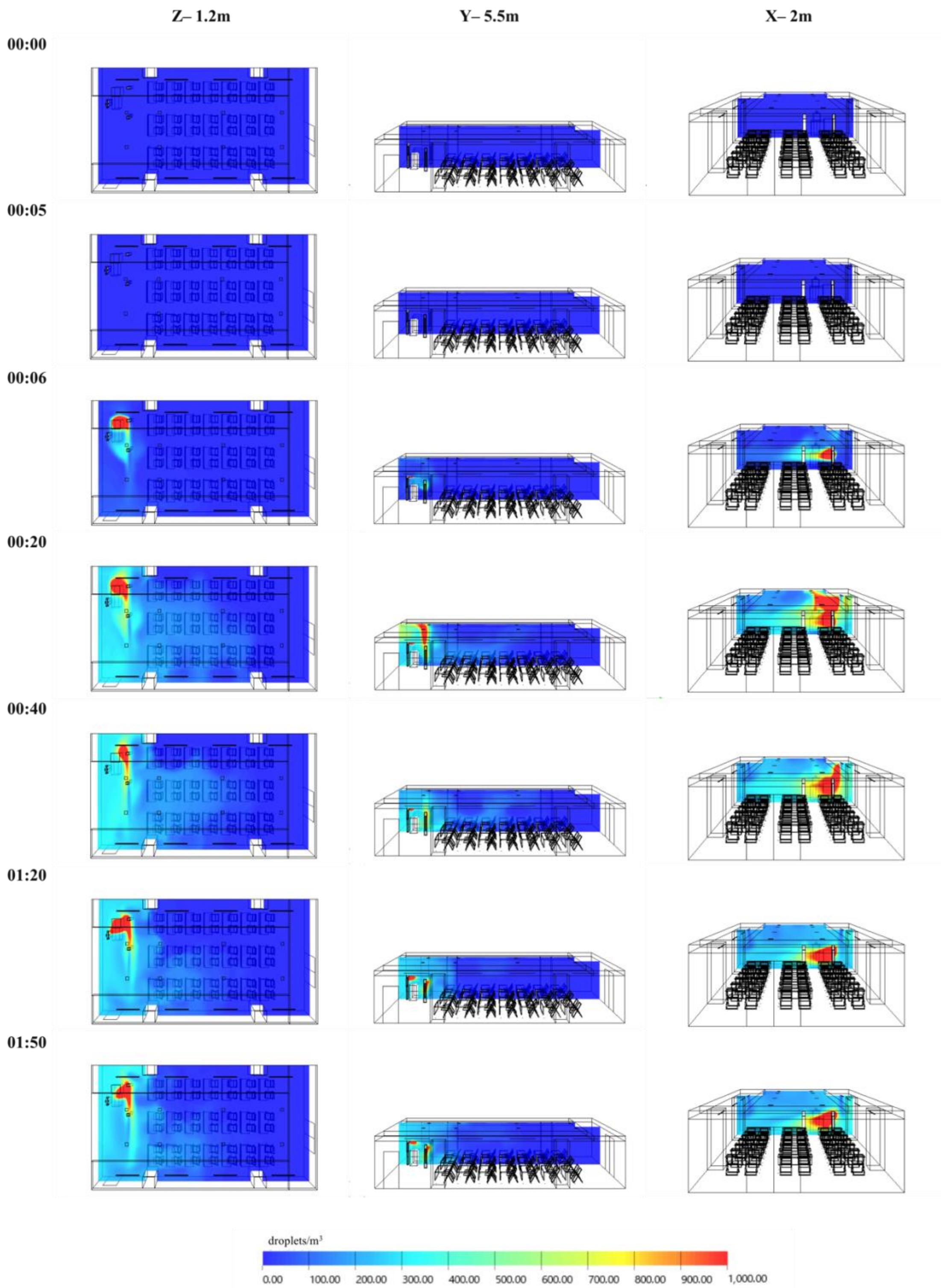

Fig. A- 15 Simulation NO. 11.

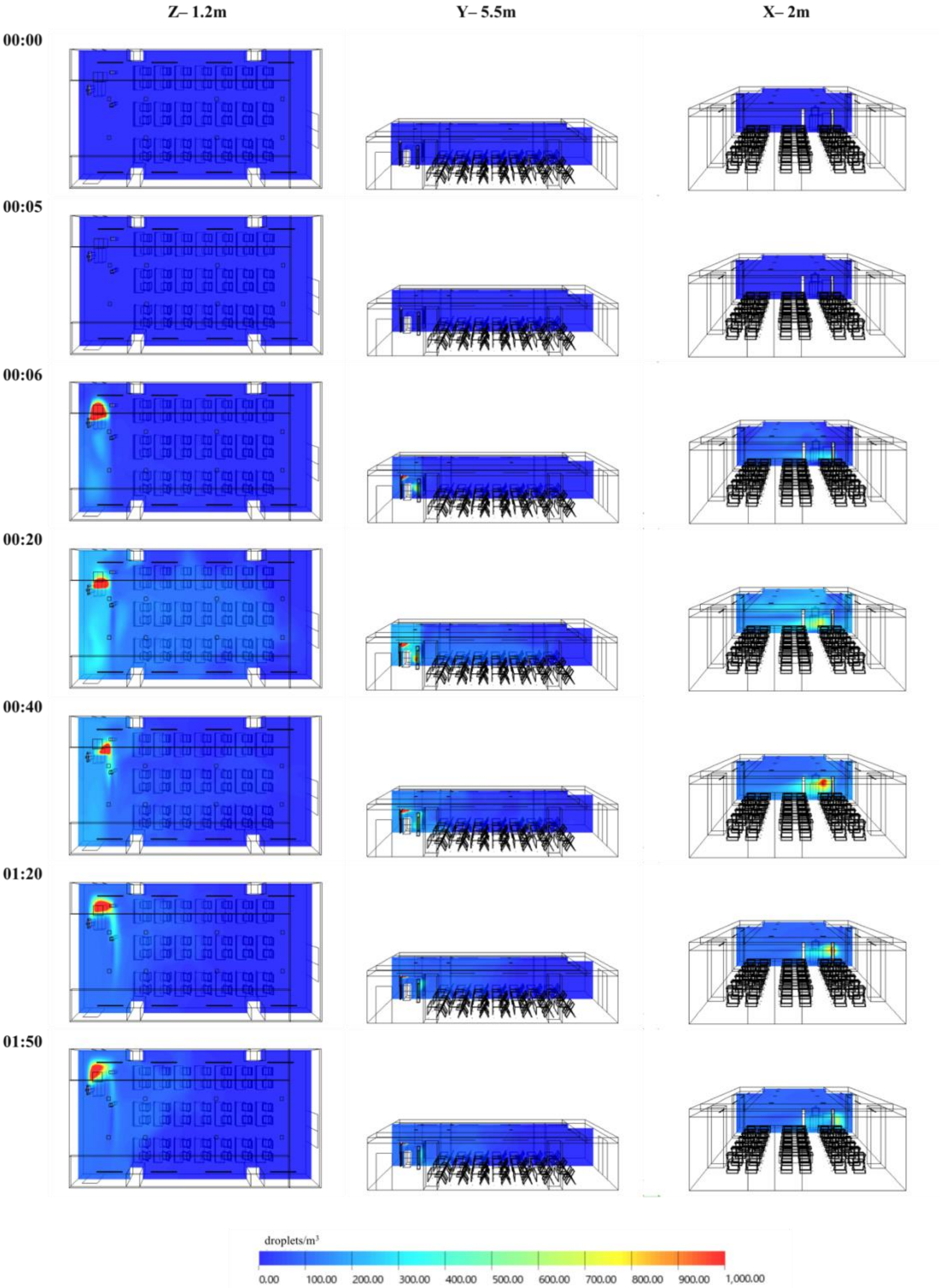

Fig. A- 16 Simulation NO. 12.

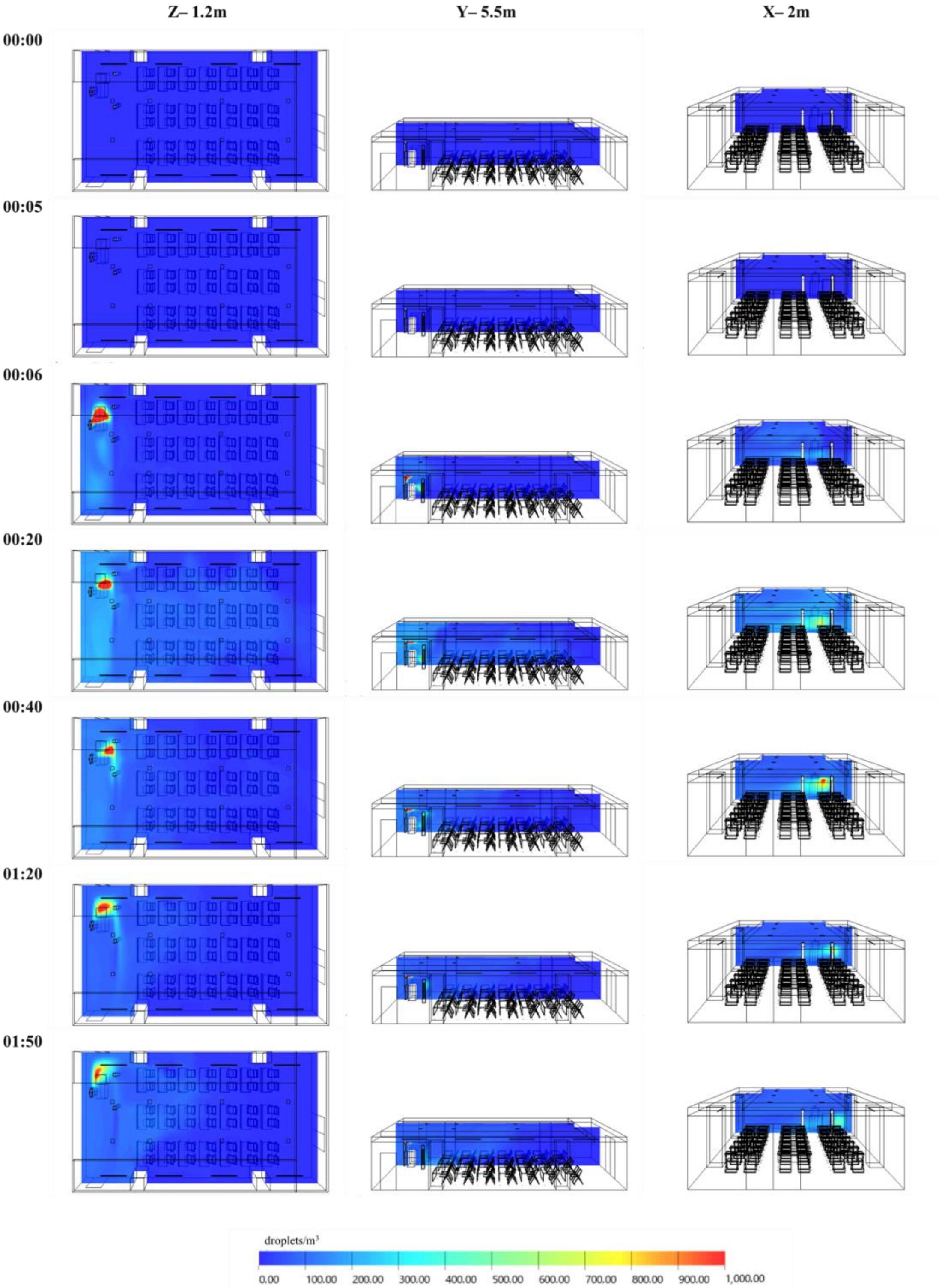

Fig. A- 17 Simulation NO. 13.

The wind speed of simulation NO. 11, NO. 7, NO. 12, and NO. 13 is 2 m/s, 4 m/s, 6-m/s and 8 m/s, respectively, the higher the wind speed, the more light-weight aerosols are sucked into the air curtain and then captured by the HEPA filters, and the number of droplets in the room becomes less.

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徐　芹