Research on Infection Risk Reduction Measures by Air Conditioning and Ventilation Systems and Evaluation of Their Performance in Infectious Disease Receiving Wards

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Summary

Various facility plans and operational improvements are needed in medical facilities to reduce the risk of infection. This paper reports on the results of the ventilation measurements and CFD analysis in the hospital room planned to reduce the risk of infection with a "switching ventilation system" developed to create negative pressure in the hospital rooms during pandemic. As a result, it was shown that negative pressure is maintained in the hospital room in the operational mode supplying 50% SOA, and that the ventilation efficiency is improved compared to the operational mode, which is exhaust ventilation.

Keywords: hospital facilities, ventilation, negative pressure, infection risk assessment

1 Introduction

The spread of the novel coronavirus disease 2019 (COVID-19) resulted in many medical facilities accepting infected patients, and it was necessary to secure hospital beds and consider measures for reducing the risk of infection. Particularly during infectious disease outbreaks (“pandemic periods”), patients must be admitted not only to designated medical institutions for infectious diseases but also to general hospital rooms. Therefore, each facility must implement various facility plan changes and operational improvements.

The “Hospital Facilities Design Guidelines (Sanitation and Plumbing) HEAS-02-2022”[1)], which was revised in 2022, is the only design guideline in Japan for the design and management of hospital facilities. These guidelines define the new terms of “aerosol infection route” for the propagation mode of COVID-19 through aerosols (microdroplets) and “aerosol infection countermeasures” for measures to prevent infection through this route. The guidelines further state that “it is appropriate to set the ventilation frequency between 2 and 12 times/hour” for hospital air conditioning equipment to prevent aerosol infection in hospital rooms.

To satisfy this guideline, we developed a negative pressure switchable ventilation system for hospital rooms (“switchable ventilation system”). This system enables general ward rooms to be switched from constant pressure in normal periods to negative pressure infection rooms during pandemic periods while ensuring the ventilation performance. This system was designed to increase the number of patients admitted during pandemic periods and increase the number of beds for infected patients; the system was installed in a newly built medical facility that handles infectious diseases.

In this report, we provide an overview of the developed “switchable ventilation system.” Additionally, we report the results of computational fluid dynamics (CFD) analyses and actual measurement surveys of the air conditioning and ventilation performance in the target hospital rooms, such as the air age and indoor air flow characteristics. Finally, we report the results of an infection risk assessment.

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2 Plan Overview

2.1 Building and equipment overview

Fig. 1 shows an overview of a newly constructed medical facility that has introduced the developed switchable ventilation system. The target hospital, Osaka Habikino Medical Center, is a core hospital that plays a central role in treating respiratory and allergic diseases, lung cancer, and infectious diseases. Design of the facility began in December 2019, construction began in February 2021, and construction was completed in December 2022.

Application	Hospital
Construction site	Osaka Prefecture
Structure	Steel frame
Number of floors	Six floors (above ground), one floor (tower)
Total floor area	34,199.70㎡
Number of beds	405 beds (305 general beds, six type 2 infectious disease beds, 45 tuberculosis beds)

Fig.1　Architecture overview

Fig. 2 shows a room plan for a four-bed general ward, and Fig. 3 shows an overview of the air conditioning and ventilation equipment. Air supply ports were installed in the passageways that serve as conduits for healthcare workers, and exhaust ports were located above the washrooms. The design specified a ventilation frequency of two times per hour and a ventilation volume of 200 m^3/h. Additionally, the four-way ceiling cassette air conditioner in the center of the room was rotated 45° relative to the room, thus improving the ability of the conditioned air to reach each bed.

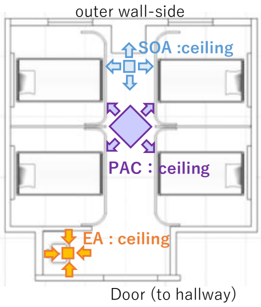
Plan view	Interior view
	

Fig.2　Hospital rooms' plan

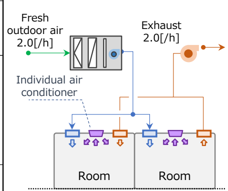
		System diagram
Ventilation method	Fresh outdoor air is introduced 2.0 times per hour using external air conditioner	
Ventilation volume	200㎥/h	
Differential pressure between rooms	Normal period: equal pressure Pandemic period: negative pressure	
Air conditioning method	individual air conditioners (Ceiling cassette type: four-way) Cooling 4.5 kW, heating 5.0 kW	

Fig.3　Ventilation system of hospital rooms

2.2 Negative pressure switchable ventilation system for hospital rooms

The conventional method for creating negative pressure in general ward rooms during emergencies such as pandemics involves the installation of many negative pressure exhaust fans and ducts. However, this equipment is not used during normal periods, and thus it requires additional costs and space; moreover, increasing the air volume of the outdoor air conditioner increases the equipment capacity and energy consumption. Therefore, we devised a system that enables the use of normal equipment as much as possible and can easily create negative pressure in hospital rooms without increasing the overall ventilation volume.

Fig. 4 shows an overview of the developed switchable ventilation system. We installed a branch duct and air volume adjustment damper in the air supply duct from the outdoor air conditioner. The air supply destination can then be switched from the hospital room to the hallway during pandemic periods, thereby creating negative pressure in the hospital room. This enables the use of equipment from normal periods as-is during pandemic periods, thus eliminating the need to increase the air volume of dedicated fans, ducts, or external air conditioners.

During normal periods, the air supply and exhaust air volume are the same, the target hospital room is provided with Class 1 ventilation, and the pressure in the hospital room is the same as that of the hallway (Fig. 4(a)). During pandemic periods, closing the damper at the branch of the air supply duct on the hospital room side and opening that on the hallway side causes the hospital room to be provided with Class 3 ventilation and provides negative pressure (Fig. 4(b)). Furthermore, the damper opening can be

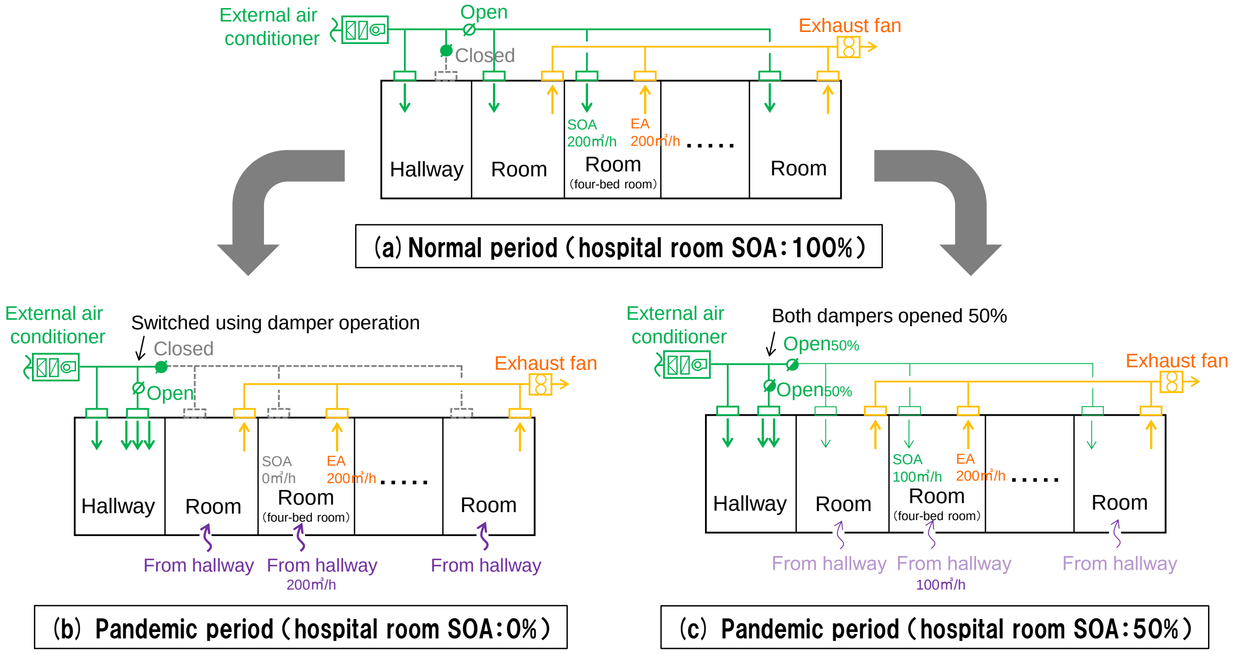


Fig.4 Overview of switchable ventilation system

adjusted manually, which enables the negative pressure in the hospital room to be maintained while supplying 50% of the SOA during normal periods (Fig. 4(c)).

At the Osaka Habikino Medical Center, the newly developed switchable ventilation system was installed in the general ward adjacent to the Type 2 infectious disease ward, with plans to expand the ward accepting infected patients in stages during pandemic periods.

3 CFD analysis overview and results

3.1 CFD analysis overview

CFD analysis was performed for the four-bed room before installation to verify that the hospital room would achieve negative pressure and adequate ventilation performance. Fig. 5 shows the analysis model, Table 1 presents an overview of the analysis, and Table 2 lists the details of the analysis cases. We conducted steady-state analysis using an unstructured grid with a small number of meshes and high shape approximation accuracy.

In Cases A-1–3, the air outlet angle of the air conditioner was adjusted to 30° downward during cooling. In Cases B-1–3, the air outlet angle of the air conditioner was set to 55° downward during heating. The ventilation frequency was two times per hour in all cases.

The settings in Cases A-1 and B-1 were designed to represent normal periods, with Class 1 ventilation and equal pressure conditions. In Cases A-2 and B-2, the settings

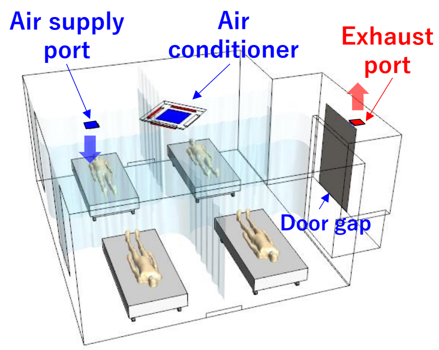


Fig.5 CFD analysis model

Table 1 Outline of CFD analysis

Software	STAR-CCM (Siemens社)
Turbulence model	Low Re number-type Realizable k-model
Number of meshes	2.15 million (unstructured grids)

Table 2 CFD analysis cases

Case	Operational mode	Differential pressure	ACH	Supply air volume		Exhaust air volume	Air conditioner	
				Ceiling (SOA)	Door gap	Ceiling (EA)	Operation mode	Circulating air volume
			#/h	㎥/h	㎥/h	㎥/h		㎥/h
CaseA-1	Normal period	equal pressure	2	200	0	200	Cooling (30° downward)	720
CaseA-2	Pandemic period	negative pressure	2	0	200	200	Cooling (30° downward)	720
CaseA-3	Pandemic period	negative pressure	2	100	100	200	Cooling (30° downward)	720
CaseB-1	Normal period	equal pressure	2	200	0	200	Heating (55° downward)	720
CaseB-2	Pandemic period	negative pressure	2	0	200	200	Heating (55° downward)	720
CaseB-3	Pandemic period	negative pressure	2	100	100	200	Heating (55° downward)	720

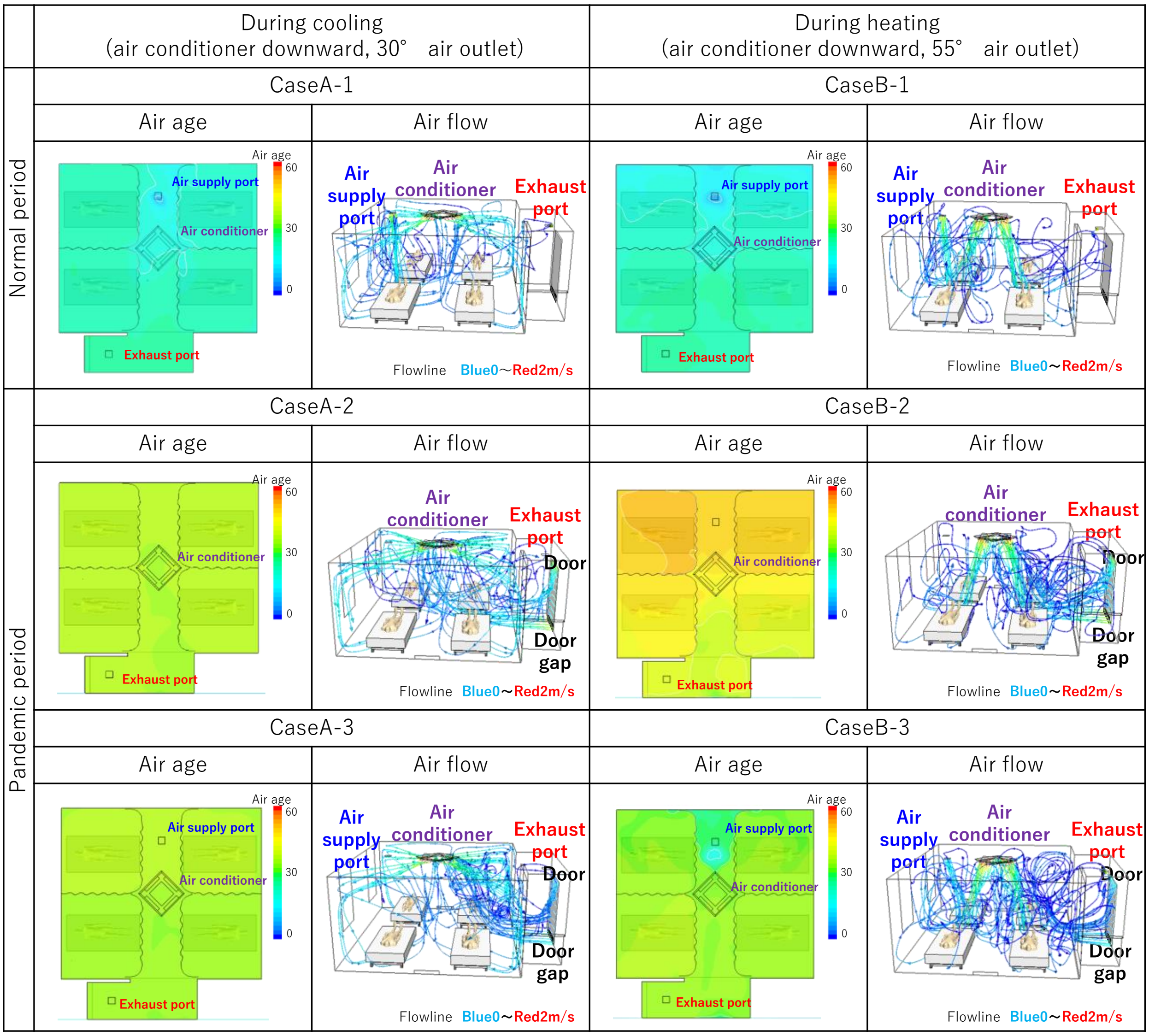


Fig.6 CFD analysis results of air age and air flow

represented pandemic periods, with Class 3 ventilation and negative pressure conditions. In Cases A-3 and B-3, the settings represented pandemic periods with Class 1 ventilation; however, negative pressure conditions were achieved by setting the SOA amount from the ceiling air supply port to 50% of that during normal periods. The analyses were conducted with the assumption of actual operation by closing the curtains around the beds in each case.

3.2 CFD analysis results

Fig. 6 shows the results of the CFD analyses. The air flow analysis diagrams show the trajectories of massless, volumeless virtual particles drawn using streamlines. In Cases A-2, A-3, B-2, and B-3, air from the hallway flowed into the room through the gap at the bottom of the door, and changes in the flow due to negative pressure were confirmed.

The air age analysis diagrams show the plane distribution 1300 mm above the floor. A comparison of Cases A-1–3 and B-1–3 show that the air age distribution was slightly biased toward the latter during heating, when the air outlet angle of the air conditioner was tilted more downward. Cases A-2 and B-2 had higher air ages than Cases A-1 and B-1 because air was supplied only through the door gap under the Class 3 ventilation. For Case B-2 in particular, the downward air flow from the air conditioner interfered with the air supply from the door gap, and the air age at the back of the room was greater than that in Case A-2. Cases A-3 and B-3 had a lower air ages than Cases A-2 and B-2 because 50% of the SOA amount during normal periods was supplied from the ceiling air supply port, which created negative pressure in the hospital room and improved the ventilation efficiency.

4 Actual measurement overview methods

An actual measurement survey was conducted to verify the ventilation performance upon completion of construction. Table 3 presents an overview of the actual measurements, and Table 4 lists the ventilation settings for the measurement cases. The measurement target room was a four-bed general hospital room. As the survey was conducted during the winter season, the air conditioner was set for heating operations. The ventilation settings were the same as those for analysis cases B-1, B-2, and B-3 in the previous section. We measured air and particle ages and visualized the air flow properties.

Table 3 Measurement overview

Measurement period	January 17–24, 2023
Target room	General ward four-bed room
Measurement item	・Air age ・Particle age ・Air flow visualization
Air conditioning settings	Heating 23 ° C
Air change rate	Two times per hour
Ventilation settings	Switched by negative pressure switchable ventilation system ・Normal period (hospital room: equal pressure) ・Pandemic period (hospital room: negative pressure)

4.1 Ventilation volume and differential pressure measurements

We conducted ventilation volume and differential pressure measurements to confirm that the ventilation volume was being maintained as designed and that the hospital room had negative pressure during pandemic periods. The anemometer used was the Climomaster anemometer 6501 manufactured by KANOMAX JAPAN Inc., and the differential pressure gauge used was the testo521-3 manufactured by Testo K.K.

Table 4 Ventilation settings for experiments

Case	Operational mode	Supply air volume	Exhaust air volume
CaseB-1	Normal period	200	200
CaseB-2	Pandemic period	0	200
CaseB-3	Pandemic period	100	200

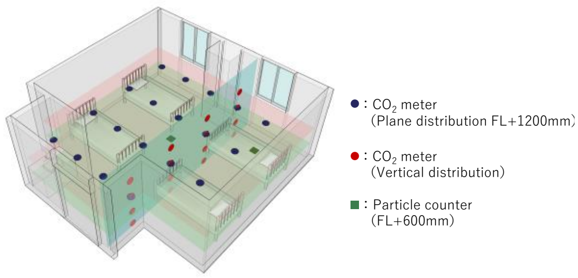


Fig.7 CO_2 and particle measuring points

4.2 Air age measurements

We measured the indoor distribution of the air age, which is an indicator of air freshness, to determine whether air stagnation occurred in various parts of the hospital room. The air age was measured in a general hospital room using a CO_2 tracer gas step-down method[2)]. The room was uniformly filled with CO_2 gas to a concentration of 3000 ppm, after which gas generation was stopped, the air conditioning ventilation system was started, and concentration measurements were recorded.

Fig. 7 shows the installation location of the portable CO_2 concentration meter (RTR-576, manufactured by T&D) used for the measurements. The plane distribution measurement points were located at a height of 1200 mm above the floor. Furthermore, we conducted measurements of the vertical distribution by establishing four measurement points in the vertical direction (100, 600, 1200, and 1800 mm above the floor) in the representative cross-section shown in Fig. 7. The outside air concentration was measured near the outside air port.

The air age was calculated using the piecewise quadrature method to determine the dimensionless difference in concentration between the inside and outside at each point, as shown in Eq. (1). The decrease in concentration after the measurement time was calculated from the definite integral using a regression equation[3)].

$$\tau_p = \int_0^{\infty} \frac{C_r(t) - C_o}{C_{r0} - C_o} dt \qquad (1)$$

τ_p	: Local average air age	[h]
C_r	: Indoor CO_2 concentration	[ppm]
C_{r0}	: Initial indoor CO_2 concentration	[ppm]
C_o	: Outside air CO_2 concentration	[ppm]
t	: Elapsed time	[h]

4.3 Particle age measurements

Comprehensively studying infection risk requires assuming the behavior of particles such as droplets and droplet nuclei that are the sources of infection. We sought to evaluate the purification performance of the ventilation system for a particulate pollution source using incense particles as the tracer substance. The age of the particles was calculated using the same method as for the air age measurement described in Section 4.2. Fig. 7 shows the installation location of the particle counter (KC-52, manufactured by RION Co., Ltd.) used for the measurements. The particle counter was installed at a height of 600 mm above the floor at two points (center of the room and near a bed). Several incense sticks were used to obtain the desired particle concentration in the room, after which a diffusion fan was used to equalize the indoor particle concentration. Then, the incense sticks were extinguished, the diffusion fan was stopped, the air conditioner was set and operated, and the suspended particle concentration in the room was measured continuously.

4.4 Measurement of air flow properties

We sought to confirm that air did not flow from the hospital rooms to the hallways during the negative pressure operation in pandemic periods. Therefore, we conducted particle image velocimetry (PIV) measurements to elucidate the air flow near the bottom of the door. Table 5 presents the details of the PIV measurement evaluation system, and Table 6 summarizes the PIV measurement parameters. During the experiment, the air conditioner was set to cooling (24 °C) to mimic the summer temperature setting during actual operation. Measurements were recorded under the conditions of Cases B-1 and B-3. Tracer particles were generated to obtain visualized images, and the images recorded after the particle behavior had stabilized were analyzed.

Table 5 Experimental equipment for PIV measurement

Camera	Phantom Miro 110 (manufactured by Vision Research)
Laser generator	PIV Laser G6000 (manufactured by Kato Koken)
Tracer particle generator	PORTA SMOKE PS-2005 (manufactured by Dainichi Co., Ltd.) Oil mist (1 μm < particle diameter < 100 μm)
Software	Flow-Expert ver1.2.17

Table 6 PIV measurement parameters

Image size	1,000 pixel × 580 pixel
Recording time	5 sec
Measurement interval	10 msec (100fps)
Measurement point spacing	0.1m

Table 7 Measured ventilation volume and differential pressure

	Air supply duct damper opening setting				Hospital room (four-bed room)		
	Room system		Hallway system				
	SOA amount	Damper blade angle※	SOA amount	Damper blade angle※	Ventilation volume		Different pressur (to hallwa
					SOA	EA	
	%	°	%	°	m3/h	m3/h	Pa
Normal period (hospital room SOA: 100%)	100	90	0	0	205	207	-0.2
Pandemic period (hospital room SOA: 0%)	0	0	100	90	0	207	-1.4
Pandemic period (hospital room SOA: 50%)	50	45	50	45	99	207	-1.2

*Fully open at 90° , fully shut at 0°

5. Measurement results

5.1 Ventilation volume and differential pressure measurements

Table 7 presents the measurement results for the ventilation volume and differential pressure. We confirmed that the necessary ventilation volume was maintained under each switching setting condition. The differential pressure between the hospital room and the hallway during pandemic periods was -1.4 Pa at 0% SOA and -1.2 Pa at 50% SOA, confirming that the hospital room was under negative pressure.

5.2 Air age measurements

Fig. 8 shows the measurement results for the air age distribution. In the vertical distribution with curtains during normal periods (Case B-1), for the air age tended to be slightly higher in the lower part of the room. A slight bias may have occurred owing to the influence of the air conditioning settings during heating, layout of the air supply and exhaust ports, and placement of the curtains. However, in the plane distribution, the air age distribution was almost uniform. Compared to the case without curtains, the air age tended to be slightly higher overall when curtains were used. As noted in previous research[4)], curtains for medical facilities with large openings in the upper and lower parts are thought to have a small effect on the plane distribution of the air age. A comparison between the normal period (Case B-1) and pandemic period (Case B-2, B-3) conditions showed that Case B-2, which had an SOA of 0%, had a higher air age than Case B-1; however, the air age in Case B-3, which had an SOA of 50%, was lower than that in Case B-2. Therefore, these results confirm that partial SOA supply to the hospital room improv ed the ventilation frequency. Furthermore, the vertical distribution of the air age showed that Cases B-2 and B-3 had a lower air ages in the lower part of the room, which reflects the flow of fresh air from the hallway into the patient room through the door gap.

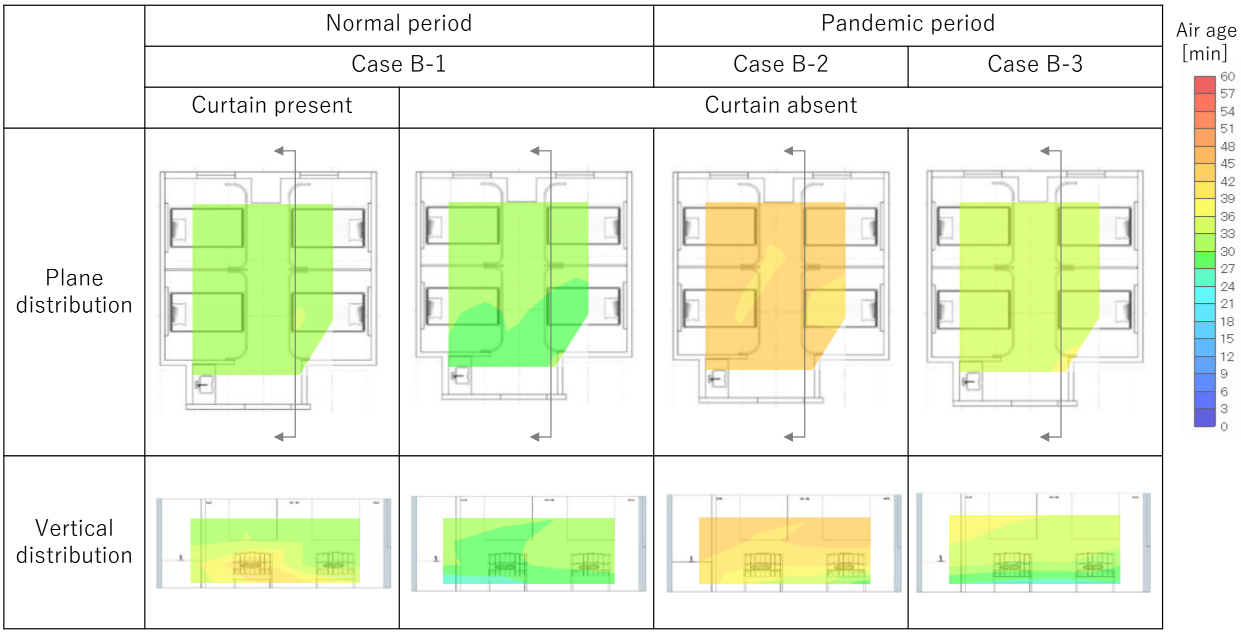


Fig.8 Measured results of air age

5.3 Particle age measurements

Fig. 9 shows the particle age for 0.3–0.5 µm particles in the center of the room and near the bed in each case. No major differences in the particle age were observed at the center of the room and the area near the bed in the different cases; however, the center of the room, which was close to the air port, had a lower particle age than the area near the bed. Additionally, the particle age was lower without a curtain than with a curtain, and a similar trend to that of the air age was confirmed.

Fig. 10 shows the measurement results for the particle age averaged at two points and the results of the room average air age calculated in Section 3.1. The results show that a larger particle size resulted in a lower particle age. Previous research[5] has shown that the air age obtained using CO_2 as a tracer and the particle age determined using particles of approximately 0.3 µm as a tracer were generally in agreement, but they did not necessarily match in the results in our study. Possible factors for this discrepancy include the effects of gravitational settling due to the particles' own mass and the effects of the cleanliness of the air in the hallways in Cases B-2 and B-3, which had negative pressure. Furthermore, the air age was calculated as the average of 19 points, whereas the particle age was calculated as the average of two points, and thus there may have been large variations in the measurement results. Evaluations using particle age are believed to be an effective indicator for considering aerosol removal performance. We plan to conduct further research in the future, including confirmation of the given conditions.

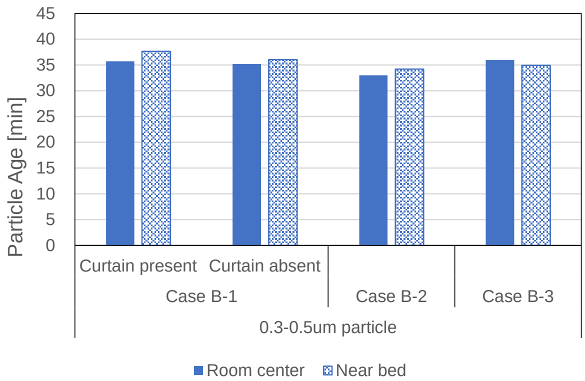


Fig.9 Measured results of particle age (0.3-0.5µm) at 2 points

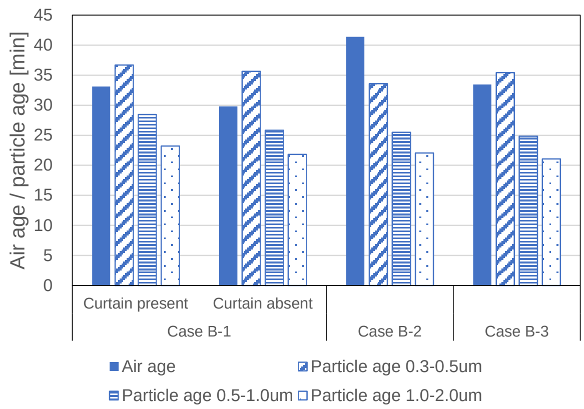
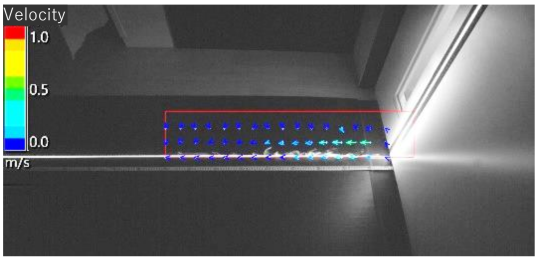


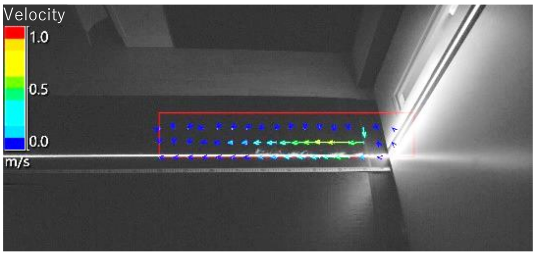
Fig.10 Room-averaged particle age and air age measurements

5.4 Air flow property measurements

Fig. 11 shows the PIV measurement results near the bottom of the door. During normal periods (Case B-1), a maximum air flow of approximately 0.3 m/s was generated from the hallway to the hospital room. Meanwhile, during pandemic periods (Cases B-2, B-3), the maximum air flow was approximately 0.7 m/s, confirming that the flow velocity increased. PIV measurements also confirmed changes in the air flow due to negative pressure in the hospital room.



(i) Case B-1



(ii) Case B-3

Fig.11 PIV measurement results

6. Infection risk assessment

6.1 Assessment overview

We performed an infection risk assessment using the Wells-Riley model[6] to assess the risk of airborne infection among healthcare workers during normal and pandemic periods (negative pressure operatio n periods). The Wells-Riley model proposed by Riley et al.[6] assumes that the indoor pollutant concentration and air flow field are stationary. However, in practice, the indoor pollutant concentration changes over time as infected people remain in the room. Therefore, we applied the extended Wells-Riley equation developed by Ochiai et al.[7], which considers changes in pollutant concentration over time. Additionally, REHVA[8] proposed a program for assessing the risk of infection between living rooms based on the Wells-Riley equation.

Table 8 Setting value of each parameter

parameter	value	parameter	value
ε_{SPFM}	0.9	V	97.76
I	4	t	1
P	0.54	ε_{IPFM}	0.65
q	10		

Eq. (2) shows the infection risk assessment equation in the Wells-Riley model, and Eq. (3) shows the calculation of the quanta concentration.

$$P_{inf} = \left(1 - e^{-(1-\varepsilon_{SPFM})\cdot I\cdot P\cdot \int_0^t C(t)dt}\right) \times 100 \qquad (2)$$

P_{inf}	: Infection probability	[%]
ε_{SPFM}	: Mask attenuation rate for non-infected people	[-]
I	: Initial number of infected people	[Num]
P	: Respiration rate	[m^3/h]
$C(t)$	: Quanta concentration	[quanta/m^3]

$$C(t) = \frac{q}{N\cdot V}\cdot[1 - e^{-Nt}]\cdot(1-\varepsilon_{IPFM}) \qquad (3)$$

q	: Quanta production	[quanta/h]
N	: Ventilation frequency	[/h]
V	: Room volume	[m^3]
t	: Residence time	[h]
ε_{IPFM}	: Mask attenuation rate for infected people	[-]

Eqs. (2) and (3) consider the effects of wearing masks among infected and non-infected people, and this study also considers the effects of wearing masks.

Table 8 lists the parameter values used in the analysis. We conducted an infection risk assessment assuming that a non-infected person ("healthcare worker") stayed in a four-bed hospital room with four infected people ("patients") for one hour. The parameters were set with reference to the REHVA[8] infection risk assessment program. It was assumed that patients wore surgical masks, and healthcare workers wore N95 masks. For patients, the rest state (mouth breathing) was used as the reference point, and the quanta production was set as q = 10, assuming light conservation and rough mouth breathing.

6.2 Assessment results

Fig. 12 shows the results of the infection risk assessment. The ventilation frequency, N, was determined based on the ventilation frequency calculated from the CO_2 tracer gas step-down method, and the equivalent ventilation frequency values were calculated using tracer particle size categories of 0.3–0.5 µm, 0.5–1.0 µm, and 1.0–2.0 µm.

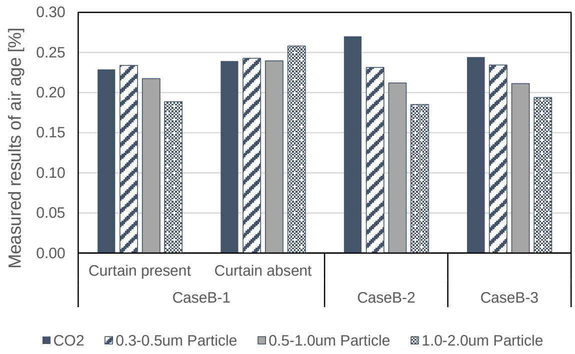


Fig.12 Results of infection risk assessment

The infection risk in a four-bed room calculated based on the ventilation frequency using CO_2 as a tracer was 0.23%–0.27%. A comparison with the infection risk during normal periods (Case B-1) showed that Case B-2, which had an SOA of 0%, exhibited an increase in infection risk of approximately 0.03%; however, Case B-3, which had an SOA of 50%, was almost identical to Case B-1. The results thus confirmed that partial SOA supply to the hospital room resulted in an infection risk in the hospital room that was approximately the same as during normal periods; moreover, creating negative pressure reduced the infection risk to the surrounding area.

Furthermore, examining the differences in infection risk assessments due to differences in the tracers shows that particles with larger diameters tended to have a smaller infection risk, and this difference was greater in Cases B-2 and B-3 than in Case B-1. This greater difference may have occurred because particles with larger diameters are affected by gravitational settling, etc., resulting in a higher calculated ventilation frequency. Moreover, Cases B-2 and B-3 also had measurement points close to a point at the back of the hospital room, where air flow tended to accumulate. Various reports have been published regarding the sizes of viruses and the droplets that contain them[9)], and these factors can be taken into account when conducting the infection risk assessment to obtain different assessment results.

7. Conclusion

We developed a negative pressure switchable ventilation system for hospital rooms that enabled the smooth acceptance of infected patients into general wards during pandemic periods. The developed system was installed in a hospital that was in the process of implementation design at the time of the COVID-19 pandemic. In this report, we aimed to clarify the air flow characteristics and ventilation performance of this system and obtain knowledge that can help prevent infection. Therefore, we reported the results of CFD analyses, actual measurements of air age and particle age, visualization of the air flow, and an infection risk assessment. The major findings are summarized below.

1) The CFD analysis confirmed that negative pressure and the ventilation performance in the hospital room were sufficiently ensured.
2) The results of actual measurements of differential pressure and air age showed that negative pressure in hospital rooms could be maintained in the operational mode assuming pandemic periods. Moreover, supplying 50% of the SOA in normal periods achieved negative pressure in the hospital room as well as improved the ventilation efficiency compared to a Class 3 ventilation case.
3) The particle age results confirmed that the difference in particle age values between cases was smaller than that observed for the air age. Evaluations using particle age were considered to be an effective indicator for considering aerosol removal performance. Further studies will be conducted in the future.
4) Changes in the air flow due to negative pressure in the hospital room were confirmed by visualizing the air flow properties.
5) The results of the infection risk assessment showed that an air supply at 50% of the SOA during normal periods to the hospital room maintained the infection risk in the hospital room at the same level as during normal periods. Moreover, negative pressure was expected to reduce the infection risk to the surrounding area.

8. Afterword

For healthcare workers, infection risk poses a major burden on medical treatment and nursing care. The burden on healthcare workers needs to be reduced by communicating the performance of air conditioning ventilation more clearly and accurately and reflecting this in mechanisms and operations that reduce the infection risk. In this project, an agreement was reached with the building owner based on the results of this study; as a result, it was decided that an operational mode of supplying 50% of the SOA during normal periods would be adopted during pandemic periods. We hope that this paper will serve as a reference for planning and designing medical facility projects and will contribute to society.

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