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Master's Thesis of Engineering

A Plan to Improve the Indoor Environment of an Emergency Switching Type Negative Pressure Isolation Ward Using a Portable Negative Pressure Units

이동형 음압기를 이용한 긴급 전환형
임시음압격리병실의 실내 환경 개선 방안 분석

February 2023

Graduate School of Engineering
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Architecture & Architectural Engineering Major

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A Plan to Improve the Indoor Environment of an Emergency Switching Type Negative Pressure Isolation Ward Using a Portable Negative Pressure Units

Advised by Prof. MyoungSouk Yeo

Submitting a master's thesis of Engineering

February 2023

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Seoul National University
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Confirming the master's thesis written by
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February 2023

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Examiner ______________________ (Seal)

Abstract

From SARS (Severe Acute Respiratory Syndrome) in 2003 to COVID-19 (corona virus disease 19) in 2019, new respiratory infectious diseases are emerging every 5 to 6 years. Respiratory infectious diseases with high contagious risk are quarantined in the early stage to suppress secondary infection and prevent spread to the community. In general, isolation is operated by installing a Negative Pressure Isolation Ward that induces air flow from a semi-clean and clean area with low pollution level to a contaminated area such as a high pollution patient ward by using air conditioning equipment in the building.

The COVID-19 infectious disease in 2019 has led to an unprecedented pandemic. As a result, the capacity of the previously installed Negative Pressure Isolation Ward has reached a limit. To solve this problem, an Emergency Switching Type Negative Pressure Isolation Ward was operated in which a Portable Negative Pressure Units was applied to convert a general patient ward into a negative pressure ward, and a study on the indoor environment of an Emergency Switching Type Negative Pressure Isolation Ward was needed.

Therefore, in this study, the criteria for a general Negative Pressure Isolation Ward and a Switching Type Negative Pressure Isolation Ward Using a Portable Negative Pressure Unit were analyzed. Afterward, measurement of the indoor environment of the Emergency Switching Type Negative Pressure Isolation Ward(Noise, Air Volume of a Portable Negative Pressure Unit, Air Velocity, Pressure difference between rooms, Airflow analysis, the spread of Contaminants) and simulation of improvement plans (Base Model, Architectural elements improvement, Building equipment elements improvement, Total elements Improvement) Through this, the effectiveness of the

measures to prevent the spread of pollutants was analyzed.

The results of this study are summarized as follows.

As a result of field measurements, when the Portable Negative Pressure Unit was operated, the patient ward was formed with negative pressure, and the contamination concentration inside the patient ward could be lowered. However, the operation of the Portable Negative Pressure Unit caused duct backflow by unbalanced the pressure of the existing central air conditioning ducts. As a result, it was found that there is a possibility that the contaminant may spread through the backflowing air. In addition, non-airtight ceilings and leakage parts of plenums were found to be the diffusion paths of contaminants.

When the pressure difference criterion between the corridor and the ward was satisfied, the air flow moved to the ward with the lowest pressure, and the contamination spread through leakage parts such as the interior wall of the ward.

Since the exhaust duct of thePortable Negative Pressure Unit installed at the site is facing the outdoor air, it was found that there is a possibility of short circuiting in which some of the contaminated air exhausted through the Portable Negative Pressure Unit in the patient ward flow into the patient ward.

As a result of the simulation, it was found that the pressure difference between patient ward increased when the airtightness of the architectural elements (Ceiling, Exterior wall, Interior wall) was improved. When the airtightness of the internal structure (Ceiling, Interior wall) of the building is improved, the amount of air introduced from the outside for make up air increases, resulting in an increase in the degree of contamination in the ward due to short circuiting. When the airtightness of the Exterior wall of the building is improved, the amount of air inflow from the outdoor is reduced, so the degree of contamination within the ward is lower than when the airtightness of the internal structure of the building is improved, but the patient ward is found to be contaminated. If only the architectural elements are improved, short circuiting cannot be prevented, so it cannot be seen as an effective improvement plan.

Among theBuilding equipment elements improvement plan, if central air conditioning is stopped and the duct supply and exhaust port is sealed, the bathroom is formed at a positive pressure than the patient ward, preventing contaminants from moving from the patient ward to the bathroom and preventing the spread of duct backflow. However, in a situation where a short circuit occurred, contaminants spread to other rooms, and contaminants spread from the corridor/ceiling to the bathroom through the leakage area where the corridor/ceiling faces the bathroom. In order to prevent short circuiting, zoning the exhaust duct of the Portable Negative Pressure Unit was analyzed to be effective in preventing the spread of contaminants in the ward by preventing short circuiting.

In the case of a Totale improvement plan that simultaneously carried out Architectural elements and Building equipment elements improvement plans, it was found to be effective in preventing the spread of contaminants due to duct backflow and short circuiting. In addition, it was analyzed that a constant differential pressure was maintained even if the air volume of the Portable Negative Pressure Unit was reduced. In addition, it was found that if the pressure in the patient ward where the contaminant source is generated is formed by controlling the air volume of the Portable Negative Pressure Unit, the spread from the contaminated patient ward can be blocked..

In the total improvement, if the Portable Negative Pressure

Unit air volume is reduced, the appropriate pressure difference maintenance, noise, and energy usage may be reduced, but the contaminant concentration of the patient ward itself may increase due to the decrease in the Air exchange rate. On the other hand, increasing the Portable Negative Pressure Unit air volume causes increased pressure differenc, noise and energy usage, but the Air exchange rate increases, which reduces the contamination concentration of the patient ward itself. In order to create a comfortable indoor environment for patients, a solution that considers noise and Contamintion degree at the same time is needed.

This study was conducted only in three consecutive wards, not the entire ward, and has limitations in that external factors could not be controlled because all wards except for the measurement area were being used. In the future, in order to more accurately identify the contaminants spread route and prepare alternatives, it is necessary to conduct additional measurement and simulation analysis of the entire ward along with external factor control.

Keyword : Portable Negative Pressure Unit, Emergency Switching Type Negative Pressure Isolation Ward, Field measurement, Dispersion experiment, Improvement plan simulation
Student Number : 2021-28647

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Chapter 1. Introduction

1.1 Study Background and Purpose

In the case of an infectious disease, it is difficult to prevent and manage compared to other diseases because it mutates every time it is prevalent and new epidemics appear. In the case of respiratory infectious diseases, new infectious diseases have been continuously emerging every 5 to 6 years since 2003, from SARS(Severe Acute Respiratory Syndrome) in 2003 H1N1(Novel Swine-Origin Influenza) in 2009, MERS(Middle East Respiratory Syndrome), COVID-19(corona virus disease 19)in 2019. To prevent the spread of these infectious diseases, many studies have been conducted, and the infection route and cause of transmission have been identified.

In the case of respiratory infectious diseases, the causes of transmission are largely classified into two types: droplet infection and airborne infection. Among them, droplet infection is transmitted through droplets (secretions) of large particles with a particle size of 5 μm or more through coughing, sneezing, and talking. Since droplets are relatively heavy, they are deposited at a short distance within 2m by gravity, but can be spread over a wider range by air conditioning facilities that affect indoor airflow.[1][2][3] In the case of airborne infection, the moisture

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1) https://www.ksid.or.kr/rang_board/list.html?num=3416&code=ncov_faq

2) Park, J. M, Park, S. W, Cai, Y, & Song, D. S. (2021). Analysis of transmission characteristics and infection rate by the location of pollutants and airflow from the air-conditioner in the classroom. SHAREK. workshop presentation file pp. 548-551 2021, 21-W-136

component of the droplets discharged through the patient's body fluid evaporates, and the remaining small droplet nucleus particles of 5 μm or less spread through the air. Droplet nuclei are less affected by gravity, so they have a longer floating time and spread over a wide range through the air.[4] Airborne infection spreads and moves relatively faster than other media, making it difficult to prevent and control infection.

In order to suppress secondary infection and prevent spread to the community through isolation of respiratory infectious diseases with such a high risk of transmission in the early stages of outbreak, Negative Pressure Isolation Ward has been installed and operated. In general, a negative pressure isolation room forms a pressure difference between rooms using air conditioning equipment in the building. Through the pressure difference formed, the flow of air is induced in one direction from a semi-clean/clean area with a low degree of contamination to a contaminated area such as a patient room with a high degree of contamination to suppress the spread of infectious..

However, COVID-19, which occurred in 2019, caused a pandemic with an unprecedented infectious disease. As a result, the accommodating capacity of the existing negative pressure isolation wards has reached its limit. To solve this problem, infected patients were isolated in a Switching Type Negative Pressure Isolation Ward, which was switching from a normal ward into a negative pressure room using a portable negative

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3) Sung, M. K. (2016) . 의료시설에서의 감염과 환기. SAREK. Journal v.45 no.7 (2016), 1229-6430.

4) Kwon, S. B., & Kim, C. S. (2010). 국내외 공기감염 분야 연구동향 (Review of Recent Studies on the Airborne Infection). Particle and Aerosol Research, 6(2), 81-90.

pressure unit. However, there is uncertainty about safety as it was installed urgently without clear standards or verification.

Therefore, in this study, basic environmental measurements and contamination diffusion experiments were conducted to evaluate the safety of the Switching Type Negative Pressure Isolation Ward. Through measurement data analysis and simulation, we intend to propose improvement plans within the ward.

1.2 Research Approach and Scope

In this study, the dispersion path of contaminants was determined by conducting a basic environment and contaminant diffusion experiment for a Emergency Switching Type Negative Pressure Isolation Ward using a Portable Negative Pressure Units. Afterwards, the problems discovered through experiments were implemented through simulation and a plan to prevent diffusion in the ward was suggested. Detailed research scope and methods are as follows.

1) Preliminary Study of Negative Pressure Isolation Wards

Guidelines for AIIR and Switching Type Negative Pressure Isolation Wards written national and international were analyzed. Based on this, it was used as the theoretical background of this study, and the contents to be additionally reviewed were confirmed. In addition, the requirement and direction of this study were determined by analyzing the experiment results and simulations of previous research.

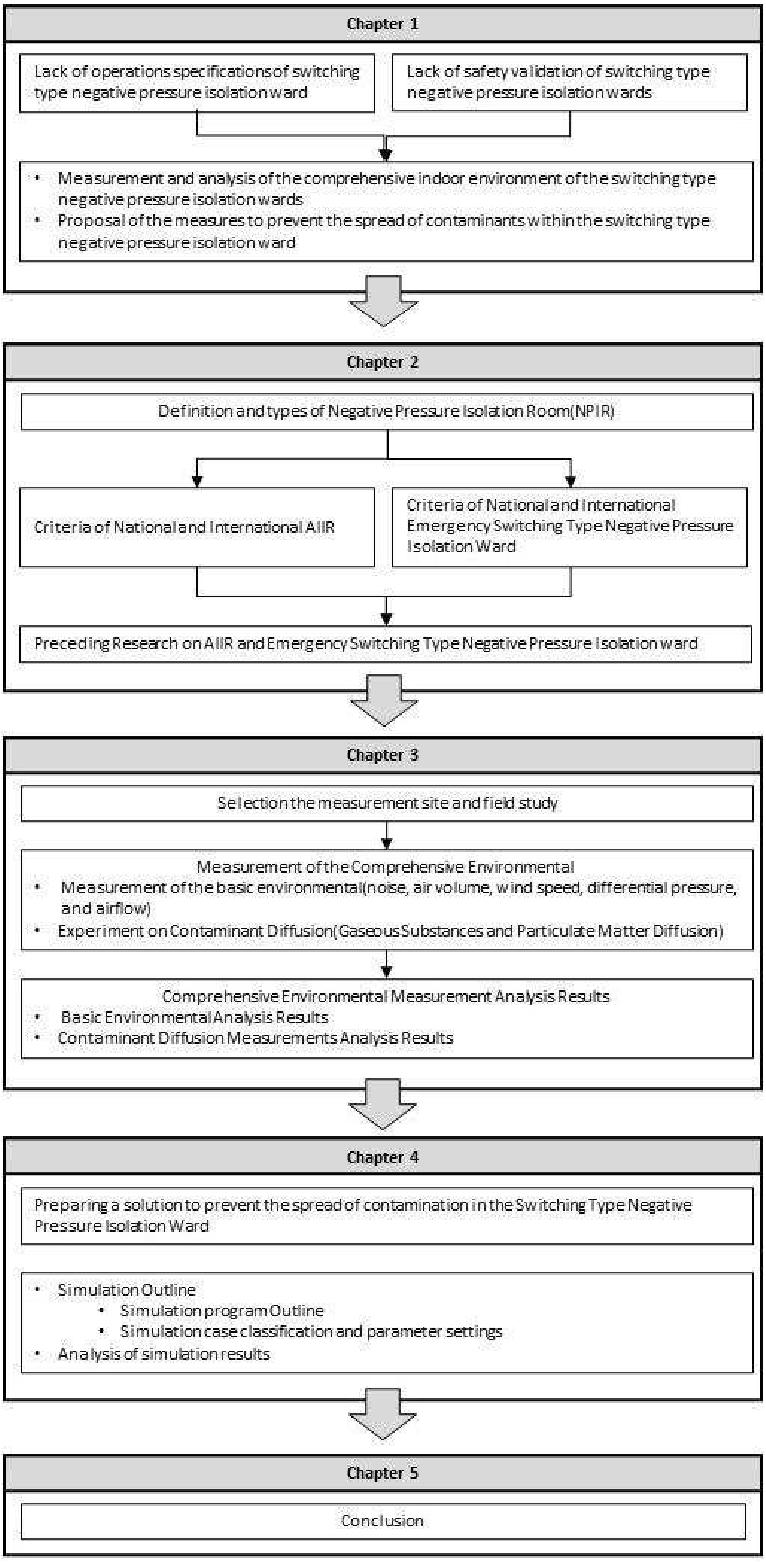
2) Comprehensive Environmental measurement and analysis of Switching Type Negative Pressure Isolation Wards

Through the research literature on Switching Type Negative Pressure Isolation Wards, problems (reverse flow, diffusion of pollutants) that may arise when installing a portable negative pressure unit were identified. Among the wards that operated Switching Type Negative Pressure Isolation Words during the COVID-19, pandemic, wards that could be operated the same as at the time were selected as measurement targets. By measuring the basic environment and contamination spread in this measurement target area, the formation of pressure difference and the spread of pollutants according to the change in air volume of the portable negative pressure unit confirmed. In addition, this measurement result data was used as basic data for simulation of future improvement measures to prevent the spread of contaminants.

3) Preparing a solution to prevent the spread of contamination in the Switching Type Negative Pressure Isolation Ward

Based on the analysis of basic environmental assessment and contaminant diffusion experiment data, a plan to apply contaminant diffusion prevention measures was established. In addition, through the CONTAM simulation AFN model, the effect of preventing the spread of contaminants due to the improvement of Architectural elements, Building equipment elements, and Total was evaluated. The leakage area of the building envelope and wall applied to the simulation was selected as CONTAM library data. The air volume of the Portable Negative Pressure Unit used the measured data. Based on the simulation model implemented, a plan to prevent diffusion in the ward was presented.

The research progress according to the above research scope and method is as shown in [Figure 1.1]. can be expressed as a diagram.



[Figure 1.1] Research Flowchart

Chapter 2. Preliminary Study

This chapter is the preliminary study of Negative Pressure Isolation Room(NPIR), covering the definition, classification of the types(Airborne Infections Isolation Room(AIIR), Switching Type Negative Pressure Isolation Room(ESTNPIW)), and the operations specifications based on the national and international guidelines. Recent studies dealt with Switching Type Negative Pressure Isolation Room and the site measurements are also reviewed to come up with the originality and aim of this study.

2.1 Definition and types of Negative Pressure Isolation Room

As shown [Figure 2.1], A Negative Pressure Isolation Room(NPIR) is a type of medical facility that employs a ventilation equipment to maintain the negative pressure inside the room (1) creating directional airflow from outside areas with lower contamination to inside with higher contamination within infectious disease control institution (2) preventing the spread of the pathogenic microbes from the patients infected by the emerging infectious disease (Ebola virus disease, Mycobacterium tuberculosis complex(MTBC), Measles, Severe Acute Respiratory Syndrome coronavirus(SRAS-CoV) and Coronavirus disease 2019 (COVID-19), Influenza Virus (H1N1), etc.) or exposed to bioterrorism agents.

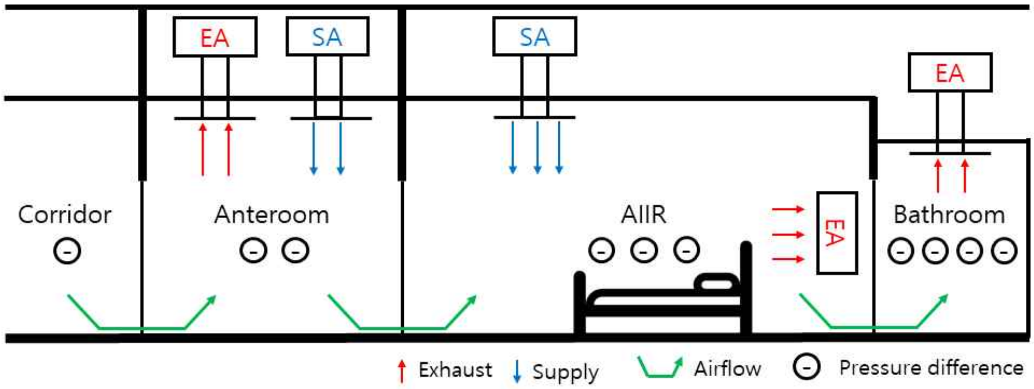
NPIR is commonly referred to A Nationally Designated

Negative Pressure Isolation Wards in national or Airborne Infectious Isolation Rooms(AIIR) international. NIPR consists of (1) an anteroom between the corridor and the room (2) a single-bed room where the highly infectious disease patient is isolated and (3) the bathroom with the lowest pressure, creating forced airflow into the bathroom.

However, with the spread of highly contagious diseases such as SRAS and COVID-19, excess hospital capacity due to limited number of the NIPR became problem. As an alternative, conversion of a single or multi-bed room to the Negative Pressure Isolation Room is proposed in Korea, which can be classified into two categories based on the method: Emergency Negative Pressure Isolation Ward by renovation and Emergency Switching Type Negative Pressure Isolation Ward(ESTNPIW) by quickly installing Portable Negative Pressure Units(PNPU).

The scope of this study is limited to the Emergency Switching Type Negative Pressure Isolation Ward(ESTNPIW) with Portable Negative Pressure Units(PNPU). In this study, general Negative Pressure Isolation Rooms at national and international were named AIIR(Airborne Infections Isolation Room) and lower-level Negative Pressure Isolation Ward which is converted by installing the PNPU are referred to as Emergency Switching Type Negative Pressure Isolation Ward(ESTNPIW).

Though a number of countries operated ESTNPIW during the COVID-19 pandemic, insufficient on-site measurements and research were done due to field conditions. Thus, experimental verification is necessary along with investigating improvement measures of it.



[Figure 2.1] Airborne Infections Isolation Room configuration

2.2 Criteria of National and International AIIR

As of December 2021, the nationalally installed AIIR(single-bed)is 213 in 38 hospitals, which has increased by 51% compared to 2019, showing surged number of infectious disease control institutions with the outbreak of the COVID-19 pandemic. The national AIIR installation and operation guidelines adopted the guidelines of the USCDC. Based on the published national guideline, <Table 2.1> summarizes the Architectural and Building equipment standard of AIIR facilities.

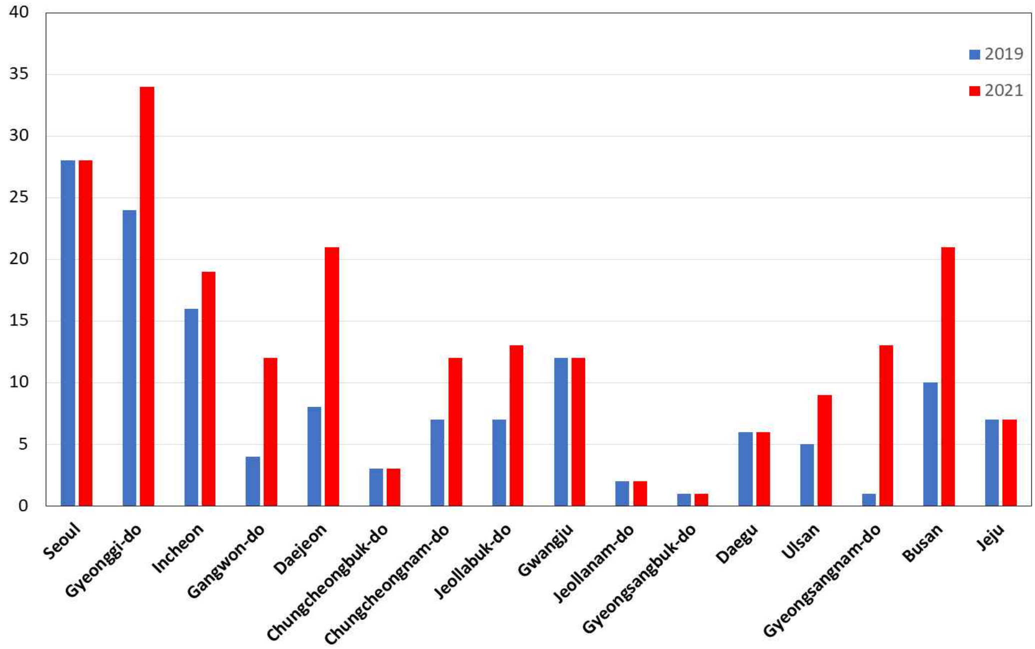
In this section, national and international literature and guidelines for AIIR from four different countries (United States(US), United Kingdom(UK), Europe, and Australia) are reviewed and compared. Each of them consists of architectural and Building equipment standard for AIIR and guidelines to prevent the spread of the disease. The guidelines and documents prepared in each country are as shown in <Table 2.2>, and the contents related to air conditioning equipment are summarized in <Table 2.3>.

Specifically, the presence of an anteroom, pressure difference between rooms, air change per hour, the presence of high-efficiency particulate air(HEPA) filters at supply and exhaust ports, air re-circulation, etc. are compared in <Table 2.3>.

According to national regulations, airflow and pressure should be adjusted to maintain the differential pressure of 2.5Pa or more between each room, restricting the outflow of pathogens from the AIIR). The minimum pressure difference value is the same as that of the US but is different from the others depending on the presence of the anteroom. In the case of Korea, Europe, and Australia, where the anteroom is obligatory, the standard is set as 5Pa, 20~30Pa, and 30Pa each; the standard is 2.5Pa and 5Pa each for the US and the United UK where the anteroom is a recommendation. Despite the facilities installed for the same purpose, the range was at least 2.5 to 30 Pa. As a result, it is decided that various countries have varied pressure differential standards presented in the guidelines.

Sufficient ventilation can dilute and remove pathogens from the infected patients, maintaining the indoor air quality inside the hospital rooms. The minimum/recommended or established/newly built hospital times of air change per hour in the are suggested in the guidelines. The number varies between 6ACH to 15ACH, while the national guideline sets a minimum of 6ACH and recommends 12ACH or more. However, as most countries utilize a 100% outdoor air ventilation system to prevent cross-infection, the increase in the number of ventilation leads to a surge in energy consumption. To cope with this problem, in the US, recirculation is allowed and the number of introductions of the outdoor air is relieved to at least twice per hour as long as the air is filtered through a HEPA filter in the corresponding room.

Similarly, an appropriate method that can simultaneously address indoor air quality issues and energy consumption problems is required.



[Figure 2.2] AIIR(Airborne Infections Isolation Room) present condition

<Table 2.1> National AIIR Facility Standard

Category	Standard
Architectural Elements	• Composition of airborne infectious isolation area - Negative pressure isolation area must be physically separated from other areas. - In principle, a single room including a bathroom in a patient room is installed . • Airtight structure - The floor, walls, and ceilings must be airtight to prevent the air movement and air leakage. - To block the airflow, the walls and the floor slab of the upper floor must be closely attached. - To maintain the negative air pressure in the room, windows must be airtight • Windows and doors - To maintain the negative air pressure, the windows should be opened only in the case of emergency - Doors on the both sides of the adjacent rooms near the AIIR must be interlocked - Doors in Corridor anterooms, AIIR anterooms, and AIIR should be automatic doors
Building Equipment Elements	• Air Conditioning equipment - Air conditioning equipment must have a dedicated supply and exhaust system, and be operated in a 100% outdoor exhaust system - To prevent the backflow of the contaminated air, a check damper must be installed or a high-efficiency particulate air (HEPA) filter or a filter with the same or higher level must be installed at the supply and exhaust ports - Even if the air is filtered with high-efficiency particulate air (HEPA) filter, the exhausted air from the AIIR or AIIR Anteroom must not be recirculated in the other spaces - To prevent summer season Virus, no fan coil unit (FCU) or System Air-Conditioner

<Table 2.2> National Guideline List for AIIR

	Main agency	Year	Guideline
US	USCDC	2019	- Guidelines for Environmental Infection Control in Health-Care Facilities[5)]
	ASHRAE	2017	- Ventilation of Health Care Facilities. 8400(ANSI/ASHRAE/ASHE Standard 170-2017)[6)]
UK	HBN	2009	- HBN 04-01 Supplement 1 isolation facilities for infectious patients in acute settings (2009)[7)]
		2013	- HBN04-01Adultin-patientfacilities(2013)[8)]
		2013	- HBN04-02Criticalcareunits(2013)[9)]
EU	ENHID	2011	- Manual for the safe and appropriate management of Highly Infectious Diseases patients in isolation facilities[10)]
	REHVA	2021	- REHVA COVID-19 guidance document[11)]
AU	VAC	2007	- Guidelines for the classification and design of isolation rooms in health care facilities (2007)[12)]
	AHFG	2016	- Part D-Infection Prevention Control (2016)[13)]
KR	KCDC	2022	- 국가지정 입원치료병상 운영과 관리지침(2022)[14)]

5) CDC. (2003). Healthcare Infection Control Practices Advisory Committee (HICPAC): Guidelines for Environmental Infection Control in Health-Care Facilities. *U.S. Department of Health and Human Services Centers for Disease Control and Prevention (CDC) Atlanta, GA 30329, July*, 1-235.

6) Sheerin, M. P., Granzow, F. E., Anderson, D. J., Burley, B. J., Dombrowski, J. M., English, T. R., Erickson, D. S., Fauber, J. P., Flannery, J. J., Friedman, S. D., Hauck, D. J., Heinlein, R. N., Hosking, N., Johnson, A. L., Keen, M. R., Koenigshofer, D., Langowski, P. H., Locke, M. D., Mages, S. J., … Humble, J. (2020). Ventilation of Health Care Facilities. ANSI/ASHRAE/ASHE, 8400.

7) Department of Health. (2009). Health Building Note 04-01. Supplement 1: Isolation facilities for infectious patients in acute settings. National Health Service.

8) Department of Health. (2013a). Health Building Note 04-02 Cr itical care units. Department of Health.

9) Department of Health. (2013b). In-patient care Health Building Note 04-01: Adult in-patient facilities. Health Building Note 04-01: Adult in-Patient Facilities, 6.

10) REHVA, Federation of European Heating, V. and A. C. Associations. (2012). REHVA Covid19 HVAC Guidance. European University Institute, 2020(2), 2-5.

11) Bannister, Barbara; Brodt, H.-R. (2011). EuroNHID project European

<Table 2.3> Comparison of national Guideline for AIIR

Category			KR	US	UK	EU	AU
Plan	Anteroom	Mandatory	○			○	○
		Optimal		○	○		
Air system	Pressure Difference [Pa]		2.5	2.5	5	10-15	15
	Air Change Rate [ACH]	Mandatory	6				12
		Optimal	12		10		15
		Old Construction		6		6	
		New Construction		12		12	
	HEPA Filter Install		○	○	○	○	○
	Air Recirculation		X	○	X	X	X
	Minimum Outdoor Air Changes Per Hour (ACH)		-	2	-	-	-
Other	Heat Exchange		-	○	-	-	○
	Room Pressure Monitoring System		○	○	○	○	○

2.3 Criteria of National and International Emergency Switching Type Negative Pressure Isolation Ward

Despite the expansion of AIIR facilities due to the prolonged COVID-19 pandemic, which is unprecedented worldwide, the ward occupancy rate has faced saturation. In order to secure wards, an alternative was proposed to switch a general ward in a multi-person ward into a negative pressure isolation ward, and it was intended to switch(build) into a negative pressure

Network for Highly Infectious Diseases Manual for the safe and appropriate management of Highly Infectious Diseases patients in isolation facilities. ENHID, February, 1-209.

12) VACIC. (2007). Guidelines for the classification and design of isolation rooms in health care facilities. Victorian Advisory Committee on Infection Control.

13) Australasian Health Infrastructure Alliance. (2016). Part D: Infection Prevention and Control | AusHFG (Revision 7.0). AHIA, November, 1-40.

14) KCDC. (2022). 국가지정 입원치료병상 운영과 관리 지침. 질병관리본부.

isolation ward in a short period of time using a PNPU. In the case of international, guidelines for switching general ward into negative pressure ward of various types have been prepared by applying PNPU since the late 2000s. In national, There was a guideline for using PNPU when expanding the number of AIIR wards that required to be legally secured, but there was no such standard for switching general ward. Therefore, based on national and international guidelines and literature, the type of ESTNPIW was analyzed in this section.

2.3.1 Analysis of Types and Criteria of International Emergency Switching Type Negative Pressure Isolation Ward

The characteristics of each type of application of PNPU were researched into and analyzed when switching a general room into a negative pressure isolation refer to international guidelines and literature. After that, it was newly classified by type. Depending on the location the air inside the patient ward was exhausted, it could be divided into two types outdoor air exhaust type and internal circulation type.

1) Outdoor air exhaust type

The outdoor air exhaust type is one that is finally exhausted to the outside via the PNPU exhaust port, and the direct exhaust type and indirect exhaust type are categorized based on where the negative pressure device exhaust duct is installed.

(1) Direct exhaust type

The direct exhaust type is one in which a PNPU is placed within the patient ward or outside the building, and the contaminated air inside is directly exhausted by connecting the PNPU' s exhaust duct to the window facing the outdoor air. Feature consist of follows; ① The exhaust duct inside the patient ward should be sealed to prevent air backflow through the exhaust duct. ② The PNPU's output must be set to maintain a pressure differential of 2.5 Pa or greater between corridor and ward. ③ The door should be closed and operated to prevent the spread of contaminants. ④ When installing in cold(zero) areas, it is recommended to install the damper or louver outside to reduce condensation and snow−induced airflow restrictions. [15][16][17]

(2) Indirect exhaust type

The indirect exhaust type is one in which a PNPU is placed inside the patient ward and the PNPU's exhaust duct is connected to the ward's exhaust duct, so that the contaminated air inside is indirectly exhausted to the outside air via the ward's exhaust duct. Feature consist of follows; ① Except for the exhaust duct connected to the PNPU, the exhaust duct inside the patient ward must be sealed to prevent air backflow through the exhaust duct. ② The PNPU's output must be set to maintain

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15) Anderson, J., Geeslin, A., & Streifel, A. (2017). Airborne Infectious Disease management. Methods for temporary negative pressure isolation. Office of Emergency Preparedness. Minnesota Department of Health, 6−7.
16) Booth, R. D., Corso, G. J., Booth, O. M., Martinez, L. M., & Rubin, L. F. (2021). Current / Updated Health Care Facilities Ventilation Controls and Guidelines for Management of Patients with Suspected or Confirmed Naval Medicine Readiness and Training Command , Naval Hospital Camp Pendleton Industrial Hygiene Department Head Naval Hosp, 12−13.
17) Minnesota Department of Health. (2020). Guidelines for Temporary Negative Pressure Isolation Rooms. 1-2.

a pressure differential of 2.5 Pa or greater between corridor and ward. ③ The door should be closed and operated to prevent the spread of contaminants. ④ In the type of indirect exhaust, the effect of the entire air conditioning system on the negative pressure formation of adjacent rooms must be considered.[18][19]

2) Internal circulation type

The internal circulation type filters contaminated air with a HEPA filter installed within a PNPU to reduce pollution level□and circulate it within the patient ward. According to the type of equipment connected to the PNPU, it may be categorized into curtain (partition) type, headboard type, and portable anteroom type.

(1) Curtain (Partition) type

The curtain type is area around the patient□bed is sealed with a plastic curtain (partition) and The contaminated air inside the curtain is exhausted to the patient ward by the PNPU. Feature consist of follows; ① To minimize leakage, the connection area (wall, floor, etc.) with the plastic curtain must be sealed. ② The PNPU's inlet must be located inside the curtain, and the exhaust port must be located outside the curtain. ③ Appropriate when isolating a patient who is unable to walk. ④ A sealed area with a plastic curtain can form a relatively negative pressure, but the entire room cannot.[20][21]

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18) op.cit., Anderson, J., Geeslin, A., & Streifel, A. (2017), 8-9.
19) op.cit., Booth, R. D., Corso, G. J., Booth, O. M., Martinez, L. M., & Rubin, L. F. (2021), 14-15.
20) op.cit., Anderson, J., Geeslin, A., & Streifel, A. (2017), 10-12.
21) Mead, K., Feng, A., Hammond, D., Shulman, S., Engineering, of Applied Research, P. H. B. D., & Technology. (2012). Expedient Methods for Surge Airborne Isolation within Healthcare Settings during Response to a Natural

(2) Headboard type

The PNPU's duct is connected to the headboard type ventilation device to ventilate the local area (in charge of the patient's head) and exhaust it inside the ward. Feature consist of follows; ① When the ventilation device is installed alone, the airflow does not have a certain directionality. ② When combined with the plastic side wall, the air flow has a predetermined direction and the pollutant particles do not flow out to the outside of the sidewall. ③ When connected by a plastic side wall, the side wall component can form a relatively negative pressure, but the entire ward cannot.[22)23)]

(3) Portable anteroom type

It is a type of temporary construction of negative anteroom using a PNPU at the entrance of the patient ward, and contaminated air inside the ward is exhausted into the corridor through a PNPU. Feature consist of follows; ① The temporary anteroom must be at least 1 x by 2 m in size. ② Except when moving to the room for pressure difference formation, the entrance door to the patient room shall be open, and the anteroom' s door shall be closed. ③ There are no regulations for the pressure differential between the temporary anteroom and the patient ward, as well as for the equipment output.[24)25)]

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or Manmade Epidemic. EPHB 301-05f, 144-150.

22) Ibid., 53-55.

23) Johnson, D. L. (2005). Oklahoma State Department of Health Design and Implementation Guidelines for Airborne Infectious Isolation under Epidemic Emergency Response Conditions Prepared. 41-43.

24) op.cit., Anderson, J., Geeslin, A., & Streifel, A. (2017), 13-15.

25) op.cit., Booth, R. D., Corso, G. J., Booth, O. M., Martinez, L. M., & Rubin, L. F. (2021), 13-14.

<Table 2.4> summarizes the Guidelines and characteristics of central air conditioning operation by detailed type. international guidelines and literature were written focusing on the switching of single ward. Except for the air conditioning operation guidelines in the outdoor air exhaust type, no specific criteria were presented for air conditioning systems of other types and wards.

The PNPU has the advantage of forming a negative pressure environment in the patient ward and reducing indoor contaminants. However, when installed in the ward, the noise level rises due to equipment operation, and in the type of internal circulation, air is not exhausted to the outside air, making it difficult to remove odor from the patient. In addition, indirect exhaust types suggest, according to Shadpour et al(2020)[26], that contaminated air discharged from the exhaust duct may be mixed with supplied air, potentially contaminating the entire ward.

Therefore, it is decided that the air conditioning operating plan standard for the entire ward, including the ward, should be established based on experimental type verification.

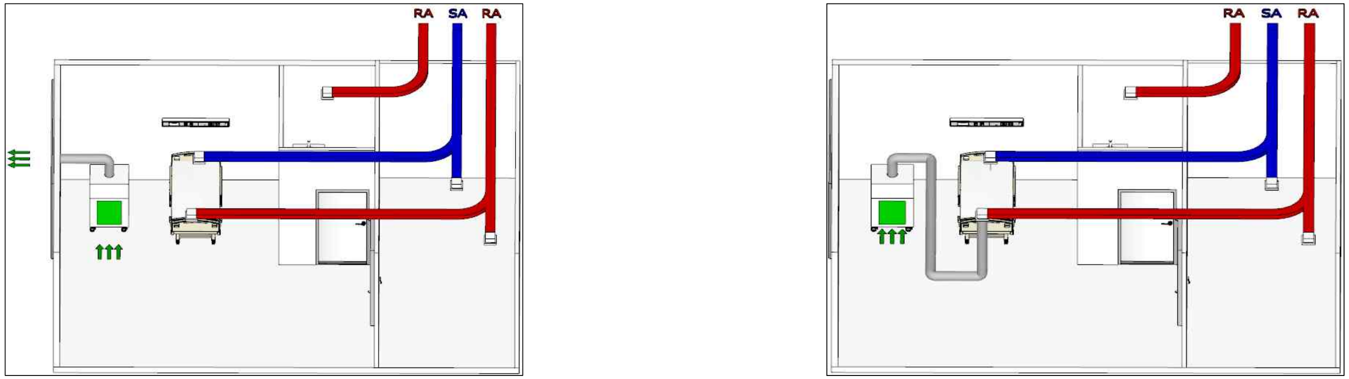
26) SHADPOUR, F., & JOHNSON, S. (2020). Makeshift negative pressure patient rooms in response to COVID-19. ASHRAE Journal, 62(7), 24-31.

<Table 2.4> Central Air Conditioning System Operation guideline Analysis Table by Type of ESTNPIW

Category			Outdoor air exhaust type		Internal circulation type		
Type			Direct exhaust type	Indirect exhaust type	Curtain (partition) type	Headboard type	Portable anteroom type
Exhaust location			Outside of the patient room (outdoor air)	Outside of the patient room (exhaust air duct)	Patient room	Patient room	Corridor
Installation position			Patient room	Patient room	Patient room	Patient room	Patient roon entrance door
Negative pressure area			Patient room	patient room	Inside curtain (partition)	-	Portable anteroom
Pressure difference			2.5 Pa	2.5 Pa	-	-	-
central air conditioning system operating standards	Patient room	Supply	O	O	△	△	O
		Exhaust	X	O	△	△	△
	Corridor	Supply	?	?	?	?	?
		Exhaust	?	?	?	?	?
	Bathroom	Exhaust	△	?	△	△	△

※ central air conditioning system operating standards :

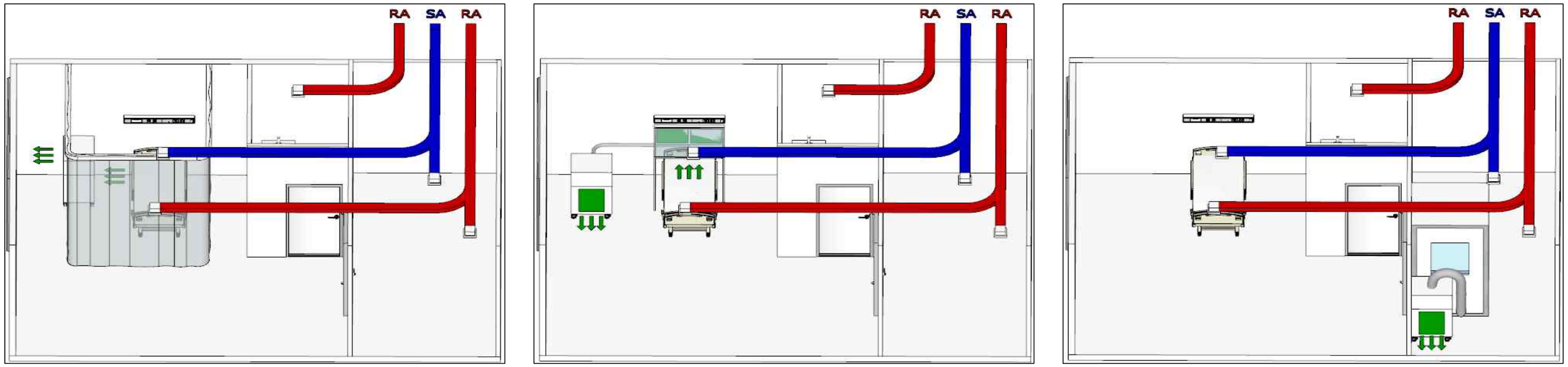
O: Operate △: Operating standards are different X: Unoperate ?: Nonspecified



a) Discharging air to the outside

b) Discharging air to return air system

[Figure 2.3] Outdoor air exhaust type



a) Curtain TNPI

b) Headboard system

c) Portable anteroom system

[Figure 2.4] Internal circulation type

2.3.2 Analysis of Criteria of national Emergency Switching Type Negative Pressure Isolation Ward

In the case of international, as in Section 2.3.1, guideline for various types of ESTNPIW using PNPU have been be written. In national, there were no guidelines for ESTNPIW. However, if the installation and operation standards of <Table 2.5>[27] were satisfied for the expansion of AIIR that must be legally secured, there was an installation standard manual that recognized the patient room with a PNPU as AIIR.(It is not recognized as AIIR after 3 years from 2019.1.1.)

In the case of AIIR using a PNPU specified in the handbook, most of the contents are similar to the "2022년 의료기관 개설 및 의료법인 설립 운영편람" but The contents of the operation of the air conditioning equipment, which prohibits the operation of the air supply in the patient room and the exhaust fan in the bathroom, have been revised and written. Although it is a standard to be referred to when applying a national ESTNPIW, it has a limitation in that it was installed and operated in a single room.

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27) 보건복지부. 2022년 의료기관 개설 및 의료법인 설립 운영편람. Published online 1386.

<Table 2.5> National Switching Type Negative Pressure Isolation Ward Standard

Category		note
Air Conditioning equipment	Air supply	- In order to prevent the spread of the source of infection to other patient rooms, a HEPA filter or a backdraft damper must be installed in the air supply duct, or Provide 100% outside air supply method must be provided - When installing a PNPU, it is necessary to seal central air conditioning equipment in the patient room.
	Air exhaustion	- Installation of PNPU equipped with HEPA filter - There should be no other air-conditioning system inlets around the exhaust duct.
	Pressure control	- differential pressure must be maintained at least 2.5 Pa at between rooms - Installing a differential pressure gauge at the entrance to the patient room - Mandatory installation of alarm devices to prevent abnormal operation of portable negative pressure units
Wall, Ceiling, Window, Door		- The gaps in the patient room are sealed with tape and sheet. - Fix windows so that they do not open and close and seal gaps - Airtight treatment to minimize gaps in the upper and side views of the door
Bathroom·Shower Facility		- There must be a toilet and shower facilities inside the patient room - Do not operate the bathroom exhaust fan - Consider exhaust through HEPA filter
Anteroom		- Mandatory installation of anteroom (or Portable anteroom) - There is no need to maintain more than 2.5 Pa between the anteroom (Portable anteroom) and the external space

2.4 Preliminary Study of AIIR and Emergency Switching Type Negative Pressure Isolation Ward

Due to the ongoing spread of infectious diseases, research on negative pressure isolation facilities has been going on both national and international since the 2000s. Prior to the COVID-19 pandemic, most studies focused on research on AIIR. However, after COVID-19, research on a switching negative pressure isolation ward that switching a general ward into a negative pressure isolation ward by using a portable negative pressure units is also being conducted. Therefore, in this section, previous studies were considered on the diffusion experiment of contaminant conducted in facilities that formed negative pressure by using AIIR facilities and portable negative pressure units.

2.4.1 Preliminary Study of AIIR

Jeong-Yeon Park et al. (2015)[28] conducted a study on the spread of contaminants in the isolation ward during abnormal operation of the facilites. In this study, SF_6 gas was assumed as a contaminant, and CFD simulation was also performed for the same case. As results of the tracer gas experiment and CFD simulation indicate that the contaminants can spread out to other areas under the abnormal condition. In particular, when only the exhaust facilities were stopped, the pressure difference between the rooms changed to positive pressure, so more contaminant air spread than

28) Park, J. Y., & Sung, M. K. (2015). A study on the contaminant dispersion from isolation ward under abnormal operation of facilities. Energy Procedia, 78, 1239-1244

when the door was opened or all facilities were stopped.

The study of Soonjung-Kwon et al.(2016)[29] can be referred to for the isolation effect of Progressive Space Organization in AIIR. In this study, SF_6 gas was assumed as a contaminants, The relative concentration of SF_6 spread from the negative pressure isolation room to the outside(Internal negative pressure corridor, anteroom corridor, external corridors (general area)) when the medical team entered was measured. As a result of the study, passing through the Progressive Space is advantageous in preventing the exhaled breath of a patients from being discharged to the outside. However, the efficiency is shown to be less efficient beyond stage 3, as the decay rate lowers as the stage continues.

In a study by Jinkyun-Cho. et al. (2017)[30], the air conditioning system and differential pressure performance of the target building were verified through CONTAM simulation. Based on this, a CFD numerical analysis was performed to choose the best placement for the exhaust port for the installation of the AIIR ventilation system. Subsequently, an SF_6 gas concentration test was conducted based on CFD numerical analysis. As a result of the study, the ventilation system installed on both walls of the patient's head formed a stable one-way airflow to prevent contaminants from mixing, and the removal efficiency of contaminants was improved by about 30% compared to the existing upper supply/exhaust method.

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29) Kwon, S., & Sung, M. (2016). Isolation Effectiveness by Progressive Space Organization in Negative Pressured Isolation Unit. Journal of The Korea Institute of Healthcare Architecture, 22(4), 79-86.

30) Cho, J., Woo, K., & Kang, H. (2017). Experimental Study of an AIIR Ventilation System for Effective Removal of Airborne Contamination in Hospitals. Journal of the Architectural Institute of Korea Structure & Construction, 33(3), 85-90.

2.4.2 Preliminary Study of Emergency Switching Type Negative Pressure Isolation Ward

Kenneth Mead. et al. (2004)[31] tested the isolation performance of multi−bedroom using portable negative pressure units for the Curtain (Partition) type described in Section 2.3.2. With 1.65 μm polystyrene latex microsphere as the particle of contamination, the migration of contaminants was evaluated in 2−patient and single−patient isolation areas generated using portable negative pressure units and common hardware supplies. As a result of the experiment, it was found that the migration of contaminant was the least when both the air supply and exhaust central air conditioning in the ward were stopped and kept a certain distance from the bedside for smooth air circulation.

Shelly L.Miller et al. (2017)[32] conducted a study to construct a temporary negative pressure anteroom at the entrance of a ward using a portable negative pressure units. Even though air pressure differentials well exceeded CDC and Prevention guidelines, airflow reversals problem occurred. this shows that few studies have detailed the effectiveness of Temporary Negative Pressure Isolation(TNPI), more knowledge and field experience are needed to guide decisions about TNPI growth.

Ehsan S. Mousavi et al.(2020)[33] conducted a study on

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31) Mead, K., & Johnson, D. L. (2004). An evaluation of portable high−efficiency particulate air filtration for expedient patient isolation in epidemic and emergency response. Annals of Emergency Medicine, 44(6), 635-645.

32) Miller, S. L., Clements, N., Elliott, S. A., Subhash, S. S., Eagan, A., & Radonovich, L. J. (2017). Implementing a negative−pressure isolation ward for a surge in airborne infectious patients. American Journal of Infection Control, 45(6), 652-659.

Performance analysis of portable Negative pressure units and temporary plastic anterooms on the spread of contaminant. the isolation ward and anteroom were divided with a plastic barrier, and a negative pressure ward was formed using a portable negative pressure units. As a result of the experiment, even if the negative pressure was not formed due to the operation of the negative pressure units being stopped, the spread of contaminants could be prevented some extent with only the plastic barrier. Although negative pressure formation was effective in reducing the concentration of contaminant, there was a problem that some contaminant spread to other rooms even in the situation where all rooms were formed with negative pressure. consequently, it was found that The negative pressure magnitude alone was not the only important parameter but equipped with temporary anteroom was also important.

By considered the previous studies, It has been shown that the installation of the anteroom is effective in preventing the spread of contaminant. However, it could be seen that more than a certain number of anteroom did not significantly affect the density decay rate. In order to prevent the spread of contaminant, abnormal operation of facilities should not occur first, and appropriate ventilation measures should be considered.

When establishing a switching negative pressure isolation ward, there is no clear standard for central air conditioning operation standards, and even if negative pressure is formed, there are problems with the spread of contaminant. Therefore, in

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33) Mousavi, E. S., Godri Pollitt, K. J., Sherman, J., & Martinello, R. A. (2020). Performance analysis of portable HEPA filters and temporary plastic anterooms on the spread of surrogate coronavirus. Building and Environment, 183(July), 107186.

order to prevent the spread, it is necessary to derive an improvement plan through additional experiments and establish an air conditioning operation standard.

2.5 Summary

In this chapter, a Preceding Research was conducted to confirm the necessity and select the direction of this study. First of all, the definition and type of AIIR & ESTNPIW were identified, and the national and overseas operation guidelines and literature of AIIR and switching negative pressure isolation ward were analyzed. In addition, by examining previous studies on negative pressure isolation ward, additional research content was established. The contents of this chapter are summarized as follows.

1) Currently, the national AIIR is installed and operated based on the "Guidelines for Operation and Management of Inpatient Treatment Beds designated by the country(2022)", and it has been confirmed that the regulations for construction and air conditioning equipments have been written in detail. international also operating AIIR based on guidelines for each country. However, in the case of ESTNPIW, there are no guidelines in national, and there are U.S. guidelines that can refer to the criteria for each type of ESTNPIW, but this also does not provide clear standards. Therefore, it is decided that it is necessary to prepare standards for construction and central air conditioning system.

2) Based on previous research literature, it is expected that the installation of the anteroom will have some effect in preventing the spread of pollutants. However, in the case of a facility converted to a negative pressure room using a PNPU, the spread and airflow reversals of contaminant occur even if formed under negative pressure.

Therefore, this study intends to derive improvement measures for the operation of Architectural and Building equipment to prevent the spread of contaminants.

Chapter 3. Measurement and Analysis of the Comprehensive environment in a Emergency Switching Type Negative Pressure Isolation Ward

In this chapter, contaminant spread to adjacent areas with Emergency Switching Type Negative Pressure Isolation Ward(ESTNPIW) was intensively measured and analyzed.

In order to predict the path where the spread is likely to occur, an analysis of architectural and equipment drawings was conducted, and the represent ward was selected. After that, the indoor Comprehensive Environment (noise, air volume, air velocity, airflow, pressure difference / contaminant spread) were measured.

3.1 Selecting measurement location and field study

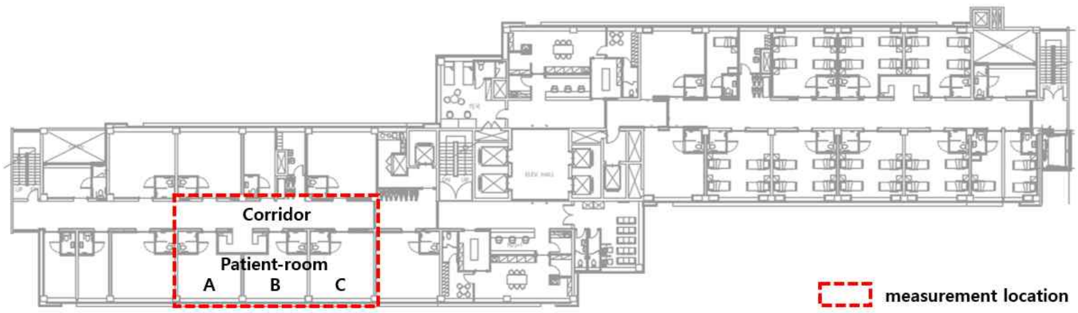
3.1.1 Selecting measurement location to experiment

A public general hospital that constructed a ESTNPIW by using a PNPU during the pandemic was chosen as the target building in order to conduct measurements in a set up that was as similar to the COVID-19 pandemic situation as possible. The ward of the building was selected as the dispersion experiment site after the architectural and building equipment drawings were analyzed to determine that the possibility of spreading the patient ward and corridor on both sides in contact with the base ward would be occur.

3.1.2 A field study

Each ward in the measurement site was equipped with a PNPU installed in the form of direct exhaust to the outside, and the patient ward and corridor were placed around the patient ward B(base ward) that released contaminants as shown in [Figure 3.1].

As during the pandemic, the target floor's central air conditioning system was turned off during the measurement period except for the bathroom’ s exhaust. that time, all air conditioning system port ends were not sealed. In addition, since patients and medical staff resided in the patient ward and NS(nurse station), control was impossible except for the measurement site in the ward.



[Figure 3.1] experimental measurement location

3.2 Measurement of the comprehensive environment

From 09:00 on September 20 to 15:00 on September 22, 2022, an indoor basic environmental(noise, air volume, pressure difference) and contaminant diffusion was conducted on three consecutive wards and corridor with PNPU installed in the ESTNPIW.

The difference in air volume between the PNPU and the air supply and exhaust ports creates a pressure difference between wards that dominantly affect the airflow in a negative pressure isolation ward. The flow path is expected to be confirmed by comparing the concentration of each sampling location to the change in air volume and pressure difference during the diffusion test, so the experiment was carried out by setting the flow volume of the PNPU as shown in <Table 3.1>.

Case 1 represents a scenario in which the PNPUI in each Patient Wards operated normally, while Case 2 represents a scenario when the PNPU in the Base Patient Ward stopped to operate. that time Throughout the measurement, the door to each room was closed in order to create a pressure differential between them.

<Table 3.1> PNPU Setting Air Volume

Case		Portable Negative Pressure Unit Air Volume		
		Patient Ward A	Patient Ward B (Base)	Patient Ward C
Case 1	Case 1-1	Medium	Medium	Medium
	Case 1-2	Max	Max	Max
Case 2	Case 2-1	Medium	Off	Medium
	Case 2-2	Max	Off	Max

3.2,1 Measurement of the basic environment factors

1) Measurement of air volume, air velocity, and Pressure difference in the target location

The air volume of the PNPU, the air velocity of the supply and exhaust ports, and the pressure difference between ward were measured in analyzing the contaminant diffusion path response to changes in air volume and differential pressure.

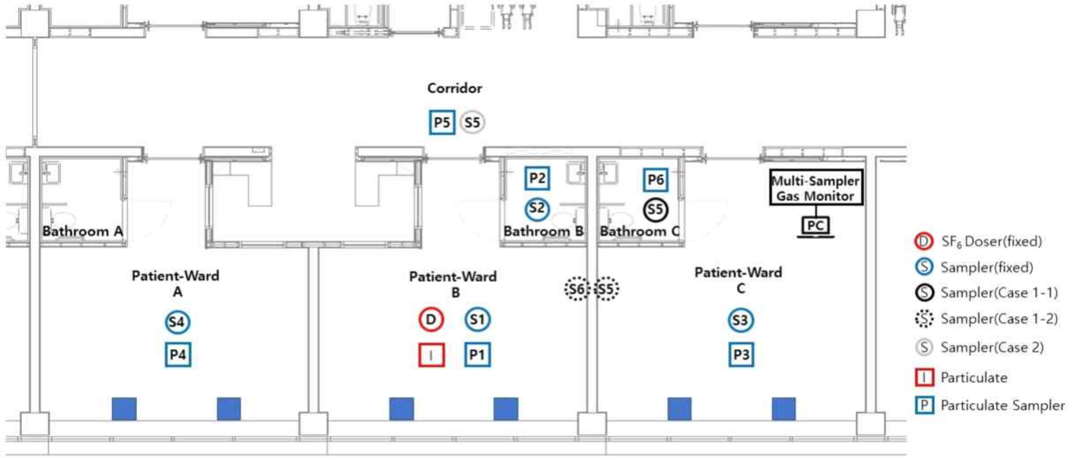
The air volume of the PNPU was measured by attached to hood-type air volume meter to the exhaust port. However, the central air-conditioning system air flow measurement was performed using a digital hot-wire anemometer because it was impossible to attach a hood-type air volume meter due to ceiling finish problems. A differential pressure gauge was used to measure the pressure difference between the room between each corridor and patient ward, as well as between the patient ward and the bathroom. Finally, a fog machine was utilized to verify the operating direction of each ward's supply and exhaust ports as well as the movement direction of the indoor air flow.

2) Measurement of noise in the target location

Noise in the patient ward and corridor was measured for one minute using a noise meter to analyze the noise effect of the PNPU in the patient ward.

3.2.2 Experiment on contaminant diffusion

The purpose of this experiment was to analyze the indoor diffusion path of airborne infections in which droplet nuclei particles of 5㎛ or less spread through the air. The air infection, which is less influenced by gravity and floats through a wide range for a long time, was simulate with gaseous and particulate matter to perform a diffusion experiment. As shown in [Figure 3.2], diffusion experiments were carried out using equipment capable of measuring each substance and shifting the sampling point for each case.



[Figure 3.2] Location of measuring equipment installation for infection source simulation diffusion experiment

1) Experiment on gaseous substance diffusion

In general, the tracer gas(SF_6) used in experiment does not occur naturally in the atmosphere and can be detected at extremely low concentrations therefore it is used in experiments to quantify the amount of contaminants in location. (David L. Johnson. 2005).[34]

When using the HEPA filter, particles with a size of 0.3 μm in the air are filtered 99.97% of the time but SF_6 gas is not filtered. thus the experiment was conducted by simulate the most dangerous scenario in which the source of infection is not filtered.

The concentration of SF_6 gas simulated as the source of infection was consistently released at 15mL/s during the gas phase substance diffusion test which is approximately 10% of the average adult respiratory rate. The gas discharge and sample

34) op.cit., Johnson, D. L. (2005). p. 24

location was set at 1.2m assuming the patient was lying down the bed or sitting. When sampling was performed in the plenum space the gas concentration was measured by attaching a sampling tube at a height of 2.4m.

Prior to the gaseous substance diffusion experiment each case was ventilated for 1 to 2 hours to stabilize the background concentration. Thereafter the gas was discharged at a constant concentration of 15mL/s for about 1 to 2 hours so that the indoor contamination concentration converges. At this time the real-time concentration change in the measurement location was measured with a multi-gas monitor.

2) Experiment on particulate matter diffusion

In the particulate matter diffusion experiment particles generated by commercially available mosquito coils were simulated as the source of infection. When the mosquito coil ignition it was assumed that the majority of it was scattered with a particle size of 0.1~0.3㎛ (Weili Liu, 2003)[35]. PurpleAir(PA-II), a low-cost sensor with high accuracy for measuring the concentration of particles of 2.5㎛(PM2.5) or below (B. C. Singer, 2018[36], Shruti Hegde, 2020[37]) was used

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35) Liu, W., Zhang, J., Hashim, J. H., Jalaludin, J., Hashim, Z., & Goldstein, B. D. (2003). Mosquito coil emissions and health implications. Environmental Health Perspectives, 111(12), 1454-1460.

36) Singer, B. C., & Delp, W. W. (2018). Response of consumer and research grade indoor air quality monitors to residential sources of fine particles. Indoor Air, 28(4), 624-639.

37) Hegde, S., Min, K. T., Moore, J., Lundrigan, P., Patwari, N., Collingwood, S., Balch, A., & Kelly, K. E. (2020). Indoor household particulate matter measurements using a network of low-cost sensors. Aerosol and Air Quality Research, 20(2), 381-394.

for the measurement and the height of the measurement point was 1.2 m.

Like with the gaseous substance diffusion experiment each case was ventilated for 1 to 2 hours before to the experiment to stabilize the background concentration and particles were generated for 1 to 2 hours so that the indoor contamination concentration converges. The background concentration at each point as well as the concentration change during the experiment were measured in real time by connecting the above equipment to the experimental PC.

<Table 3.2, 3.3> outline the measuring equipment used for field measurement and [Figure 3.3] and [Figure 3.4] show equipment installation photos for each measurement element.

<Table 3.2> Measuring Equipment outline(Basic Environment)_(To be continued in the next page)

Measuring equipment	CNDH-100	Testo 816-1	Air Trace-S
Equipment Picture			
Measuring Element	Negative Pressure Formation	Decibel A / C	Visualization of airflow direction
Measuring Range	• 0 ~ 26 CMM	• + 30.0 ~ + 130.0 dB	• 100 cubic feet / minute
Measuring Error	-	• ± 1.4 dB	-

<Table 3.2>

Measuring Equipment	Testo 420	CLIMOMASTER 6501	Testo 400
Equipment Picture			
Measuring Element	Portable Negative Pressure Unit Air Volume	Supply/Exhaust port velocity	Pressure difference
Measuring Range	• 40 ~ 4000 m^3/h	• 2 to 9840 FPM • (0.01 to 50.0m/s)	• 0 ~ +200 hPa
Measuring Error	• ±3 measured % + 12 m^3/h at +22 °C • 1013 hPa (85 ~ 3500 m^3/h)	• ±2 % of reading or 0.015m/s whichever is greater	• ±(0.3 pa + 1 measured %) ±1 Digit (0 ~ 25 hPa) • ±(0.1 hPa + 1.5 measured %) ±1 Digit (25.001 ~ 200 hPa)

<Table 3.3> Measuring Equipment outline(Contaminant Diffusion)

Measuring Equipment	Multi-point Sampler and Doser type INNOVA 1303 & Photoacoustic Multi-Gas Monitor INNOVA 1412i-T5	PurpleAir PA-II
Equipment picture		
Measuring Element	Tracer gas concentration(Gaseous Substances)	PM2.5 Particle concentration(Particulate Matter)
Measuring Range	• gas emission rate(Dozing) : 0.5 ~ 15ml/s • gas suction rate(Sampling) : 20kPa, 15ml/s	• 0.3, 0.5, 1.0, 2.5, 5.0, & 10 μm • Effective range (PM2.5 standard) : 0 to 500 μg/m^3 • Maximum range (PM2.5 standard) : ≥1000 μg/m^3
Measuring Error	• gasses emission(Dozing) : ±2%	• Maximum consistency error (PM2.5 standard) : • ±10% at 100 to 500μg/m^3 & • ±10μg/m^3 at 0 to 100μg/m^3

(a) Air Volume (b) Supply/Exhaust port velocity (c) Air Flow

[Figure 3.3] Installation of a basic environmental measurement equipment

(a) Tracer gas concentration (b) Particulate Matter

[Figure 3.4] Installation of a contaminant diffusion measurement equipment

3.3 Comprehensive environment measurement analysis results

3.3.1 Basic environment measurement analysis results

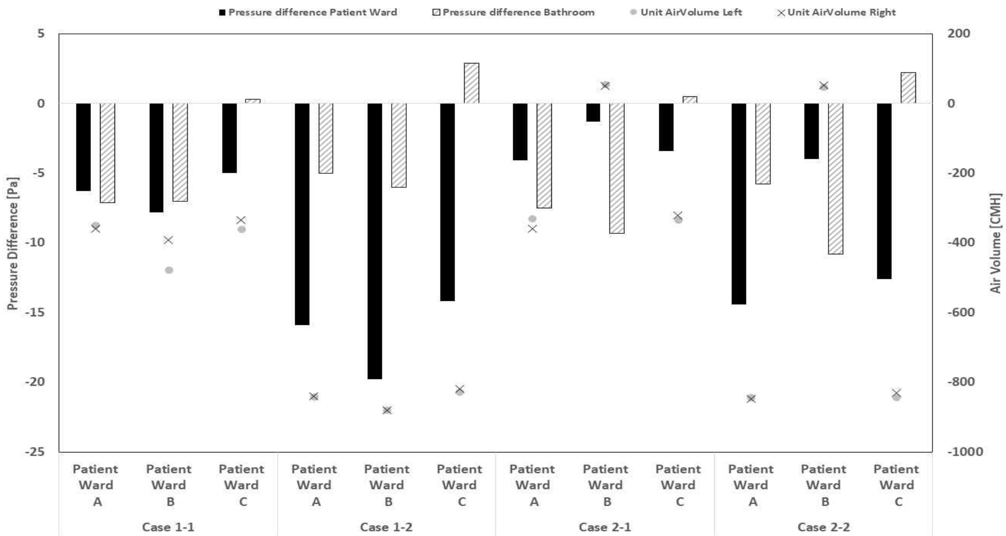
1) Air volume, Air velocity, Pressure difference, Airflow visualization analysis results

When comparing Case 1-1, which used the PNPU at medium level air volume and Case 1-2, which used the PNPU at maximum level air volume it was found that the room-to-room pressure differnece increased as the PNPU's air volume increased. It shown in [Figure 3.5] and <Table 3.4>.

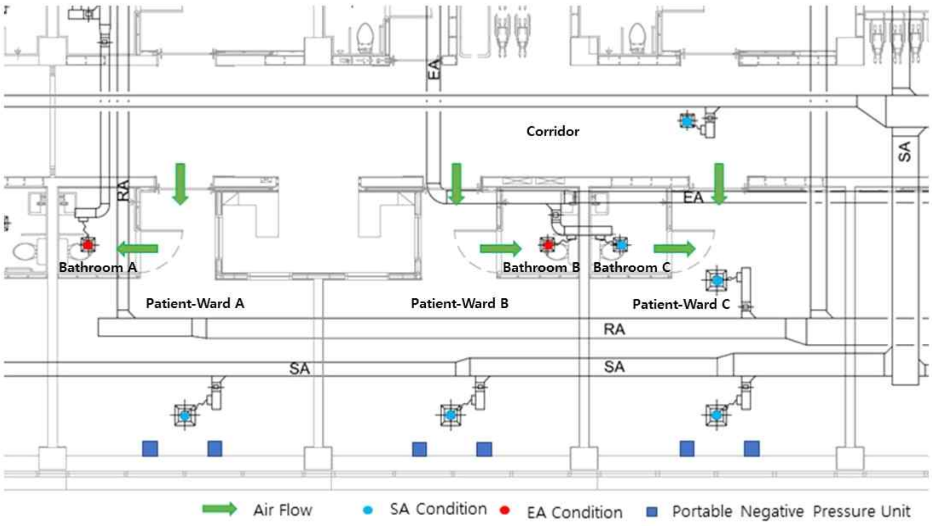
Case 2-1, in which the PNPU in the patient ward B(base ward) was turned off and the air volume in the adjacent wards (A, C) was set to medium level, and Case 2-2, in which the air volume was set to maximum level, were compared. In the patient ward B, the pressure difference between the corridor was significantly lower than in the adjacent ward. At this time, it was discovered that the negative pressure in the patient ward B was caused by the interaction between the air volume of the bathroom B exhaust port and the air volume of the adjacent ward's PNPU. It shown in [Figure 3.5], <Table 3.4>.

Additionally it was confirmed that air backflow from the bathroom C exhaust port due to a pressure imbalance in the bathroom duct when the PNPU was opertation and airflow from the bathroom C infiltrated the patient ward C. It was confirmed that downward airflow was generated from the ceiling of the room where there was a significant leakage due to the visualization of airflow using a a fog machine. It shown in [Figure 3.6].

In addition, the increase in the air volume of the PNPU increased the wind speed at the unsealed air supply/Exhaust port and the bathroom exhaust port, leading to an increase in backflow and an increase in air flow from the ceiling leakage area.



[Figure 3.5] PNPU air volume and room pressure difference by case



[Figure 3.6] Movement of airflow through doors and port

<Table 3.4> Measurements of PNPU air volume and inter-room pressure difference by case

Unit [Air Volume: CMH, Pressure Difference: Pa]

Case \ Air Volume		Portable Unit Air Volume		Pressure Difference	
		Left	Right	Patient Room	Bathroom
Case 1-1	Patient Ward A	- 348	- 360	- 6.3	- 7.1
	Patient Ward B	- 478	- 392	- 7.8	- 7.0
	Patient Ward C	- 360	- 334	- 5.0	+ 0.3
Case 1-2	Patient Ward A	- 840	- 840	- 15.9	- 5.0
	Patient Ward B	- 879	- 881	- 19.8	- 6.0
	Patient Ward C	- 828	- 818	- 14.2	+ 2.9
Case 2-1	Patient Ward A	- 329	- 360	- 4.1	- 7.5
	Patient Ward B	+ 56	+ 51	- 1.3	- 9.3
	Patient Ward C	- 334	- 322	- 3.4	+ 0.5
Case 2-2	Patient Ward A	- 842	- 847	- 14.4	- 5.8
	Patient Ward B	+ 48	+ 53	- 4.0	- 10.8
	Patient Ward C	- 842	- 830	- 12.6	+ 2.2

Note: [+: the direction of air supply into the room, -: Direction of exhaust to the outside]

<Table 3.5> Measurement of the air velocity of the Supply/Exhaust port by case

Unit [Air Velocity: m/s]

Case \ Air Velocity			Port Air Velocity		
			SA	RA	EA
Case 1-1	Patient Ward A	Patient Ward	0.3 (↓)	-	-
		Bathroom	-	-	4.6~-4.8 (↑)
	Patient Ward B	Patient Ward	1.7 (↓)	-	-
		Bathroom	-	-	3.5~-3.6 (↑)
	Patient Ward C	Patient Ward	1.2 (↓)	1.24 (↓)	-
		Bathroom	-	-	0.3 (↓)
	Corridor		0.1 (↓)	-	-
Case 1-2	Patient Ward A	Patient Ward	0.6 (↓)	-	-
		Bathroom	-	-	4.0 (↑)
	Patient Ward B	Patient Ward	2.1 (↓)	-	-
		Bathroom	-	-	3.1 (↑)
	Patient Ward C	Patient Ward	2.0 (↓)	2.1 (↓)	-
		Bathroom	-	-	1.2 (↓)
	Corridor		0.5 (↓)	-	-
Case 2-1	Patient Ward A	Patient Ward	0.3 (↓)	-	-
		Bathroom	-	-	5.3~-5.4 (↑)
	Patient Ward B	Patient Ward	0.8 (↓)	-	-
		Bathroom	-	-	4.3~-4.6 (↑)
	Patient Ward C	Patient Ward	1.0 (↓)	1.05 (↓)	-
		Bathroom	-	-	0.3~0.4 (↓)
	Corridor		0.1 (↓)	-	-
Case 2-2	Patient Ward A	Patient Ward	0.5 (↓)	-	-
		Bathroom	-	-	-5.4 (↑)
	Patient Ward B	Patient Ward	0.9 (↓)	-	-
		Bathroom	-	-	2.7~-2.8 (↑)
	Patient Ward C	Patient Ward	1.9 (↓)	1.85 (↓)	-
		Bathroom	-	-	1.1 (↓)
	Corridor		0.2 (↓)	-	-

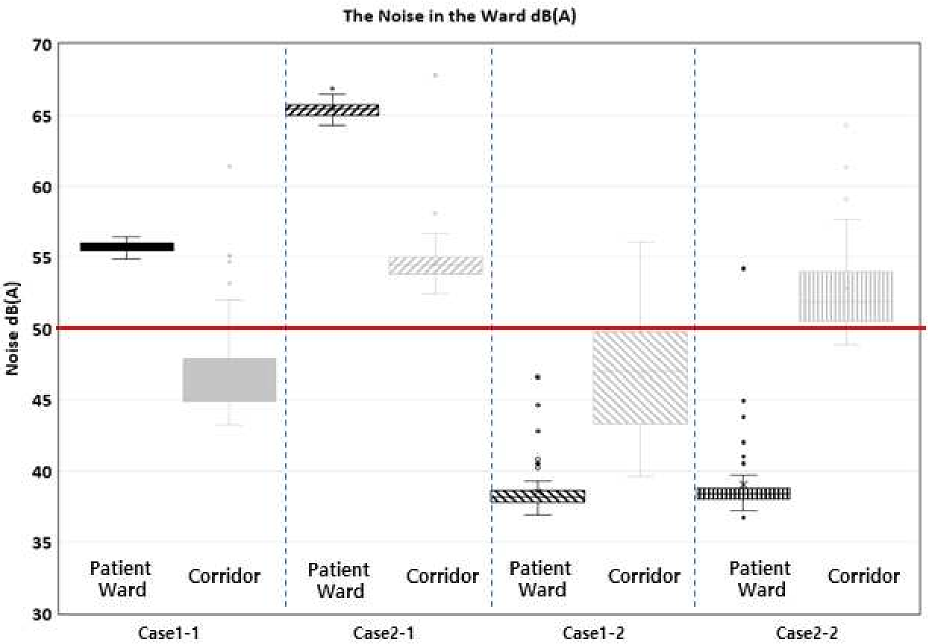
Note: [↑: Airflow rising to the Inside of the port, ↓: Airflow descending to the outside of the port]

2) Noise analysis results

When the PNPU was operated, the noise in the Patient Ward did not comply with the AIIR standard of 50 dB(A) or less, according the results of the noise measurement analysis by case. In particular, the noise level increases along with the PNPU's air volume.

Interviews with medical staff revealed that patients frequently complained about the PNPU's noise, and that it was a problem that the air volume had to be raised to make up for the pressure differential between the rooms.

When the air tightness of the Patient Ward is improved, sufficient pressure difference may be formed even with a small amount of air volume. Therefore, it is determined that improving the interior air tightness of the Patient Ward should proceed first in order to lower the unit's noise level and maintain the room-to-room pressure difference.



[Figure 3.7] Results of noise analysis in the ward by Case

3.3.2 Contaminant diffusion measurements analysis results

The concentration distribution of the infectious agent simulation substance at measurement location was evaluated to determine the path of the infectious agent's spread as a result of the PNPU's operational air volume. The measured values used at this time were based on the period after the concentration of ward B, which emitted contaminants, stabilized, and the values were analyzed from approximately 20 minutes following the start of emission until the end of the measurement.

1) Gaseous substance diffusion measurements analysis results

(1) Operation of the entire ward PNPU [Comparing Case1-1 and Case1-2]

Comparing Case1 in which a PNPU was operated each patient ward the relative concentration detected in the rooms adjacent to the base patient ward looks like increase as the air volume of the PNPU increases. However as PNPU’ s air volume increases, exhaust volume increase so the average concentration of the patient ward B(Base ward) is lower than the medium level air volume Case, and the real average concentration detected in the majority of nearby wards, with the exception of ward A, is also low.

The relative concentration of SF_6 gas detected in the bathroom B was at least 70.6% and as high as 88.8%; this gas was revealed to be vented through the bathroom and a PNPU. When the PNPU is operated, however, the pressure in the connected bathroom ducts becomes imbalanced, resulting in backflow in some bathroom ducts. Thus, a concentration of 1.8 ppm of SF_6 gas was detected in the bathroom C, where it had diffused through the air flowing back to the duct of ward C from the bathroom of ward B. A concentration of 3.2~3.3ppm was detected within negative pressure ward A, and the concentration in patient ward C (4.9ppm) was higher than that in the bathroom (1.4ppm). In addition to backflow due to pressure imbalance in bathroom C ducts, it was expected to spread through other routes; ① short circuiting of air through an outdoor, ② Backflow occurs in the patient wards where the patient is hospitalized.

Additionally, the detection of SF_6 gas in the upper plenum of the B and C patient ward (10.5%, 7.6%) proved that not only the interior space of the patient ward but also the non-airtight plenum area was a diffusion path.

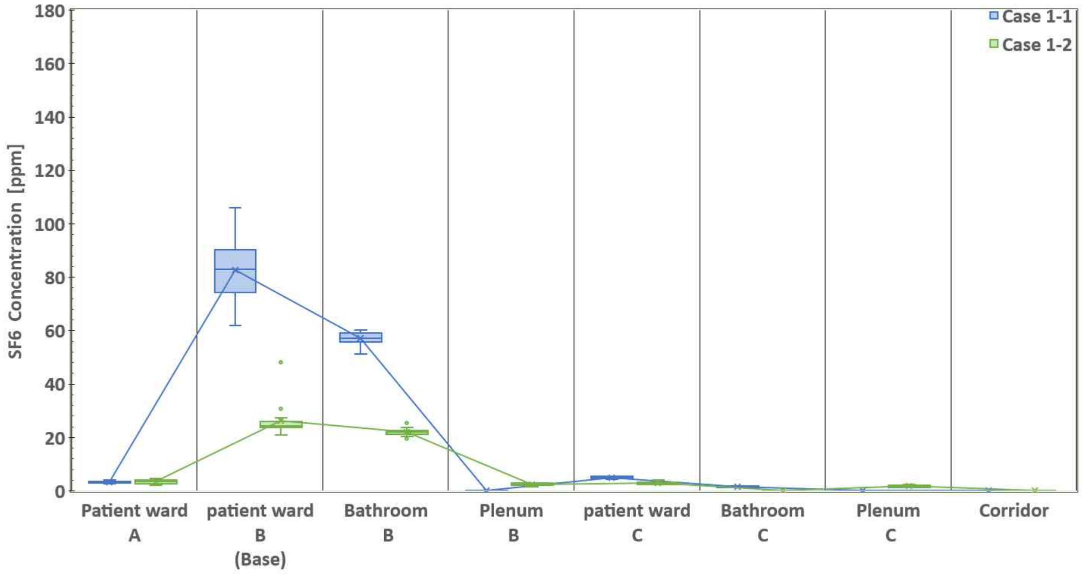
(2) Stop of the operation for Patient ward B PNPU Case [Comparing Case 2-1 and Case 2-2]

When the PNPU in ward B, the Base ward that emits SF_6 gas, was turned off, the relative concentration detected in the bathroom of the Patient ward B(Base ward) was at least 90% and up to 95.5%, and it was confirmed that the airflow primarily moved through the bathroom.

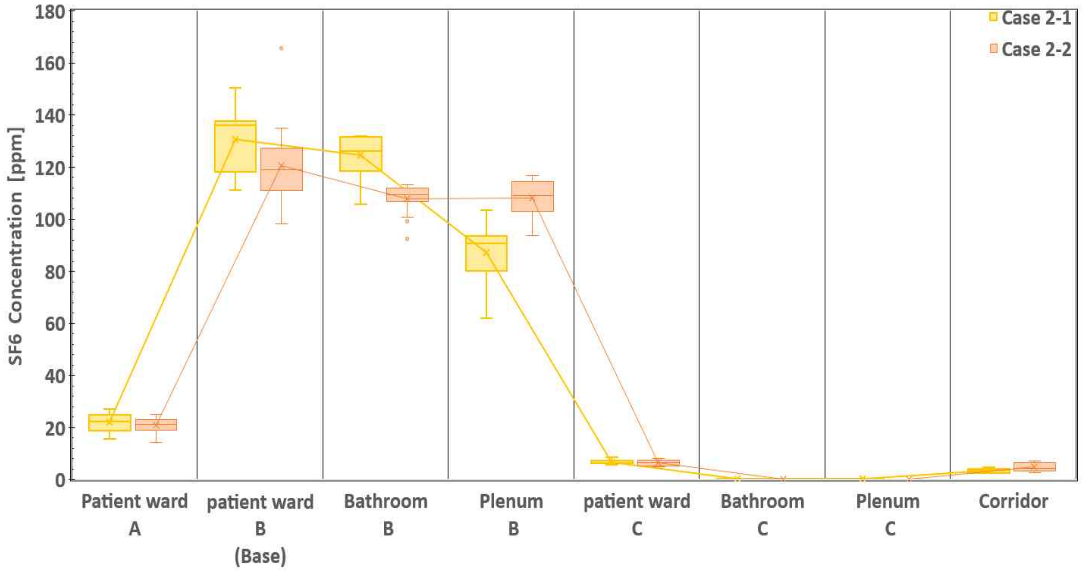
The relative concentration of the plenum in room B was 66.6% when operating the PNPU in both adjacent rooms with medium level air volume and 90.4% when operating with maximum level, and it was found that the plenum acted as the major path of diffusion and spread to adjacent wards and corridors.

Comparing the relative concentrations of adjacent wards by case, Case 2-1 had a concentration of 16.6% in A ward and 5.1% in C ward, while Case 2-2 had a concentration of 17.3% in A ward and 5.1% in C ward, which was 3.2 times more spread to A ward with high pressure difference. In addition, the SF_6 gas transferred to the plenum diffused to the corridor and the patient ward through the non-airtight ceiling leak location's descending air.

Based on the relative concentration measured in the corridor and the Air velocity of <Table 3.5>, the increase in air volume of the PNPU increased the amount of backflow of the bathroom duct and non-airtight ceiling descending air, thereby increasing the spread to patient ward and corridor.



[Figure 3.8] Case 1 SF_6 Gas Concentration Distribution in the Experiment



[Figure 3.9] Case 2 SF_6 Gas Concentration Distribution in the Experiment

<Table 3.6> SF_6 Average (relative) Concentration by Measurement Point

Unit [absolute concentration: ppm, (relative concentration: %)]

Case \ Absolute(Relative) concentration		Patient ward A	Patient ward B (Base)	Bathroom B	Plenum B	Patient ward C	Bathroom C	Plenum C	Corridor
Case 1	Case 1-1	3.2 (4.0)	82.5 (100)	57.0 (70.6)	-	4.9 (6.1)	1.4 (1.8)	-	-
	Case 1-2	3.3 (15.2)	26.2 (100)	21.9 (88.8)	2.3 (10.5)	2.9 (12.9)	-	1.6 (7.6)	-
Case 2	Case 2-1	21.8 (16.6)	130.6 (100)	124.3 (95.5)	87.1 (66.6)	6.6 (5.1)	-	-	3.3 (2.5)
	Case 2-2	21.1 (17.3)	120.7 (100)	107.9 (90.4)	108.2 (90.4)	6.4 (5.3)	-	-	4.8 (4.2)

2) Particulate matter diffusion measurements analysis results

(1) Operation of the entire ward PNPU [Comparing Case 1-1 and Case 1-2]

Comparing Case 1 in which a PNPU was operated□each patient ward, the exhaust quantity increases as the air volume of the PNPU grows, resulting in a decrease in the average concentration of the base ward. though, patient ward A and C, which are directly affected by PNPU, were analyzed to increase the average concentration as the quantity of particles existing inside the existing room (floor, ceiling) floated into the air as the air volume increased.

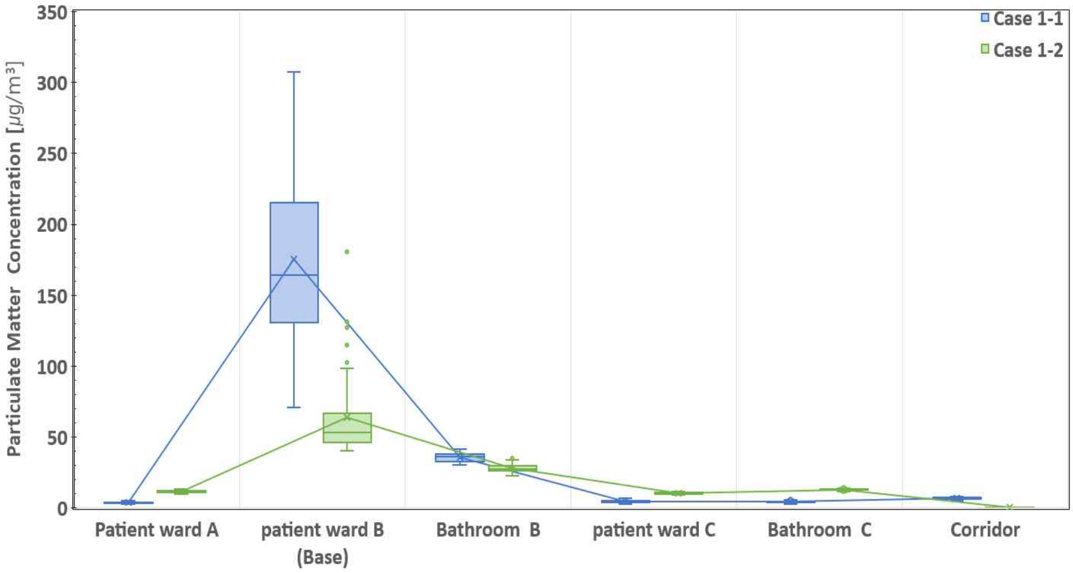
In same way as gaseous material, particulate matter diffusion was exhausted via a PNPU and a bathroom duct. Among these, it is decided that a portion of the particulate matter exhausted from the bathroom B duct has spread to the bathroom C via the air that flows back to the bathroom C duct. In addition, it was found that the average concentration of toilets in Case 1-2 (12.7 ppm) was more than three times that of Case 1-2 (4.2 ppm), so the increase in the air volume of the unit aggravated the pressure imbalance in the duct and increased the amount of backflow and diffusion.

(2) Stop of the operation for Patient ward B PNPU Case [Comparing Case 2-1 and Case 2-2]

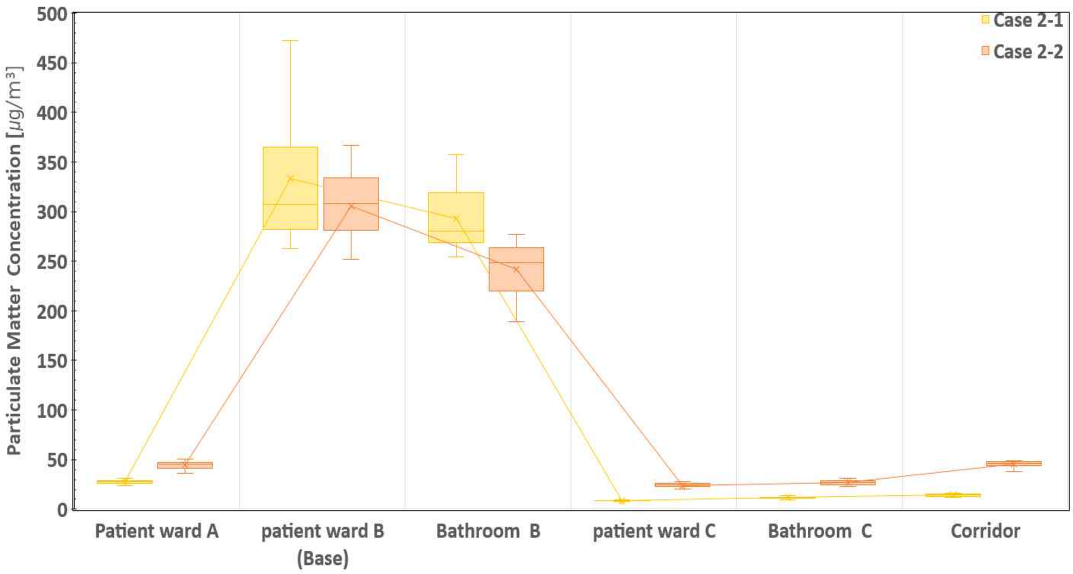
When the unit in Patient ward B was turned off, a relative concentration with at least 79.4% and up to 89.2% was found in the bathroom B. This had shown that the airflow moved to the bathroom.

However, the operation of the unit in the adjacent rooms on both sides operated backflow in the duct, causing in the spread of particulate matter to the bathroom C. In addition, as in the previous case, the increase in air air volume increased the backflow and spread of contaminants, suggesting that the relative concentration of Case 2−2 (8.8%) with high air volume was more than twice that of Case 2−1 (3.8%).

Comparing the relative concentration of adjacent wards between cases, it spread at least 1.8 times and up to 3.1 times more to the A room with high pressure differential among the two rooms through the leakage area between the wards. thus, it is decided that, like gaseous substance particulate matter spreads more to Patient wards with high differential pressure.



[Figure 3.10] Case 1 PM2.5 Concentration Distribution in the Experiment



[Figure 3.11] Case 2 PM2.5 Concentration Distribution in the Experiment

<Table 3.7> PM2.5 Average (relative) Concentration by Measurement Point

Unit [absolute concentration: $\mu g/m^3$, (relative concentration: %)]

Case \ Absolute(Relative) concentration	Case 1		Case 2	
	Case 1-1	Case 1-2	Case 2-1	Case 2-2
Patient ward A	3.5 (2.2)	11.4 (20.4)	27.6 (8.5)	44.5 (14.6)
Patient ward B (Base)	175.1 (100)	63.7 (100)	332.9 (100)	305.3 (100)
Bathroom B	35.5 (22.5)	27.8 (48.6)	293.0 (89.2)	242.1 (79.4)
Patient ward C	4.2 (2.7)	10.2 (18.5)	8.8 (2.7)	24.2 (7.9)
Bathroom C	4.2 (2.7)	12.7 (22.9)	11.6 (3.6)	26.9 (8.8)
Corridor	6.7 (4.2)	-	14.2 (4.5)	45.7 (15.0)

3.4 Summary

The primary objective of this chapter was to conduct a contaminant diffusion experiment to identify the path of the infectious agent's spread within the ESTNPIW. The following is a summary of the results of the basic environment measurement and diffusion experiment of the infection source for identifying the diffusion pathway.

1) When operating the PNPU, exceeds the patient ward's noise standard and the problem worsens as air volume increases.

2) The air velocity and pressure differential altered as the air volume of the PNPU changed. Accordingly the spread path of the infection source could be identified based on the source's concentration at each measurement point.

3) Operate the PNPU enables the formation of a target pressure difference between ward and an increase in air volume results in a rise in this pressure difference. However the operate of the PNPU causes air backflow by imbalancing the pressure of unsealed air inlet/exhaust ports and bathroom ducts. The increase in PNPU air volume exacerbates the pressure imbalance in the duct, which worsens air backflow and diffusion.

4) On the basis of the detection of gaseous substances in the plenum of the patient ward it is predicted that the leakage area of the plenum will act as the infection source's diffusion path. In addition contaminants that have moved to the plenum are

anticipated to spread to adjacent rooms via airflow that descends to the ceiling's leakage area.

5) When patient ward B stopped working with PNPU, the pollutant was more likely to spread to adjacent ward the lowest negative pressure.

Contaminants diffuse through the pressure difference flow and leakage area formed by the PNPU. As a result maintaining the pressure differential with the airtight construction of the leak area and the suitable air volume is required.

Chapter 4. Preparing the solution to prevent the spread of contamination in the Emergency Switching Type Negative Pressure Isolation Ward

Through the preliminary study in Chapter 2 and Measurement in Chapter 3 problems that may occur when using a PNPU could be identified.

Therefore this chapter intends to establish an improvement plan for Architectural element and Building equipment elements to prevent diffusion by operation of PNPU based on the cause and route of diffusion of contaminants in ESTNPIW analyzed earlier. After that it is intended to understand the effect of the improvement plan through simulation.

4.1 Simulation Outline

As a result of the analysis in Chapter 3 it was confirmed that contaminants diffuse through duct backflow and leakage areas when PNPU is operated. In addition when the location of the exhaust port of the PNPU is adjacent to the exterior wall a short circuit occurs in which contaminants discharged into the outdoor air return to the patient ward.

Therefore it is judged that the diffusion of contaminants through the leakage area can be prevented by improving the air tightness of Architectural elements(Ceiling, Interior Wall, Exterior Wall). In addition it is thought that the duct backflow and short circuit problems can be prevented by sealing the bathroom exhaust port and improving the Building Equipment elements by zoning the PNPU exhaust duct.

Finally it was judged that the most efficient way to prevent the spread of contaminants was to improve both the Architecture(Ceiling, Interior Wall, Exterior Wall) and the Building Equipment(Duct Sealing, PNPU Zoning), and the improvements were simulated.

4.1.1 Simulation Program Outline

In this paper the COMATM Air Flow Network model was used to simulate the base model in which contaminants are diffused through leakage areas and ducts similar to the experiment. After that, the effect of preventing the spread of contaminants by improving the elements was analyzed by simulating the improvement of Architecture and Building Equipment.

1) Leakage Area

The leakage area is based on a series of pressure tests measuring the air flow rate at a series of pressure differentials ranging from approximately 10 Pa to 75 Pa. The effective leakage area is calculated by the following equation (1)[38)]

$$L = Q_r \frac{\sqrt{p/2\Delta p_r}}{C_d} \quad (1)$$

38) Dols, W. S., & Polidoro, B. J. (2020). CONTAM User Guide and Program Documentation Version 3.4. National Institute of Standards and Technology, p.226

where

L : equivalent or effective leakage area [m^2],

ΔP_r : reference pressure difference [Pa],

Q_r : predicted airflow rate at ΔP_r (from curve fit to pressurization test data) [m3/s]

C_d : discharge coefficient.

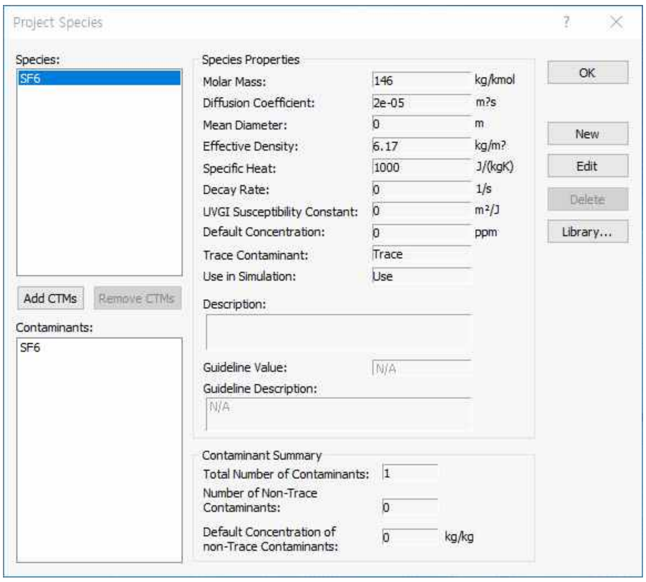
There are C_d and ΔP_r are usually use C_d = 1.0 and ΔP_r = 4 Pa or C_d = 0.6 and ΔP_r = 10 Pa.

In this study, C_d = 1.0 and ΔP_r = 4 Pa values were set.

2) Contaminant

In this study assuming SF_6 as a contaminant we simulated the diffusion of contaminants that were not filtered out by the HEPA filter as in the experiment.

The SF_6 input value in the simulation consisted of a molar mass of 146.06kg/kmol and a density of 6.17kg/m^3, and was modeled as generating 15 mL/s in patient ward B.



[Figure 4.1] SF_6 input value

4.1.2 Simulation case classification and input parameter

1) Base Model

Based on the results analyzed through field measurement the Base model was modeled to implement similar problems of moving gaseous contaminants through the leakage area and duct backflow.

<Table 4.1> Simulation Case Classification

Case			improvement plan
Base Model	Base		-
Architectural elements improvement plan	Ceiling		• Leakage area improvement area in the ceiling area of Plenum To Floor
	Interior		• Leakage area improvement in the Interior wall area of the floor
	Exterior		• Leakage area improvement in the Exterior wall area
Building Equipment elements improvement plan	Air Conditioning Duct Sealing		• Central air conditioning duct port sealing(Backflow Prevention)
	PNPU Zoning	Leakage O	• PNPU Duct Zoning(have leakage in PNPU duct)
		Leakage X	• PNPU Duct Zoning(have no leakage in PNPU duct)
Total elements improvement plan	Total Improvement 1		• Ceiling, Interior, Exterior Leakage area improvement • Central air conditioning duct port sealing(Backflow Prevention) • PNPU Duct Zoning(have no leakage in PNPU duct)
	Total Improvement 2		• Ceiling, Interior, Exterior Leakage area improvement • Central air conditioning duct sealing port(Backflow Prevention) • PNPU Duct Zoning(have no leakage in PNPU duct) • Reduce PNPU Airvolume(all patient ward)
	Total Improvement 3		• Ceiling, Interior, Exterior Leakage area improvement • Central air conditioning duct port sealing(Backflow Prevention) • PNPU Duct Zoning(have no leakage in PNPU duct) • Adjustment of the same pressure difference in Ward B and C
	Total Improvement 4		• Ceiling, Interior, Exterior Leakage area improvement • Central air conditioning duct port sealing(Backflow Prevention) • PNPU Duct Zoning(have no leakage in PNPU duct) • Reduce PNPU Airvolume(all patient ward) • Adjustment of the same pressure difference in Ward B and C

<Table 4.2> is the parameter of the Leakage Area of the Floor Plenum and Rooftop of the Base model. Plenum's assumption is a value assumed to similarly implement the problems analyzed in the field measurement. <Table 4.3> is the Leakage input value for an unsealed duct.

<Table 4.2> Leakage area input value for Building Components(Base Model)

Building components			Leakage area		Data Source
Floor	Wall	Interior	$2cm^2/m^2$	Per Unit Area	Miscellaneous Residential Leakage Data(Libraries)[39]
		Exterior	$7.6cm^2/m^2$	Per Unit Area	Summary of Commercial and Institutional Building Airtightness Data(Libraries)[40]
	Door	Close	$140cm^2$	Per Item	Miscellaneous Residential Leakage Data(Libraries)[41]
		Open	2.2m X 1.3m	Per Item	Assumed Value
	Window	Close	$2cm^2/m$	Per Unit Length	Miscellaneous Residential Leakage Data(Libraries)[42]
		Open	0.6m X 0.36m	Per Item	Assumed Value
Plenum	Wall	Interior	$50cm^2/m^2$	Per Unit Area	Assumed Value
		Exterior	$7.6cm^2/m^2$	Per Unit Area	Summary of Commercial and Institutional Building Airtightness Data(Libraries)[43]
	Plenum To Floor Ceiling	Ward A	$30cm^2/m^2$	Per Unit Area	Assumed Value[44]
		Ward B	$20cm^2/m^2$	Per Unit Area	Assumed Value
		Ward C	$10cm^2/m^2$	Per Unit Area	Assumed Value
		Bathroom	$10cm^2/m^2$	Per Unit Area	Assumed Value
		etc	$30cm^2/m^2$	Per Unit Area	Assumed Value
Rooftop	Wall	Exterior	$7.6cm^2/m^2$	Per Unit Area	Summary of Commercial and Institutional Building Airtightness Data(Libraries)[45]

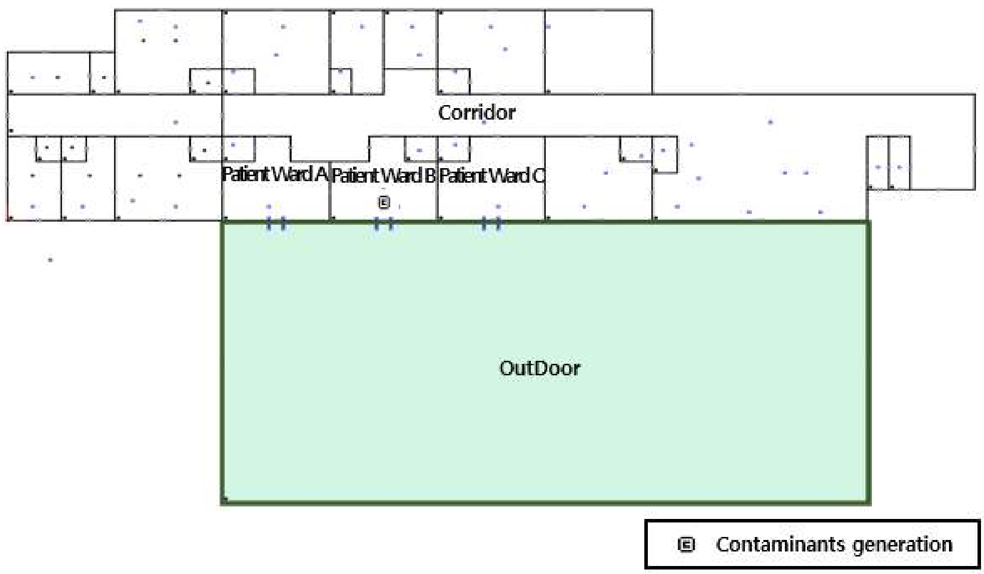
39),40),41),42),43),44),45) https://www.nist.gov/el/energy-and-environment-division-73200/nist-multizone-modeling/software/contam/input-data

<Table 4.3> Duct Leakage input value(Base Model)

	Unsealed	
Duct Type	Predicted Leakage Class	Leakage Rate, L/(s·m^2) at 250 Pa
Rectangular	68	2.5[46]

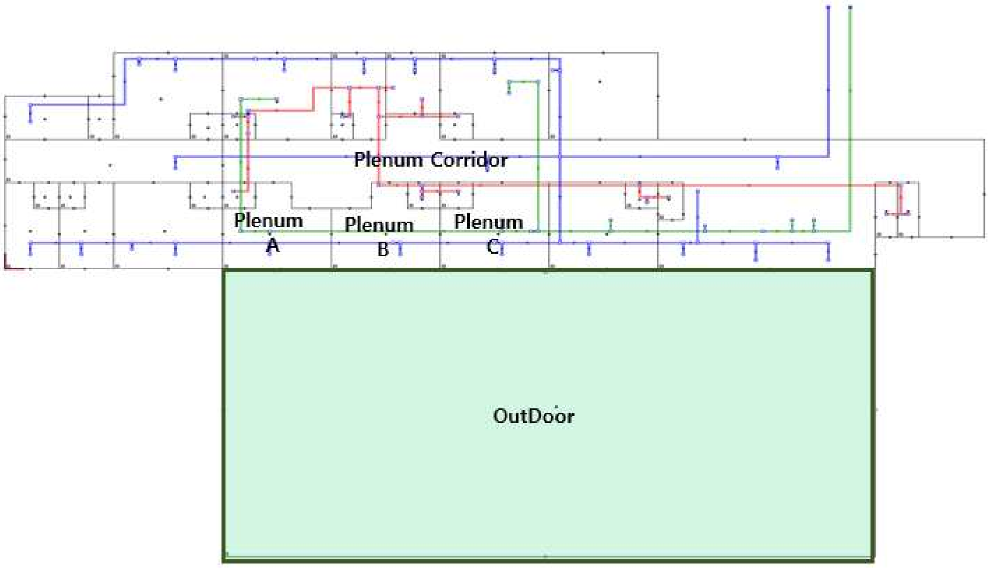
Since short circuiting was predicted to occur in the field measurement the Green part in [Figure 4.2] and [Figure 4.3] was planned so that short circuiting could occur and the formation of pressure difference in the ward and the diffusion of contaminants were simulated.

[Figure 4.3] is a plan view of the plenum layer that models the plenum leakage area reviewed in the field measurement and the backflow caused by the duct pressure imbalance

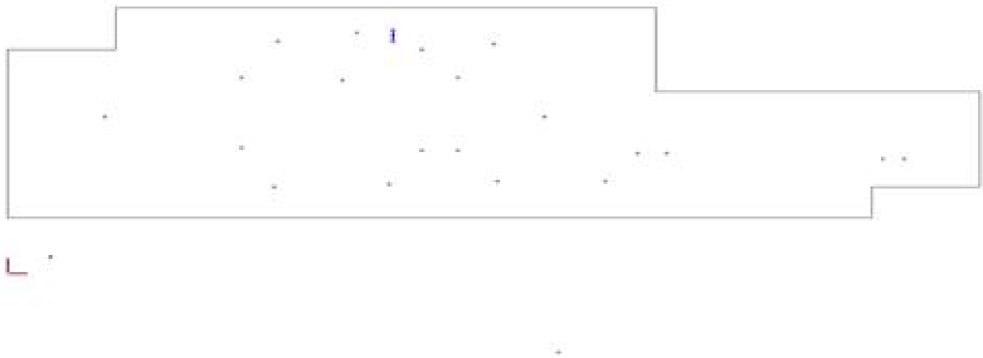


[Figure 4.2] Base Model using CONTAM (Floor)

46) ASHRAE. (2005). ASHRAE Handbook – 2005 Fundamentals, Atlanta GA.



[Figure 4.3] Base Model using CONTAM (Plenum)



[Figure 4.4] Base Model using CONTAM (Rooftop)

2) Architectural element improvement plan Model

<Table 4.4> is the leakage input value for unsealed duct, which is the same as the input value of the base model. <Table 4.5> is the Leakage Area Input Parameter of Floor, Plenum, and Roof of the architectural element improvement plan model. In the case of the exterior wall, the maximum leak area was 7.6 cm^2/m^2 and the minimum was 3.7 cm^2/m^2, and the minimum value was about half of the maximum value. Based on this, the ceiling part and the interior wall part were also simulated by reducing the area of the leaking part to 1/2.

<Table 4.4> Duct Leakage input value(Architectural element improvement Model)

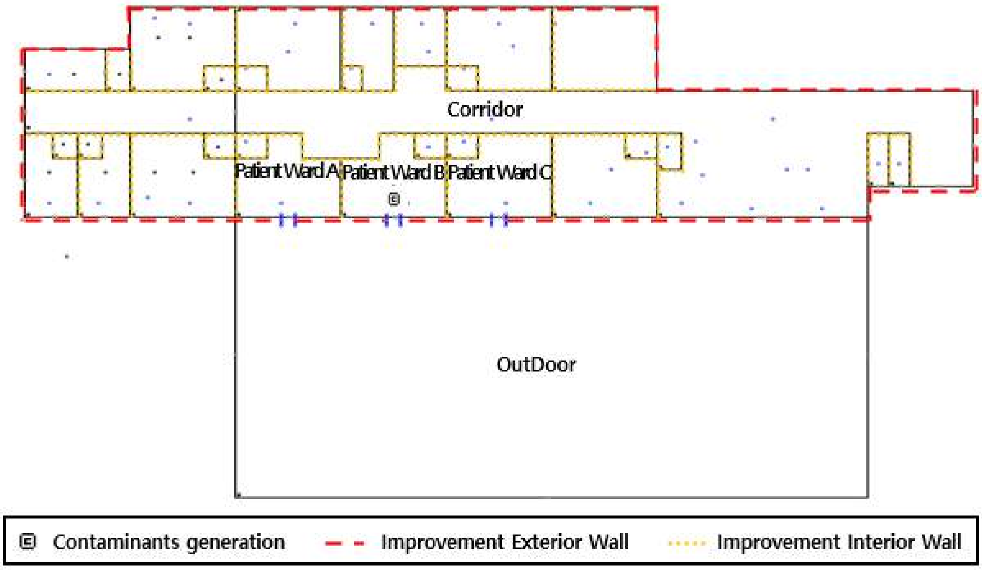
Duct Type	Model	Unsealed	
		Predicted Leakage Class	Leakage Rate, L/(s·m^2) at 250 Pa
Rectangular	Base	68	2.5

<Table 4.5> Leakage area input value for Building components(Architectural element improvement Model)

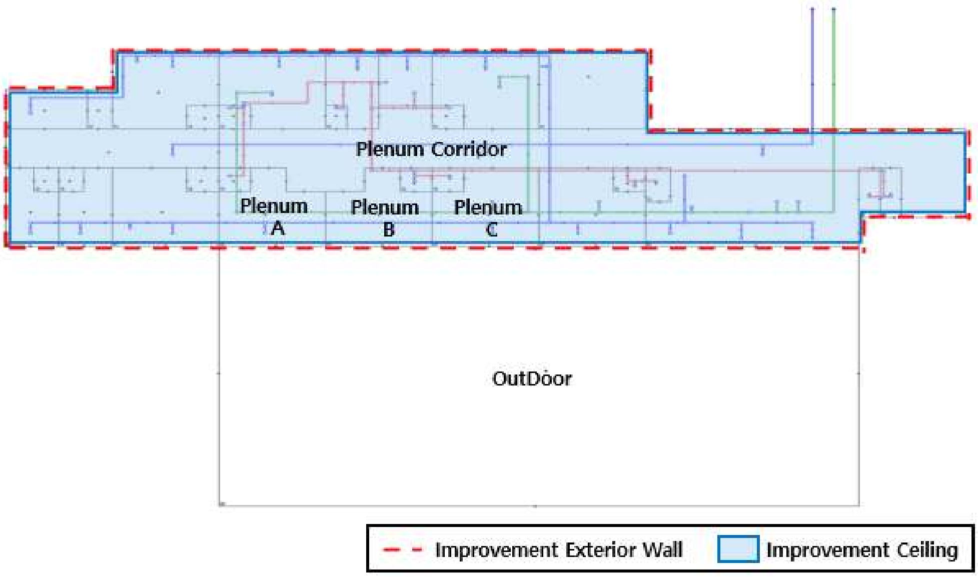
Building components			Leakage area				
			Base Model	Architectural element improvement model			Unit
				Ceiling	Floor Interior Wall	Exterior Wall	
Floor	Wall	Interior	$2cm^2/m^2$	$2cm^2/m^2$	$1cm^2/m^2$	$2cm^2/m^2$	Per Unit Area
		Exterior	$7.6cm^2/m^2$	$7.6cm^2/m^2$	$7.6cm^2/m^2$	$3.7cm^2/m^2$ [47]	Per Unit Area
	Door	Close	$140cm^2$	$140cm^2$	$140cm^2$	$140cm^2$	Per Item
		Open	2.2m X 1.3m	2.2m X 1.3m	2.2m X 1.3m	2.2m X 1.3m	Per Item
	Window	Close	$2cm^2/m$	$2cm^2/m$	$2cm^2/m$	$2cm^2/m$	Per Unit Length
		Open	0.6m X 0.36m	0.6m X 0.36m	0.6m X 0.36m	0.6m X 0.36m	Per Item
Plenum	Wall	Interior	$50cm^2/m^2$	$50cm^2/m^2$	$50cm^2/m^2$	$50cm^2/m^2$	Per Unit Area
		Exterior	$7.6cm^2/m^2$	$7.6cm^2/m^2$	$7.6cm^2/m^2$	$3.7cm^2/m^2$	Per Unit Area
	Plenum To Floor Ceiling	Ward A	$30cm^2/m^2$	$15cm^2/m^2$	$30cm^2/m^2$	$30cm^2/m^2$	Per Unit Area
		Ward B	$20cm^2/m^2$	$10cm^2/m^2$	$20cm^2/m^2$	$20cm^2/m^2$	Per Unit Area
		Ward C	$10cm^2/m^2$	$5cm^2/m^2$	$10cm^2/m^2$	$10cm^2/m^2$	Per Unit Area
		Bathroom	$10cm^2/m^2$	$5cm^2/m^2$	$10cm^2/m^2$	$10cm^2/m^2$	Per Unit Area
		etc	$30cm^2/m^2$	$15cm^2/m^2$	$30cm^2/m^2$	$30cm^2/m^2$	Per Unit Area
Rooftop	Wall	Exterior	$7.6cm^2/m^2$	$7.6cm^2/m^2$	$7.6cm^2/m^2$	$3.7cm^2/m^2$	Per Unit Area

47) https://www.nist.gov/el/energy-and-environment-division-73200/nist-multizone-modeling/software/contam/input-data

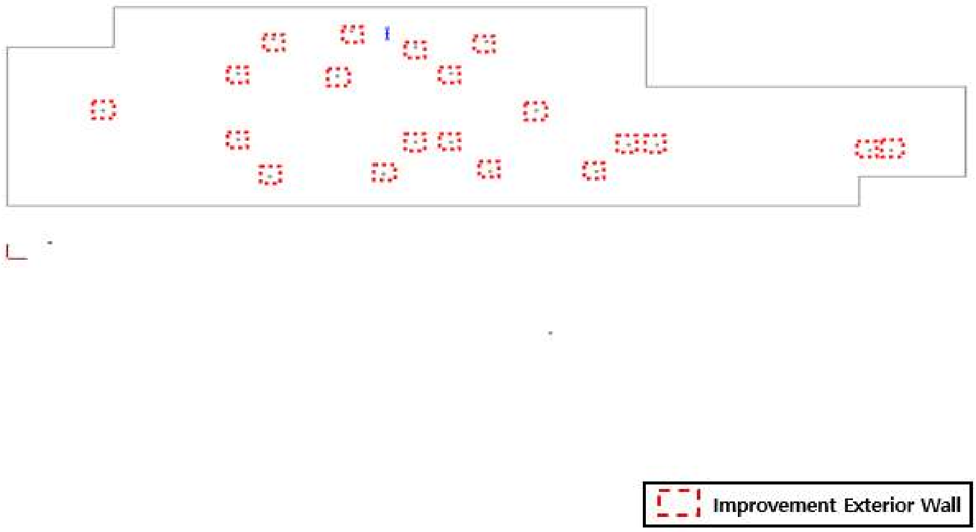
[Figure 4.5], [Figure 4.6] and [Figure 4.7] are the planes of the Floor, Plenum and Rooftop layers of the model with improved Architectural elements showing the parts of improved elements for each case.



[Figure 4.5] Architectural element improvement Model using CONTAM (Floor)



[Figure 4.6] Architectural element improvement Model using CONTAM (Plenum)



[Figure 4.7] Architectural element improvement Model using CONTAM (Rooftop)

3) Building Equipment elements improvement plan Model

<Table 4.6> shows the Duct Leakage Input Parameter of the PNPU Zoning model among the Building equipment elements improvement plan model. The Leakage area Input Parameter for architectural element in the Building Equipment elements improvement model is <Table 4.7> and is the same as the base model.

<Table 4.6> Duct Leakage input value(PNPU Zoning model)

Duct Type	model		Sealed	
			Predicted Leakage Class	Leakage Rate, L/(s·m^2) at 250 Pa
Metal, Aluminum	PNPU Zoning	Leakage O	11	0.40[48]
		Leakag eX	0	0

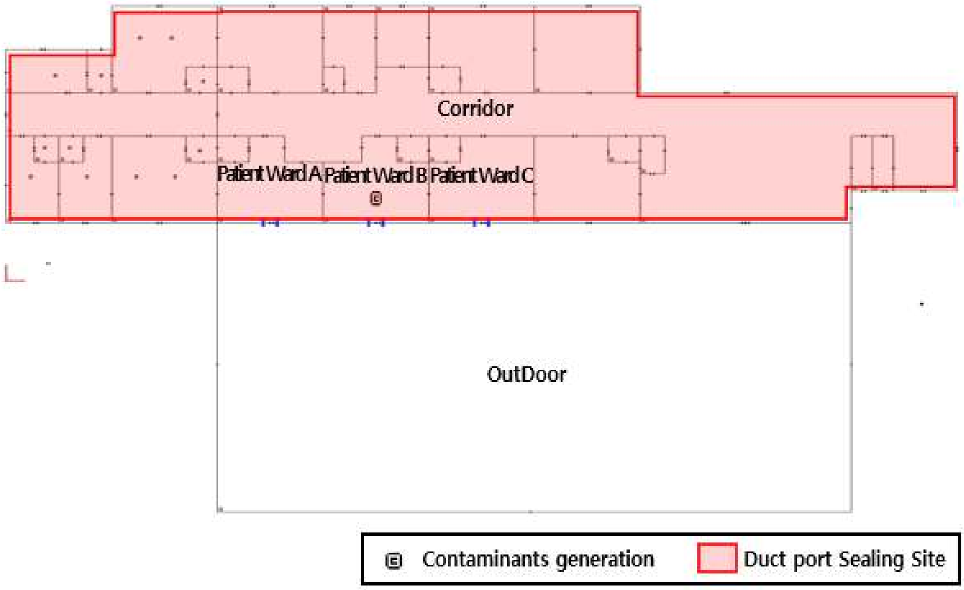
48) op.cit., ASHRAE. (2005).

<Table 4.7> Leakage area input value for Building components (Building Equipment elements improvement Model)

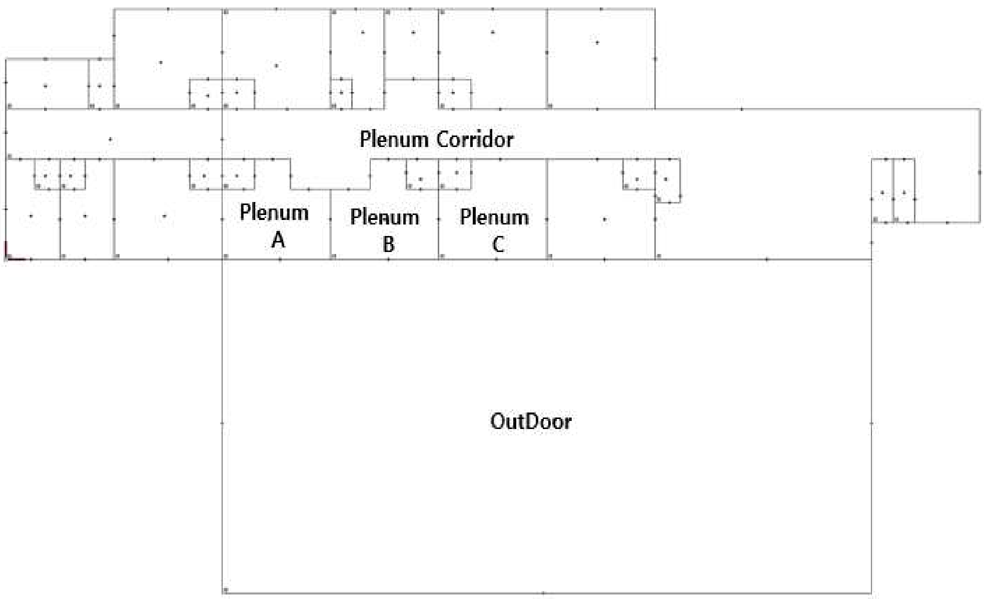
Building components			Leakage area		
			Base Model	Building equipment elements improvement Model	Unit
Floor	Wall	Interior	$2cm^2/m^2$	$2cm^2/m^2$	Per Unit Area
		Exterior	$7.6cm^2/m^2$	$7.6cm^2/m^2$	Per Unit Area
	Door	Close	$140cm^2$	$140cm^2$	Per Item
		Open	2.2m X 1.3m	2.2m X 1.3m	Per Item
	Window	Close	$2cm^2/m$	$2cm^2/m$	Per Unit Length
		Open	0.6m X 0.36m	0.6m X 0.36m	Per Item
Plenum	Wall	Interior	$50cm^2/m^2$	$50cm^2/m^2$	Per Unit Area
		Exterior	$7.6cm^2/m^2$	$7.6cm^2/m^2$	Per Unit Area
	Plenum To Floor Ceiling	Ward A	$30cm^2/m^2$	$30cm^2/m^2$	Per Unit Area
		Ward B	$20cm^2/m^2$	$20cm^2/m^2$	Per Unit Area
		Ward C	$10cm^2/m^2$	$10cm^2/m^2$	Per Unit Area
		Bathroom	$10cm^2/m^2$	$10cm^2/m^2$	Per Unit Area
		etc	$30cm^2/m^2$	$30cm^2/m^2$	Per Unit Area
Rooftop	Wall	Exterior	$7.6cm^2/m^2$	$7.6cm^2/m^2$	Per Unit Area

[Figure 4.8], [Figure 4.9] and [Figure 4.10] are plan views of sealing the ducts of the central air conditioning of the Floor, Plenum and Rooftop layers to prevent duct backflow. The plan is expressed as having no port and duct in the simulation, but in reality, it means that the central air conditioning port and duct that were stop operated are sealed.

[Figure 4.11], [Figure 4.12] and [Figure 4.13] are modeling Floor, Plenum and Rooftop plans of PNPU duct zoning cases improved to prevent short circuiting.

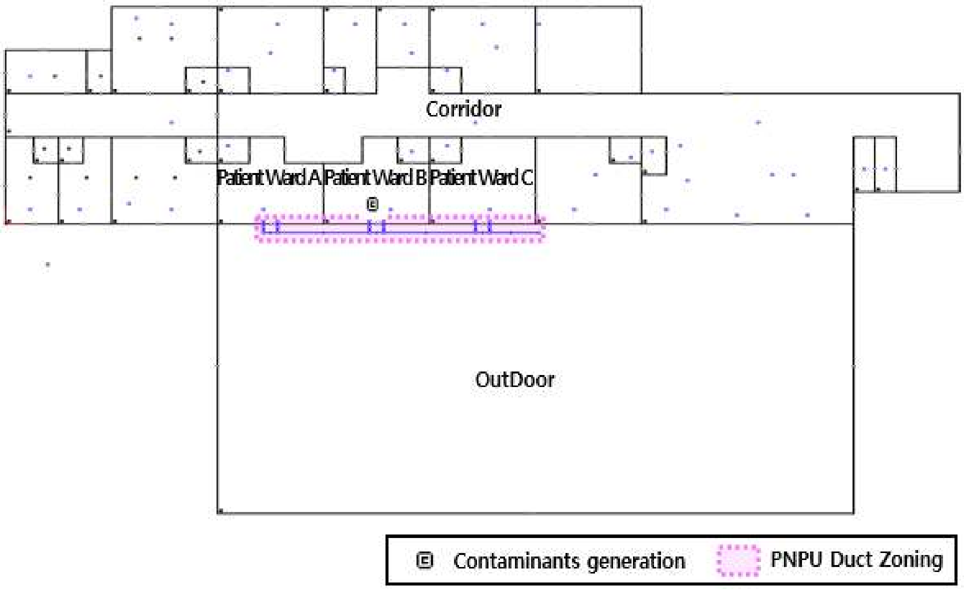


[Figure 4.8] Duct Sealing modeling using CONTAM (Floor)

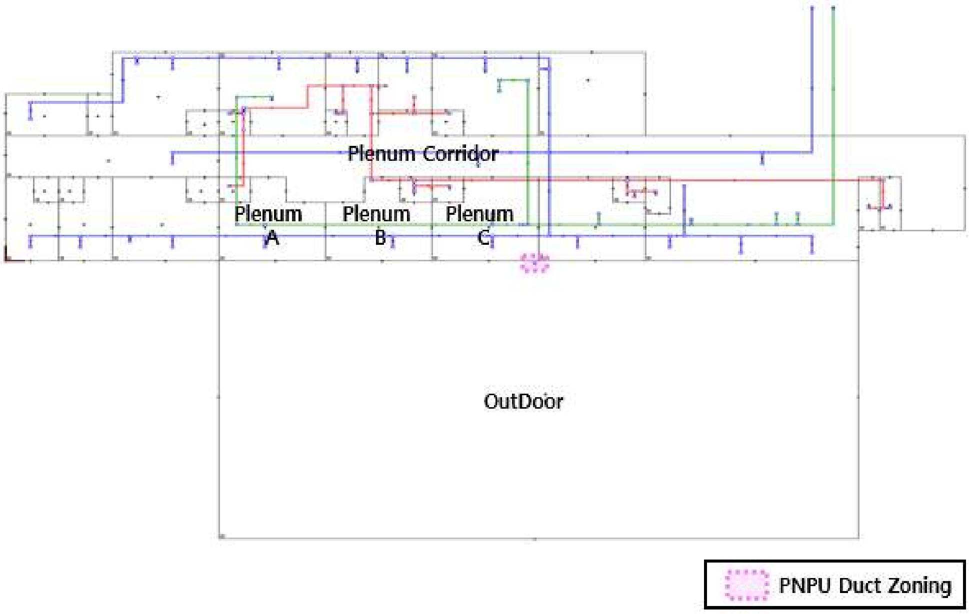


[Figure 4.9] Duct Sealing model using CONTAM (Plenum)

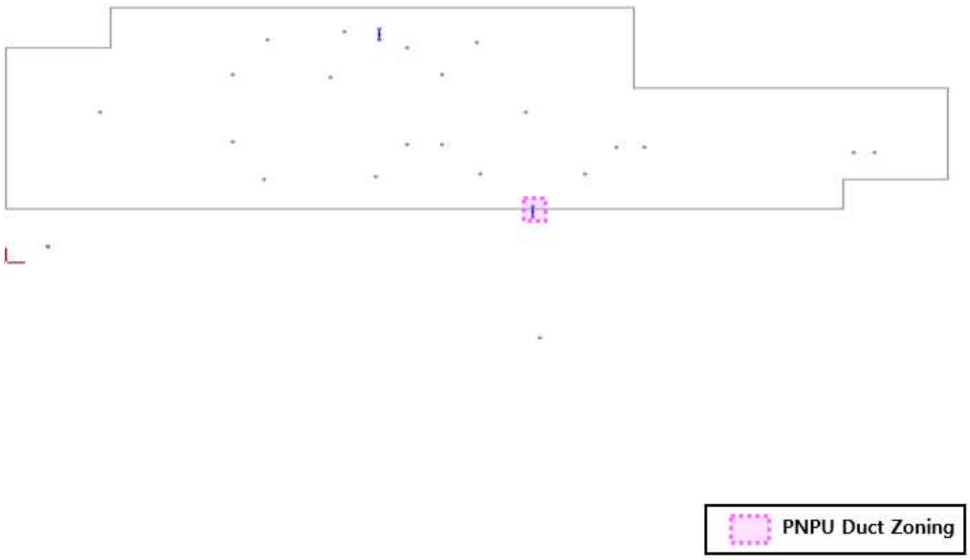
[Figure 4.10] Duct Sealing mode using CONTAMI (Rooftop)



[Figure 4.11] PNPU Zoning modeling using CONTAM (Floor)



[Figure 4.12] PNPU Zoning model using CONTAM (Plenum)



[Figure 4.13] PNPU Zoning model using CONTAM (Rooftop)

4) Total improvement plan Model

The Total improvement Plan simultaneously improved Architecture (Ceiling, Interior wall, Exterior wall) and Building Equipment elements (Duct sealing, PNPU Zoning (Leakage X)), and the model was implemented with the Input Parameter in <Table 4.8> and <Table 4.9>.

<Table 4.8> Duct Leakage input value(Total Improvement plan model)

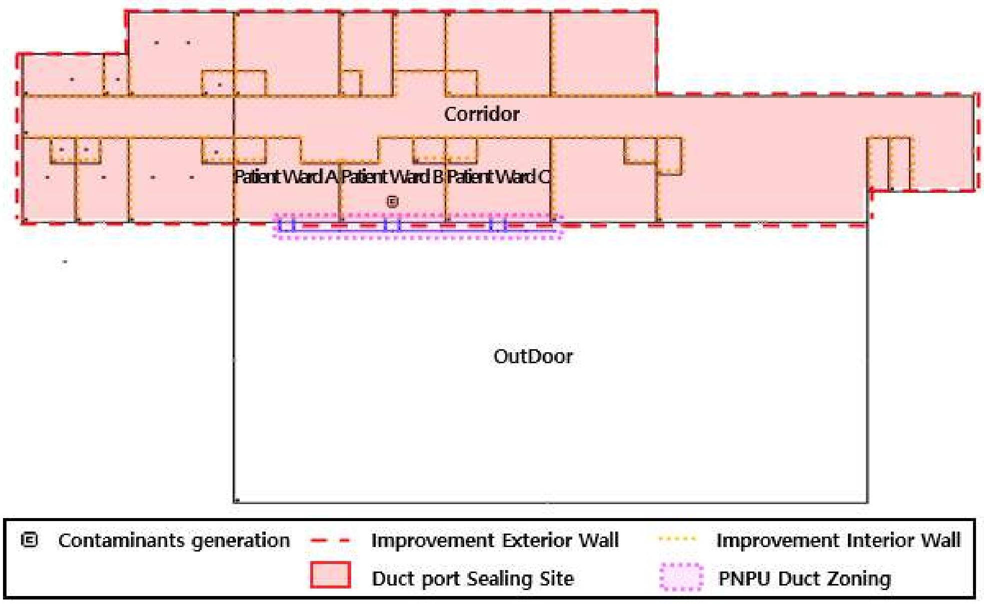
Duct Type	model		Sealed	
			Predicted Leakage Class	Leakage Rate, L/(s·m^2) at 250 Pa
Metal, aluminum	PNPU Zoning	Leakage X	0	0

<Table 4.9> Leakage area input value for Building components (Total Improvement plan model)

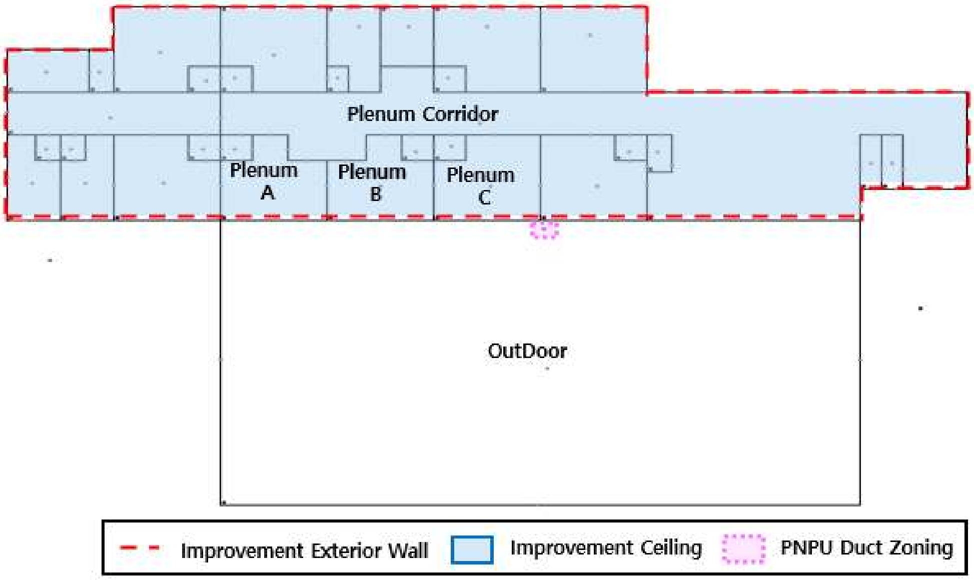
Building components			Leakage area	
Floor	Wall	Interior	$1cm^2/m^2$	Per Unit Area
		Exterior	$3.7cm^2/m^2$	Per Unit Area
	Door	Close	$140cm^2$	Per Item
		Open	2.2m X 1.3m	Per Item
	Window	Close	$2cm^2/m$	Per Unit Length
		Open	0.6 m X 0.36m	Per Item
Plenum	Wall	Interior	$50cm^2/m^2$	Per Unit Area
		Exterior	$3.7cm^2/m^2$	Per Unit Area
	Plenum To Floor	Ward A	$15cm^2/m^2$	Per Unit Area
		Ward B	$10cm^2/m^2$	Per Unit Area
		Ward C	$5cm^2/m^2$	Per Unit Area
		Bathroom	$5cm^2/m^2$	Per Unit Area
		etc	$10cm^2/m^2$	Per Unit Area
Rooftop	Wall	Exterior	$3.7cm^2/m^2$	Per Unit Area

[Figure 4.14], [Figure 4.15], and [Figure 4.16] are the Floor, Plenum, and Rooftop planes showing the improved parts of the model in which Architectural and Building Equipment improvements are simultaneously applied to prevent the spread of pollutants.

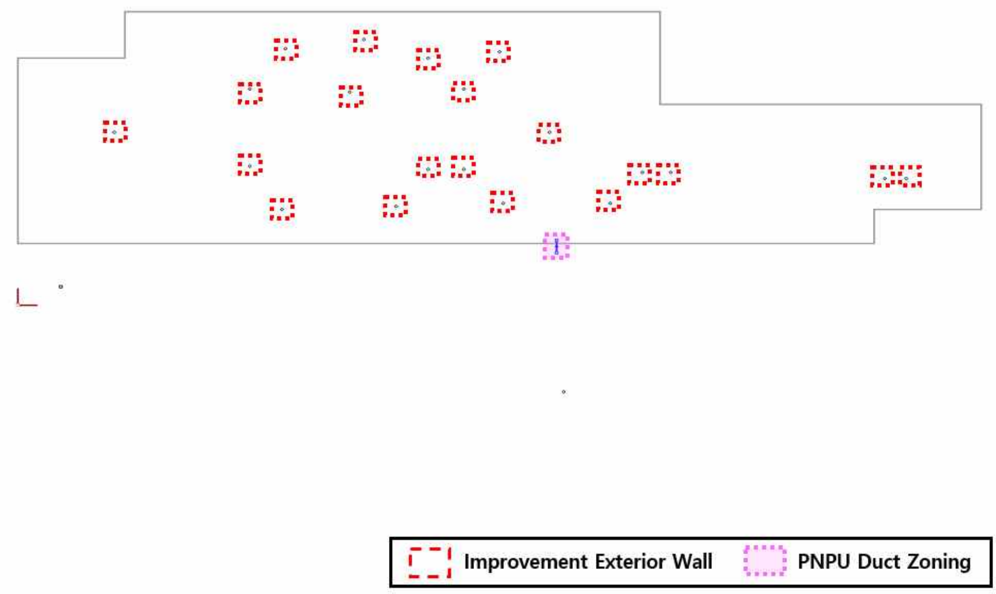
The plan is expressed as having no port and duct in the simulation, but in reality, it means that the central air conditioning port and duct that were stop operated are sealed.



[Figure 4.14] Total Improvement plan modeling using CONTAM (Floor)



[Figure 4.15] Total Improvement plan modeling using CONTAM (Plenum)



[Figure 4.16] Total Improvement plan modeling using CONTAM (Rooftop)

4.2 Simulation analysis results

1) Base Model analysis results

As a result of the simulation, the pressure difference between wards by the PNPU air volume and the Air Infiltration rate from the outside for make-up air are as shown in <Table 4.10>, [Figuure 4.17], [Figure 4.18]. At this time, the airflow in the floor and the plenum is formed as shown in [Figure 4.19] and [Figure 4.20].

The average of the absolute (relative) concentrations in each room after 20 minutes of stabilization of the SF_6 concentration in the base ward is as follows<Table 4.11>, [Figure 4.21].

The air exhausted into the outside air was flow into each ward due to short circuiting, and it was confirmed that contaminants spread and rose through the leakage part between rooms and duct backflow along the air flow direction.

A concentration of 1.8 ppm was detected in negative pressure room A, and the concentration (5.3 ppm) of patient C ward was higher than that of bathroom (3.1 ppm). Through these results, the factors that additionally spread to ward C along with the backflow of the bathroom C duct were simulated similarly to the actual measurement.

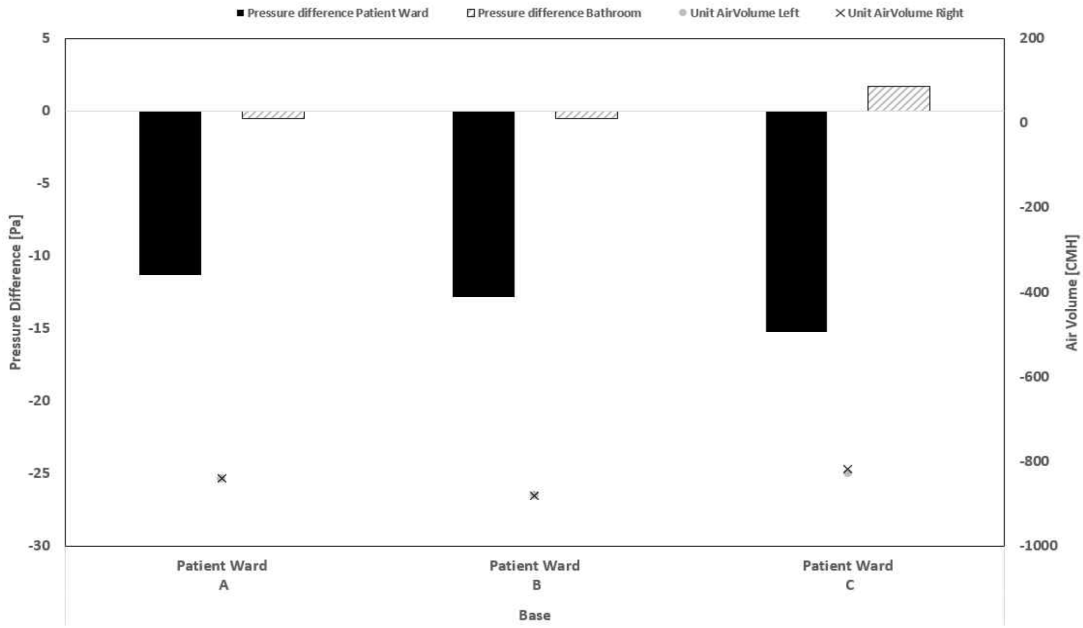
The results of this simulation were used as a basic model for the analysis of the effectiveness of measures to prevent the spread of contaminants within the ward.

<Table 4.10> PNPU air volume, inter-room pressure difference, Air Infiltration rate at Base Model

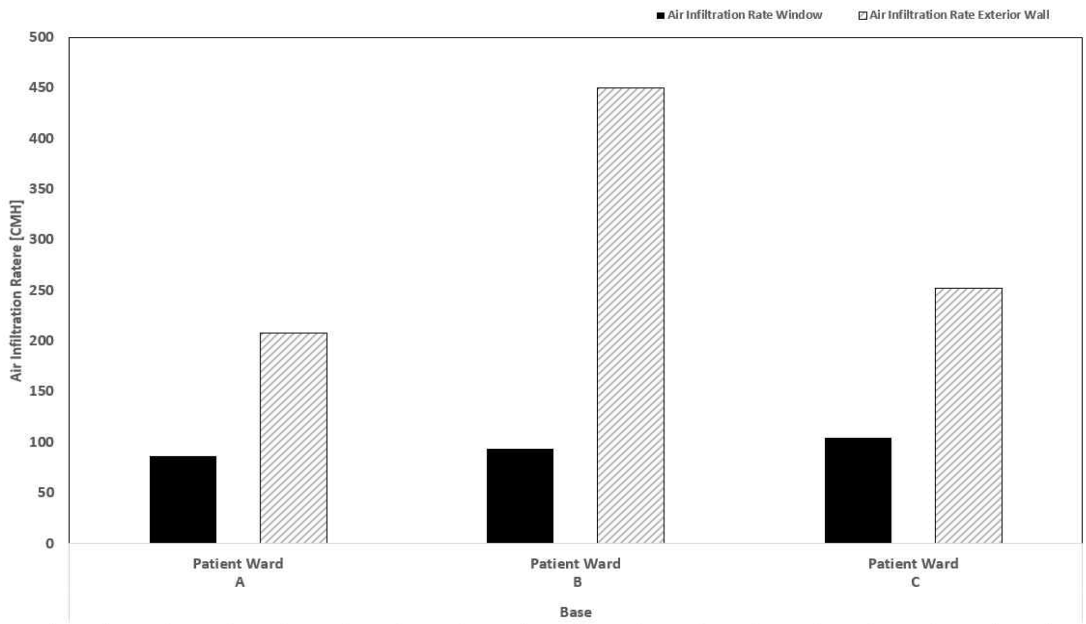
Unit [Air Volume: CMH, Pressure Difference: Pa, Air Infiltration Rate: CMH]

		Unit Air Volume		Pressure difference		Air Infiltration Rate	
		Left	Right	Patient Ward	Bath room	Window	Exterior Wall
Base	Patient Ward A	-840	-840	-11.3	-0.5	+87	+208
	Patient Ward B	-879	-881	-12.8	-0.5	+94	+450
	Patient Ward C	-828	-818	-15.2	1.7	+105	+252

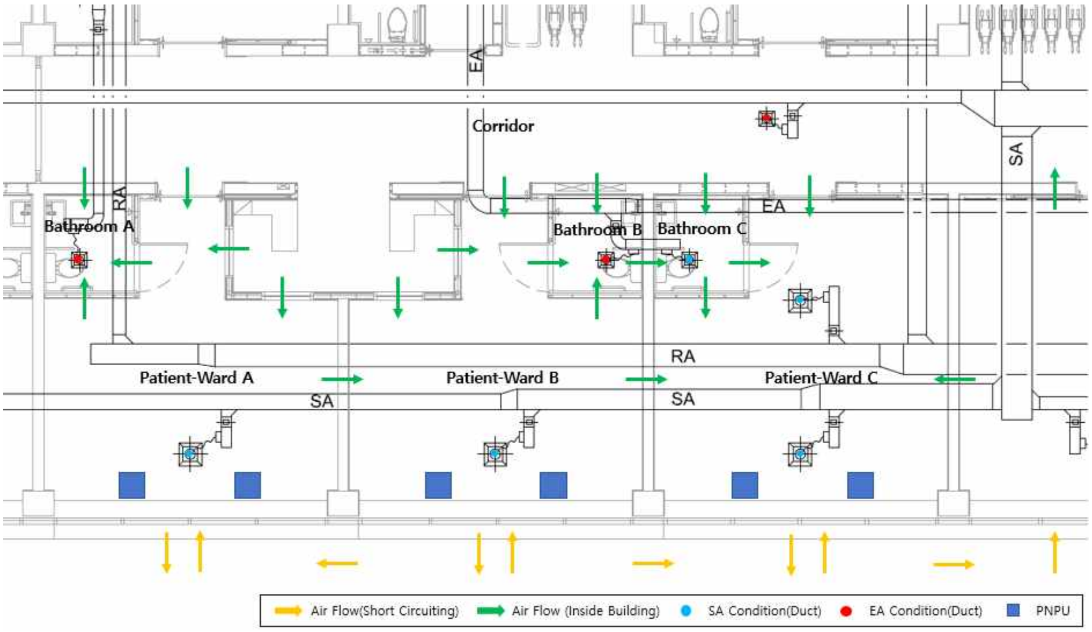
Note: [+: the direction of air supply into the room, -: Direction of exhaust to the outside]



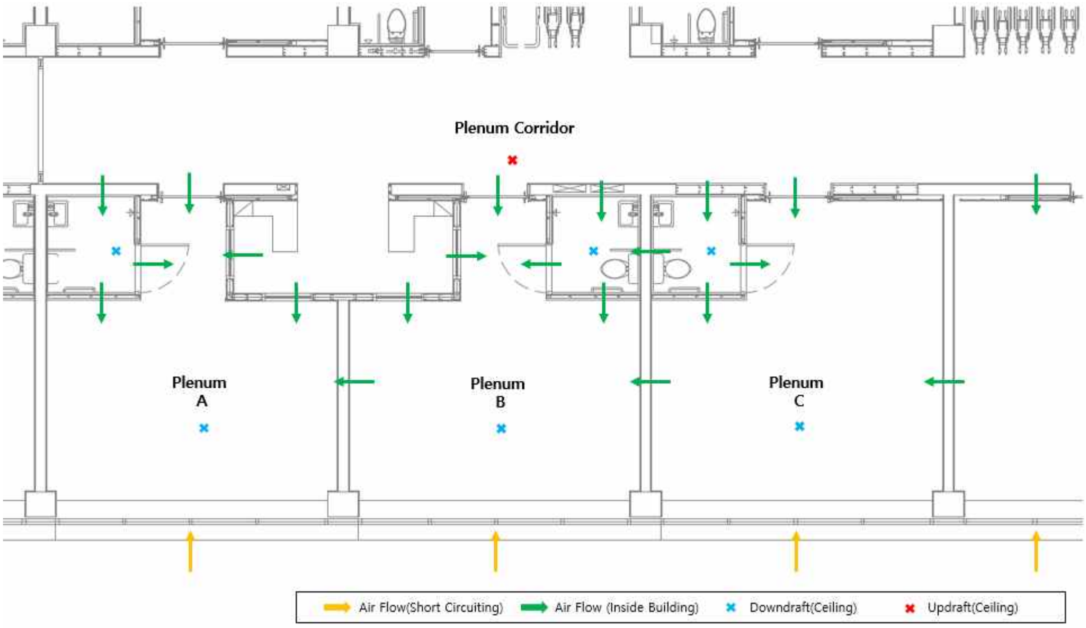
[Figure 4.17] PNPU Air Volume and Room Pressure Differential at Base Model



[Figure 4.18] Air Infiltration Rate window and Exterior Wall at Base Model



[Figure 4.19] Movement of airflow through Leakage area at Base Model(Floor)

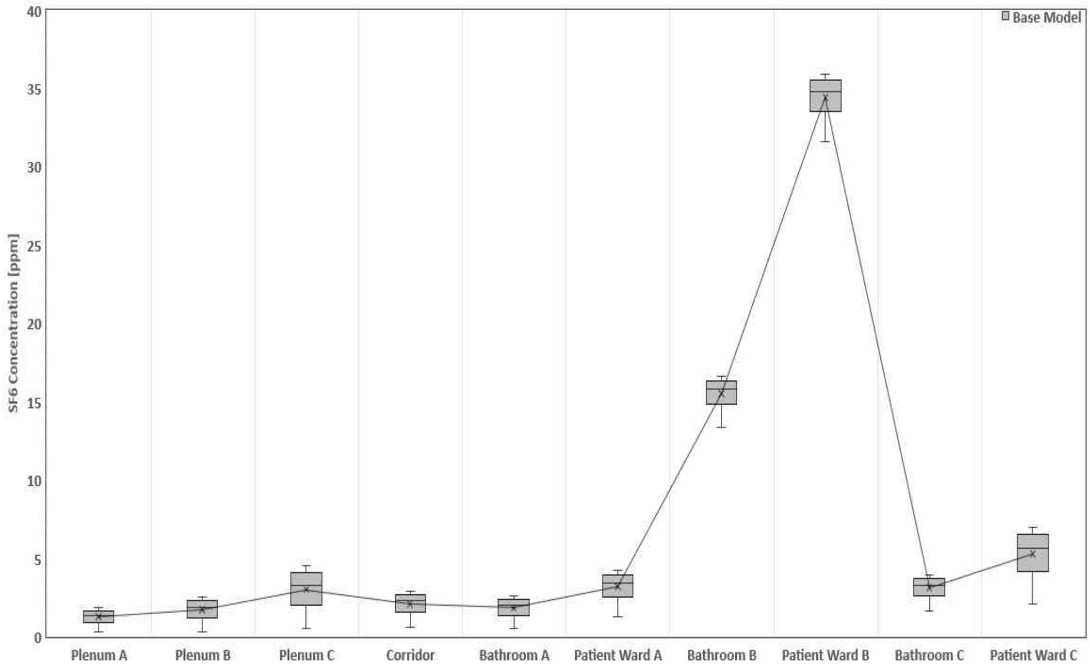


[Figure 4.20] Movement of airflow through Leakage area at Base Model(Plenum)

<Table 4.11> SF_6 Average (relative) Concentration at Base Mode

Unit [absolute concentration: ppm, relative concentration: %]

		Absolute concentration	Relative concentration
Floor	Bathroom A	1.8	6.5
	Bathroom B	15.5	45.8
	Bathroom C	3.1	10.2
	Patient ward A	3.2	10.8
	Patient Ward B	34.4	100
	Patient Ward C	5.3	17.8
	Corridor	2.1	7.3
Plenum	Plenum A	1.3	4.5
	Plenum B	1.7	6.2
	Plenum C	3.0	11



[Figure 4.21] SF_6 Gas Concentration Distribution at Base Mode

2) Architectural element improvement Model analysis results

As a result of the simulation for the case in which the airtight performance of each element of the ceiling, interior wall, and exterior wall was improved, the pressure difference between wards according to the amount of PNPU air and the outdoor Air Infiltration Rate for make-up air are shown in <Table 4..12>, [Figure 4.22], [Figure 4.23]. At this time, the air flow of the floor and plenum is formed identically as in [Figure 4.19] and [Figure 4.20] of the base model.

The average of the absolute (relative) concentrations in each room after 20 minutes of stabilization of the SF_6 concentration in the base ward is as follows <Table 4.13>, [Figure 4.24].

In the case of improving the airtightness of the ceiling, the pressure difference in A, B, and C patient wards were −15.8Pa, −17.4Pa, and −20.6Pa, respectively, which improved by −4.5~−5.4Pa compared to the base model. For make-up air, the Air Infiltration from the outside to the A, B, and C wards was 366, 665, and 435CMH, respectively, which was increased by 71~121CMH compared to the base model. At this time, the spread SF6 relative concentration in adjacent A and C wards was 12.4% and 19.3%, which increased by 1.6% and 1.5% compared to the base model.

In the case of improving the airtightness of the Interior Wall, the pressure difference in A, B, and C patient wards were −11.8Pa, −13.2Pa, and −16.2Pa, respectively, which improved by -0.4~−1.0Pa compared to the base model. For make-up air, the Air Infiltration from the outside to the A, B, and C wards was 303, 556, and 317CMH, respectively, which was increased by 6~14CMH compared to the base model. At this time, the spread SF_6 relative concentration in adjacent A and C wards was 10.9% and 16.8%, which increased by 0.1% or decreased by 1.0% compared to the base model.

In the case of improving the airtightness of the Exterior Wall, the pressure difference in A, B, and C patient wards were −14.0Pa, −16.3Pa, and −18.1Pa, respectively, which improved by -2.7~−3.5Pa compared to the base model. For make−up air, the Air Infiltration from the outside to the A, B, and C wards was 216, 367, and 256CMH, respectively, which was decreased by 79~177CMH compared to the base model. At this time, the spread SF6 relative concentration in adjacent A and C wards was 9.1% and 15.9%, which decreased by 1.7% and 1.9% compared to the base model.

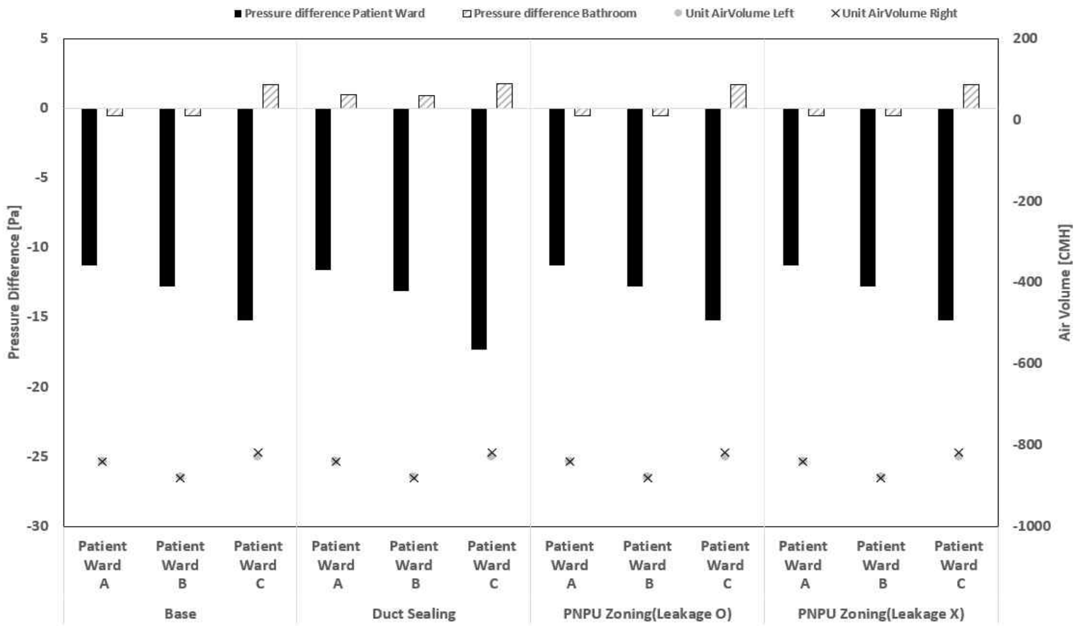
It was found that when airtightness was improved, the pressure difference between wards increased. However, if the airtightness of the ceiling is improved, the Air Infiltration from the outside increases for make−up air, resulting in an increase in contaminants due to short circuiting. the contrary Improving the airtightness of the exterior wall reduced the Air Infiltration from the outside, resulting in a decrease in the concentration of contaminants.

<Table 4.12> PNPU air volume, inter-room pressure difference, Air Infiltration rate at Architectural element improvement Model

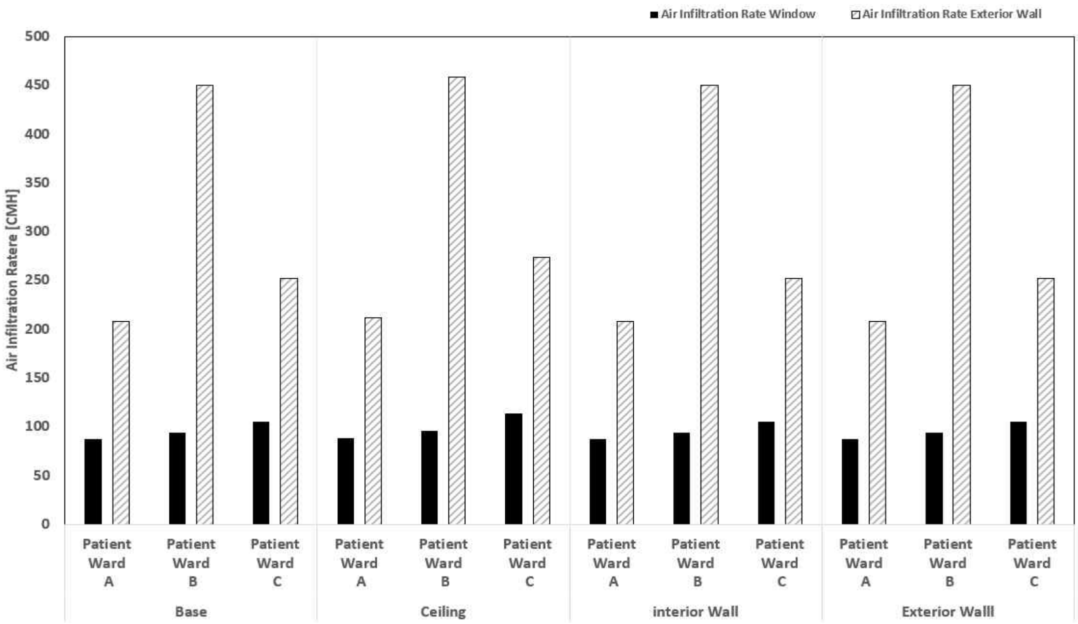
Unit [Air Volume: CMH, Pressure Difference: Pa, Air Infiltration Rate: CMH]

		Unit Air Volume		Pressure difference		Air Infiltration Rate	
		Left	Right	Patient Ward	Bath room	Window	Exterior Wall
Base	Patient Ward A	-840	-840	-11.3	-0.5	+87	+208
	Patient Ward B	-879	-881	-12.8	-0.5	+94	+450
	Patient Ward C	-828	-818	-15.2	1.7	105	+252
Ceiling	Patient Ward A	-840	-840	-15.8	-0.3	+108	+258
	Patient Ward B	-879	-881	-17.4	-0.8	+115	+550
	Patient Ward C	-828	-818	-20.6	+2.2	+128	+307
Floor interior Wall	Patient Ward A	-840	-840	-11.8	-0.7	+89	+214
	Patient Ward B	-879	-881	-13.2	-0.8	+96	+460
	Patient Ward C	-828	-818	-16.2	+1.9	+109	+262
Exterior Walll	Patient Ward A	-840	-840	-14.0	-0.3	+100	+116
	Patient Ward B	-879	-881	-16.3	-0.0	+110	+257
	Patient Ward C	-828	-818	-18.1	1.6	+118	+138

Note: [+: the direction of air supply into the room, -: Direction of exhaust to the outside]



[Figure 4.22] PNPU Air Volume and Room Pressure Differential at Architectural element improvement Model

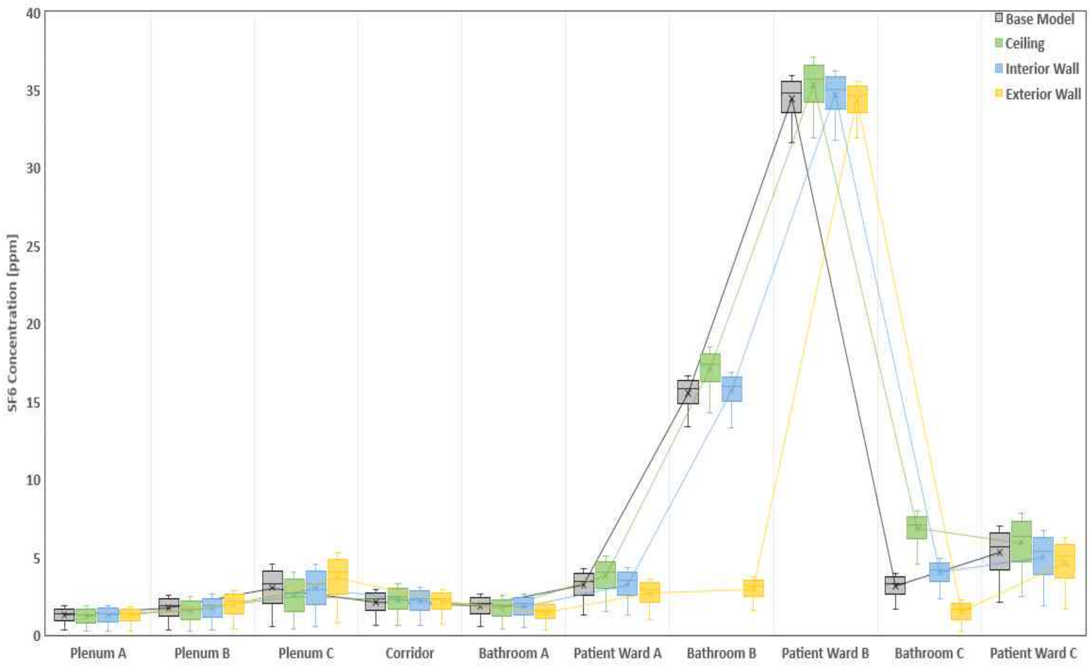


[Figure 4.23] Air Infiltration Rate window and Exterior Wall at Architectural element improvement Model

<Table 4.13> SF_6 Average (relative) Concentration at Architectural element improvement Model

Unit [absolute concentration: μg/m³, (relative concentration: %)

		Base	Ceiling	Interior Wall	Exterior Wall
Floor	Bathroom A	1.8(6.5)	1.7(5.9)	1.8(6.4)	1.4(5.2)
	Bathroom B	15.5(45.8)	17.1(49.2)	15.7(46.0)	2.9(9.7)
	Bathroom C	3.1(10.2)	6.8(20.5)	4.0(12.7)	1.5(5.5)
	Patient Ward A	3.2(10.8)	3.8(12.4)	3.2(10.9)	2.7(9.1)
	Patient Ward B	34.4(100.0)	35.3(100.0)	34.7(100.0)	34.3(100.0)
	Patient Ward C	5.3(17.8)	5.9(19.3)	5.0(16.8)	4.6(15.9)
	Corridor	2.1(7.3)	2.3(7.8)	2.2(7.5)	2.1(7.4)
Plenum	Plenum A	1.3(4.5)	1.2(4.3)	1.3(4.5)	1.3(4.6)
	Plenum B	1.7(6.2)	1.6(5.6)	1.7(6.2)	1.9(7.0)
	Plenum C	3.0(11.0)	2.5(9.1)	3.0(10.8)	3.7(13.2)



[Figure 4.24] SF_6 Gas Concentration Distribution at Architectural element improvement Model

3) Building Equipment elements improvement Model analysis results

As a result of the simulation for the case in which the Building equipment elements improvement(air conditioning duct sealing, PNPU duct Zoning), the pressure difference between wards according to the amount of PNPU air and the outdoor Air Infiltration Rate for make-up air are shown in <Table 4.14>, [Figure 4.25], [Figure 4.26]. At this time, the airflow movement of the air conditioning duct sealing model is formed as shown in [Figure 4.27], [Figure 4.28] and The airflow of the PNPU zoning model is formed as shown [Figure 4.29] and [Figure 4.30].

The average of the absolute (relative) concentrations in each room after 20 minutes of stabilization of the SF_6 concentration in the base ward is as follows<Table 4.15>, [Figure 4.31].

In the case of air conditioning duct sealing, the pressure difference in A, B, and C patient wards were −11.6Pa, −13.1Pa, and −17.3Pa, respectively, which improved by -0.3~−2.1Pa compared to the base model. The pressure difference in the bathroom was 1.0, 0.9, and 1.8Pa, respectively, and the bathroom was formed with a positive pressure rather than the patient ward. For make-up air, the Air Infiltration from the outside to the A, B, and C wards was 300, 555, and 388CMH, respectively, which was increased by 5~31CMH compared to the base model. At this time, the spread SF6 relative concentration in adjacent A and C wards was 11.2% and 18.5%, which increased by 0.4% and 0.7% compared to the base model. bathroom A, B, and C, the relative concentration was 3.4, 4.2, and 4.4%, which decreased by 3.1, 41.6, and 5.8% compared to the Bas model.

In the case of PNPU zoning, the pressure differential in

A · B · C wards and the amount of air infiltration into the wards from the outside were the same as those of the base model. When there was a leakage in the duct during PNPU Zoning, the relative concentrations of diffused SF_6 in adjacent A/C wards were 0.2 and 1.4%, respectively which decreased by 10.6 and 16.4% compared to the base model. and When there was no leakage in the PNPU zoning duct, the relative concentrations of diffused SF6 in A and C wards were 0.0 and 1.1%, respectively, which decreased by 10.8 and 16.7% compared to the base model.

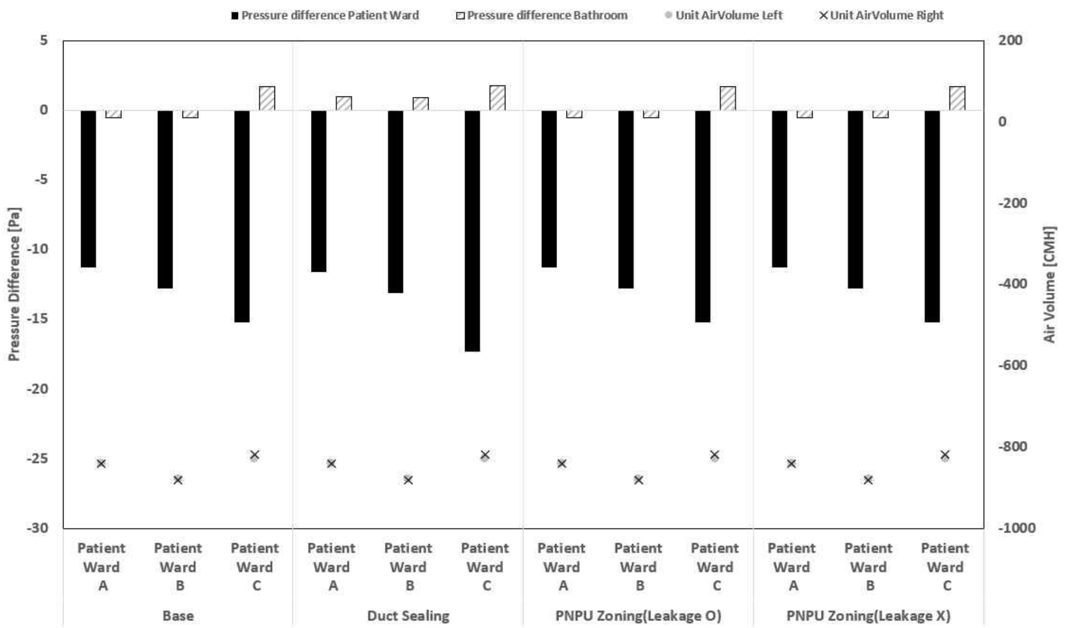
When sealing the air conditioning duct, the bathroom is formed with a positive pressure compared to the patient ward, so the spread of contaminants through the duct (backflow) can be prevented but the spread due to short circuiting cannot be prevented. On the other hand, when PNPU is zoned, diffusion due to short circuiting can be prevented and when there is a leakage in the zoning duct, a very small concentration appears to diffuse.

<Table 4.14> PNPU air volume, inter-room pressure difference, Air Infiltration rate at Building equipment elements improvement Model

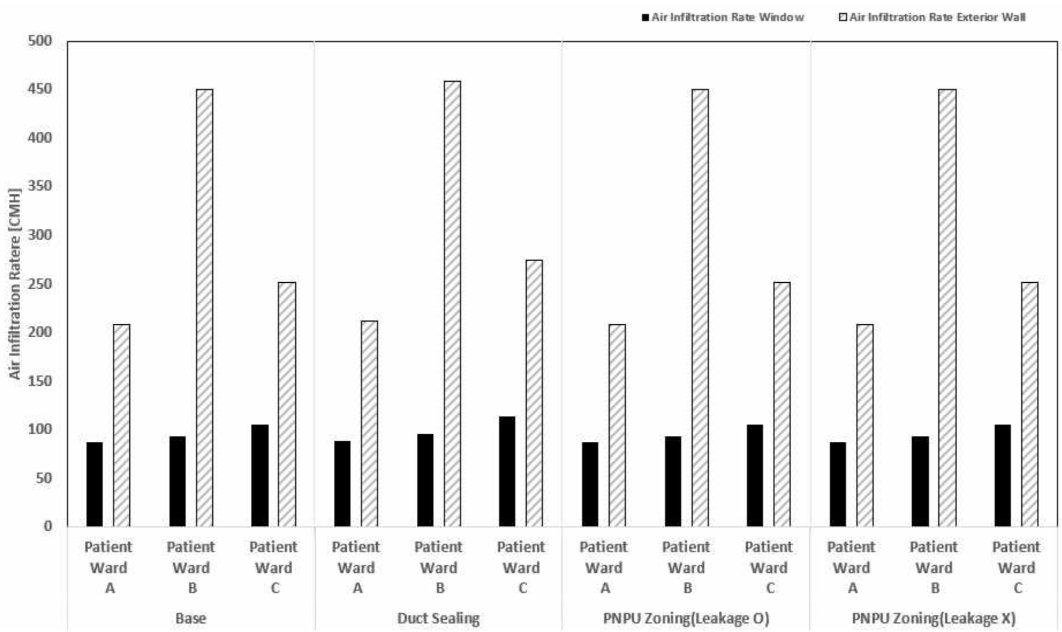
Unit [Air Volume: CMH, Pressure Difference: Pa, Air Infiltration Rate: CMH]

		Unit Air Volume		Pressure difference		Air Infiltration Rate	
		Left	Right	Patient Ward	Bath room	Window	Exterior Wall
Base	Patient Ward A	-840	-840	-11.3	-0.5	+87	+208
	Patient Ward B	-879	-881	-12.8	-0.5	+94	+450
	Patient Ward C	-828	-818	-15.2	1.7	+105	+252
Duct Sealing	Patient Ward A	-840	-840	-11.6	+1.0	+88	+212
	Patient Ward B	-879	-881	-13.1	+0.9	+96	+459
	Patient Ward C	-828	-818	-17.3	+1.8	+114	+274
PNPU Zoning (Leakage O)	Patient Ward A	-840	-840	-11.3	-0.5	+87	+208
	Patient Ward B	-879	-881	-12.8	-0.5	+94	+450
	Patient Ward C	-828	-818	-15.2	+1.7	+105	+252
PNPU Zoning (Leakage X)	Patient Ward A	-840	-840	-11.3	-0.5	+87	+208
	Patient Ward B	-879	-881	-12.8	-0.5	+94	+450
	Patient Ward C	-828	-818	-15.2	+1.7	+105	+252

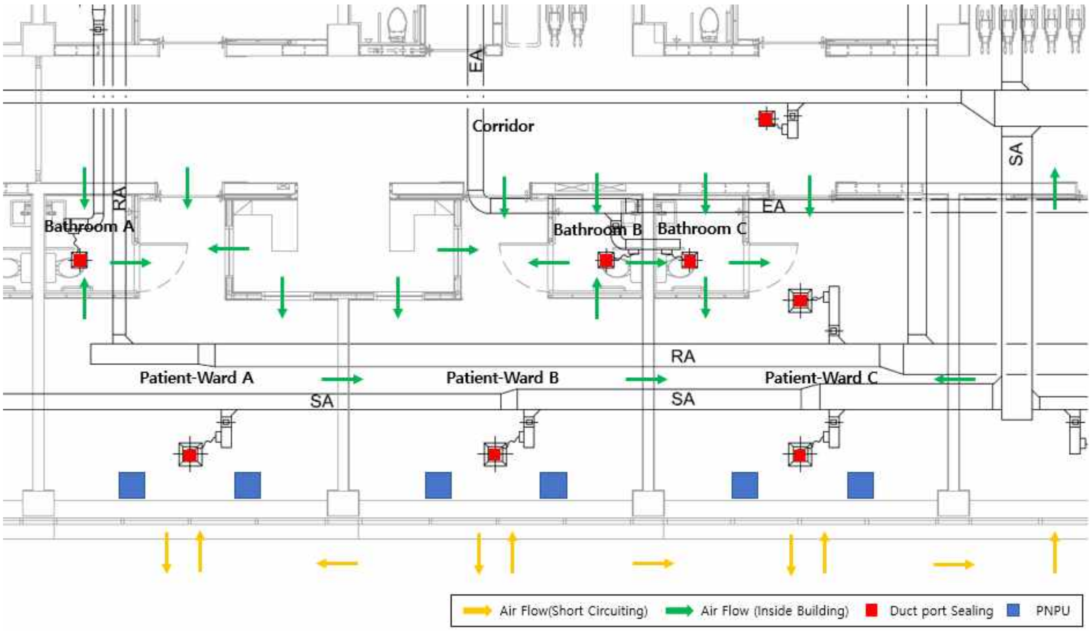
Note: [+: the direction of air supply into the room, -: Direction of exhaust to the oultside]



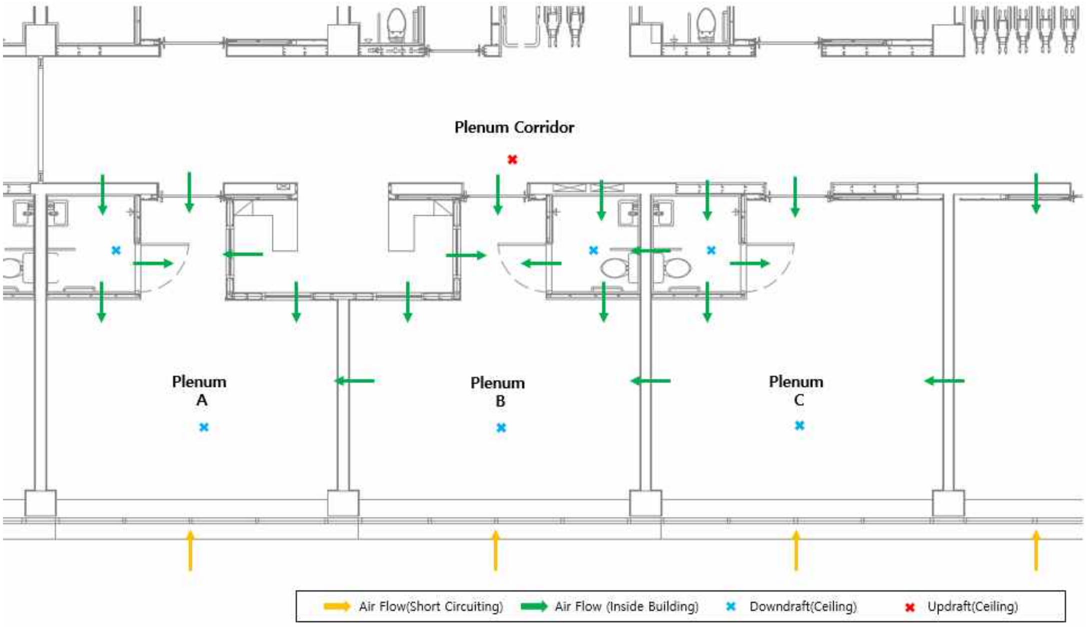
[Figure 4.25] PNPU Air Volume and Room Pressure Differential at Building equipment elements improvement Model



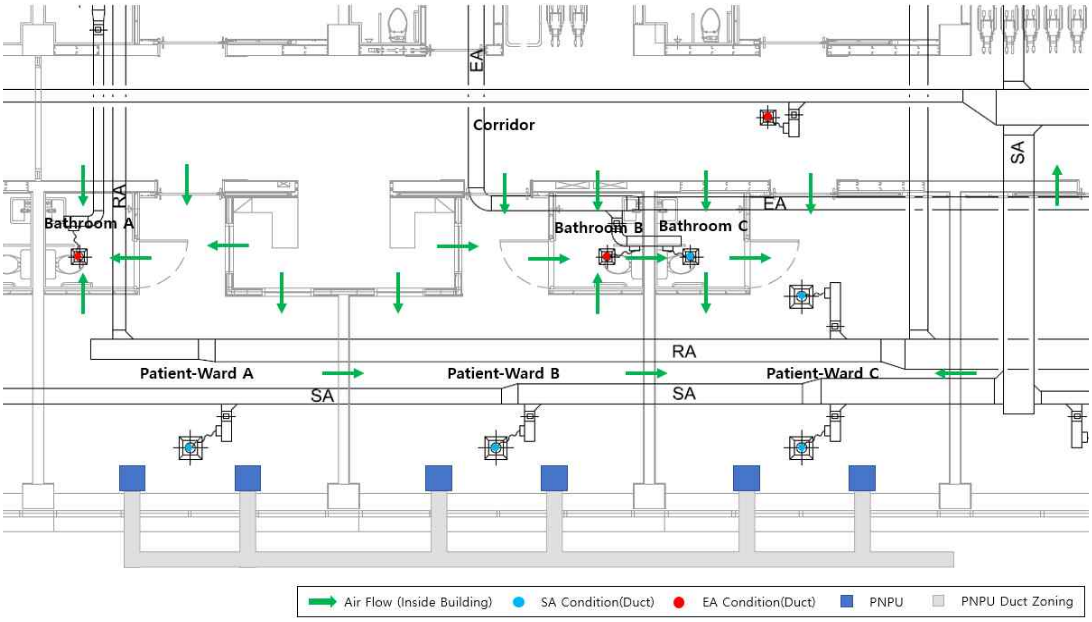
[Figure 4.26] Air Infiltration Rate window and Exterior Wall at Building equipment elements improvement Model



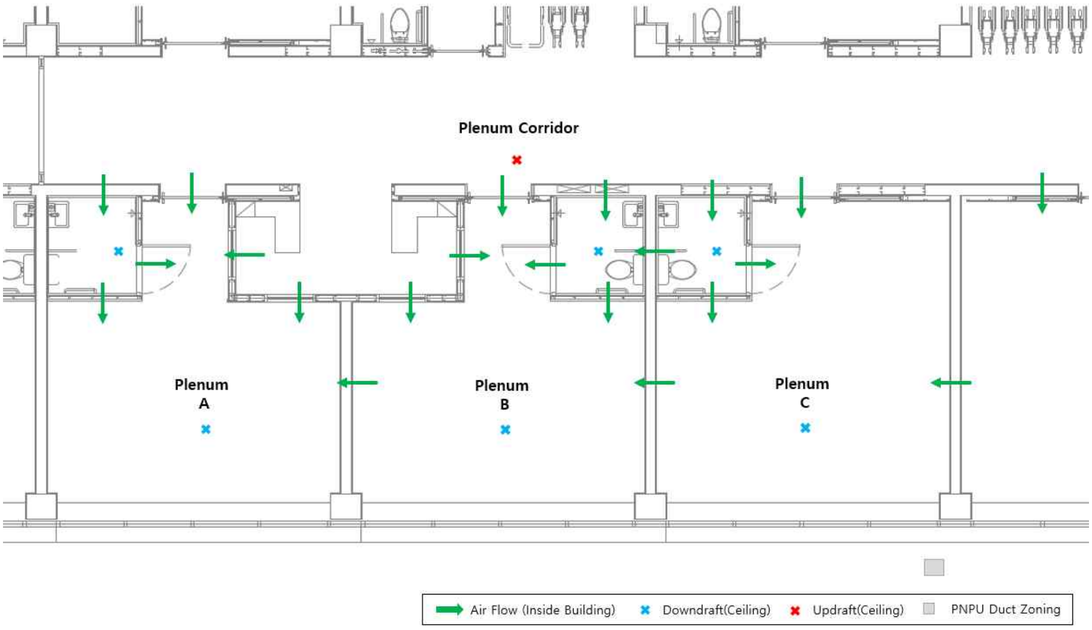
[Figure 4.27] Movement of airflow through Leakage area at Air Conditioning Duct Sealing Case Model(Floor)



[Figure 4.28] Movement of airflow through Leakage area at Air Conditioning Duct Sealing Case Model(Plenum)



[Figure 4.29] Movement of airflow through Leakage area at PNPU Zoning Case Model(Floor)

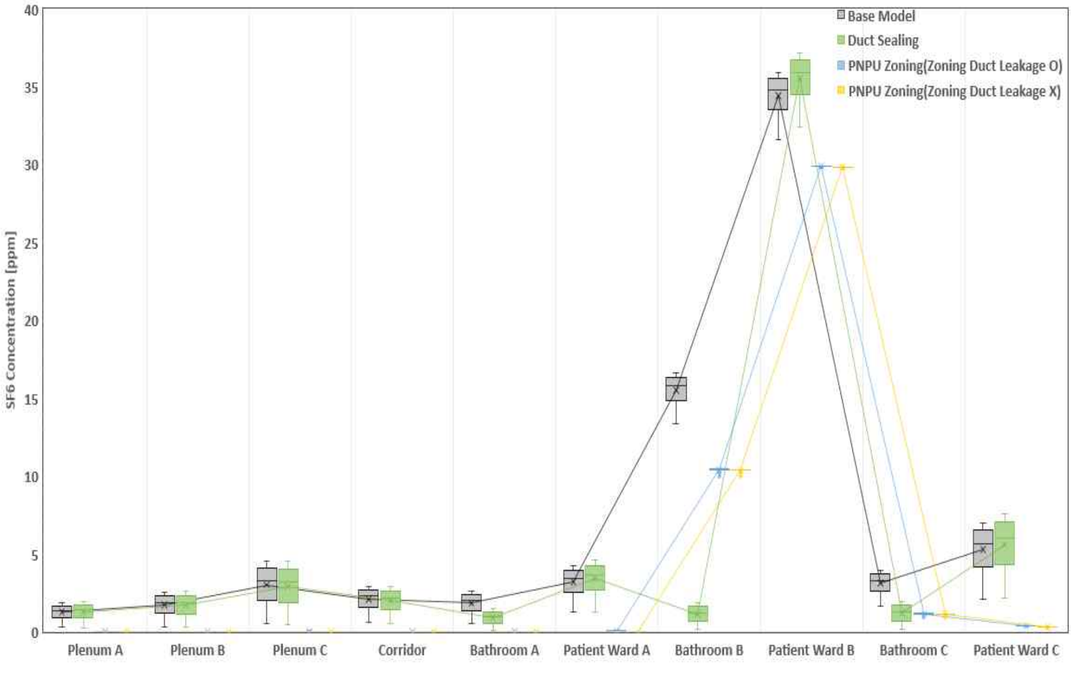


[Figure 4.30] Movement of airflow through Leakage area at PNPU Zoning Case Model(Plenum)

<Table 4.15> SF_6 Average (relative) Concentration at Building Equipment elements improvement Model

Unit [absolute concentration: μg/m³, (relative concentration: %)

		Base	Duct Sealing	PNPU Zoning (Leakage O)	PNPU Zoning (Leakage X)
Floor	Bathroom A	1.8(6.5)	0.9(3.4)	0.0(0.1)	0.0(0.0)
	Bathroom B	15.5(45.8)	1.1(4.2)	10.4(34.9)	10.4(34.8)
	Bathroom C	3.1(10.2)	1.2(4.4)	1.2(4.0)	1.1(3.9)
	Patient Ward A	3.2(10.8)	3.4(11.2)	0.0(0.2)	0.0(0.0)
	Patient Ward B	34.4(100.0)	35.5(100.0)	29.9(100.0)	29.8(100.0)
	Patient Ward C	5.3(17.8)	5.6(18.5)	0.4(1.4)	0.3(1.1)
	Corridor	2.1(7.3)	2.0(6.9)	0.0(0.1)	0.0(0.0)
Plenum	Plenum A	1.3(4.5)	1.3(4.5)	0.0(0.0)	0.0(0.0)
	Plenum B	1.7(6.2)	1.7(6.0)	0.0(0.1)	0.0(0.0)
	Plenum C	3.0(11.0)	2.9(10.5)	0.0(0.2)	0.0(0.0)



[Figure 4.31] SF_6 Gas Concentration Distribution at Building equipment elements improvement Model

4) Total improvement Model analysis results

As a result of the simulation for the case in which the Total Improvement, the pressure difference between wards according to the amount of PNPU air volume and the outdoor Air Infiltration Rate for make-up air are shown in <Table 4.16>, [Figure 4.32], [Figure 4.33].At this time, the airflow movement of the Total Improvement 1 · 2 model is formed as shown in [Figure 4.34], [Figure 4.35] and The airflow of the Total Improvement 3 · 4 model is formed as shown [Figure 4.36] and [Figure 4.37].

The average of the absolute (relative) concentrations in each room after 20 minutes of stabilization of the SF_6 concentration in the base ward is as follows <Table 4.17>, [Figure 4.38].

In the case of Total Improvement 1, the air volume of the PNPU was the same as that of the base model, and the pressure difference in A B C wards were −21.7, −25.8, and −33.6 Pa, respectively, which increased by −10.4 to −18.4 Pa compared to the base model. the pressure difference in the bathroom was 0.9, 0.8, and 1.5Pa, respectively, and the bathroom was formed with a positive pressure rather than the patient ward. At this time, the relative concentrations of diffused SF6 in the adjacent A · C wards were 0.0 and 0.9%, respectively, which decreased by 10.8 and 16.8% compared to the base model. in addition, the concentration was not detected in A, B, and C bathroom..

In the case of Total Improvement 2, the air volume of the PNPU was 1/2 that of the base model, and the pressure difference in A B C wards were −8.2, −9.0, and −11.6 Pa, respectively, which decreased by 3.1~3.8Pa compared to the base model. the pressure difference in the bathroom was 0.2, 0.3, and 0.5Pa, respectively, and the bathroom was formed with a positive pressure rather than the patient ward. At this time, the relative concentrations of diffused SF6 in the adjacent A · C wards were 0.0 and 0.9%, respectively, which decreased by 10.8 and 16.8% compared to the base model. in addition, the concentration was not detected in A, B, and C bathroom..

In the case of Total Improvement 3, the air volume of the PNPU in wards A and B was the same as that of the base model, and the air volume of the PNPU in ward C was adjusted so that the pressure difference was the same as that of ward B. the pressure difference in A B C wards were −21.6, −25.3, and −25.3 Pa, respectively, which increased by -10.1~−12.5Pa compared to the base model. the pressure difference in the bathroom was 0.9, 0.9, and 0.1Pa, respectively, and the bathroom was formed with a positive pressure rather than the patient ward. At this time, the concentrations of adjacent A · C wards and A · B · C bathrooms were not detected.

In the case of Total Improvement 4, the air volume of the PNPU in wards A and B was 1/2 of the base model, and the air volume of the PNPU in ward C was adjusted so that the pressure difference was the same as that of ward B. the pressure difference in A B C wards were −8.1, −8.9, and −8.9 Pa, respectively, which decreased by 3.2~6.3Pa compared to the base model. the pressure difference in the bathroom was 0.2, 0.3, and 0.3Pa, respectively, and the bathroom was formed with a positive pressure rather than the patient ward. At this time, the concentrations of adjacent A · C wards and A · B · C bathrooms were not detected.

When improving airtightness, PNPU Zoing, and duct sealing simultaneously, as shown in Total Improvement 2 and 4, Even if the air volume of the PNPU is reduced, it was found to be effective in preventing the spread of contaminants by maintaining a constant pressure difference, prevent short circuiting, and duct backflow problems. However, if the air volume of the PNPU is reduced, the concentration of contaminants in the patient ward itself increases due to the decrease in Air exchange rate. In addition, as in Total Improvement 3 and 4, if the pressure is formed at the lowest level in the patient ward where contaminants are generated by controlling the amount of air volume in the PNPU, air diffusion in the contaminated ward can be blocked.

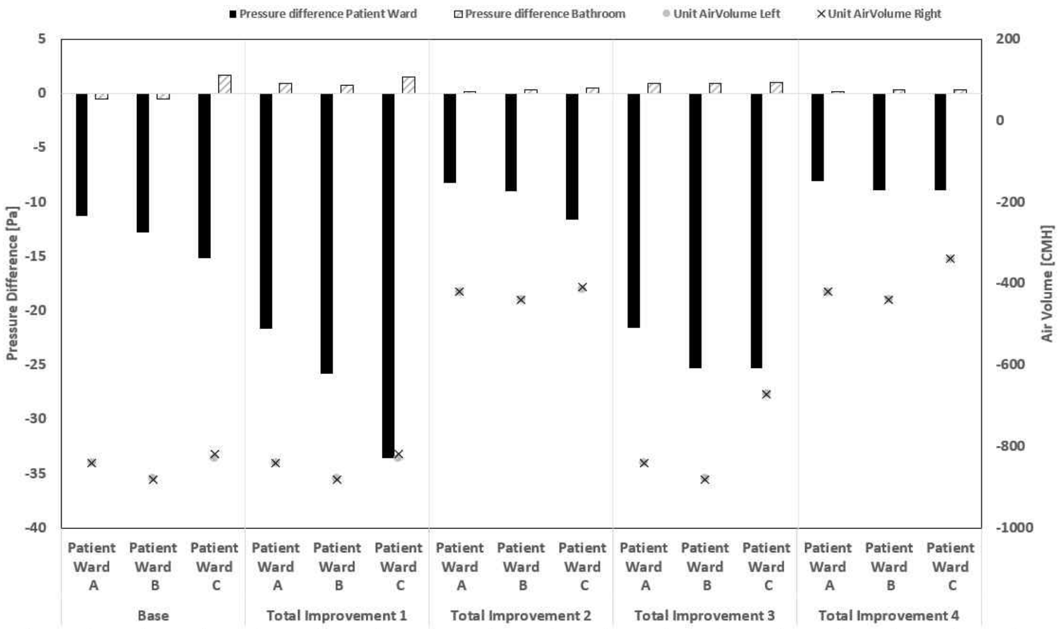
consequential in the case of Total Improvement 4, noise and energy consumption are expected to decrease due to a decrease in PNPU air volume compared to the case of Total Improvement 3. However, it was analyzed that the contamination concentration of the patient ward itself increases due to the decrease Air exchange rate.

<Table 4.16> PNPU air volume, inter-room pressure difference, Air Infiltration rate at Total improvement Model

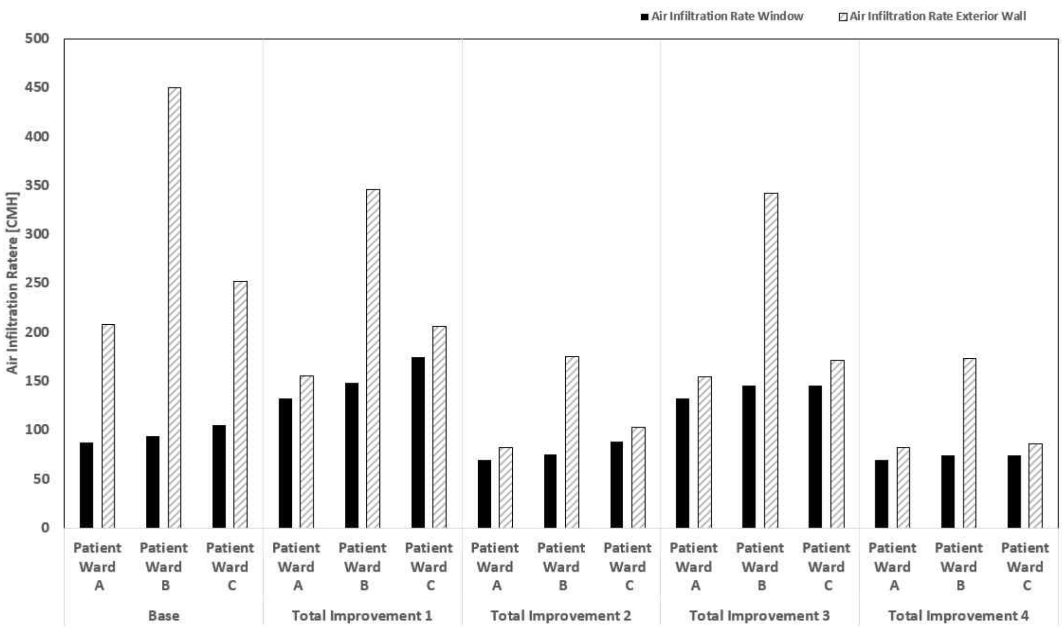
Unit [Air Volume: CMH, Pressure Difference: Pa, Air Infiltration Rate: CMH]

		Unit Air Volume		Pressure difference		Air Infiltration Rate	
		Left	Right	Patient Ward	Bath room	Window	Exterior Wall
Base	Patient Ward A	-840	-840	-11.3	-0.5	+87	+208
	Patient Ward B	-879	-881	-12.8	-0.5	+94	+450
	Patient Ward C	-828	-818	-15.2	+1.7	+105	+252
Total Improvement 1	Patient Ward A	-840	-840	-21.7	+0.9	+132	+155
	Patient Ward B	-879	-881	-25.8	+0.8	+148	+346
	Patient Ward C	-828	-818	-33.6	+1.5	+175	+206
Total Improvement 2	Patient Ward A	-420	-420	-8.2	+0.2	+70	+82
	Patient Ward B	-439	-441	-9.0	+0.3	+75	+175
	Patient Ward C	-414	-409	-11.6	+0.5	+88	+103
Total Improvement 3	Patient Ward A	-840	-840	-21.6	+0.9	+132	+154
	Patient Ward B	-879	-881	-25.3	+0.9	+146	+342
	Patient Ward C	-672	-672	-25.3	+1.0	+146	+171
Total Improvement 4	Patient Ward A	-420	-420	-8.1	+0.2	+70	+82
	Patient Ward B	-439	-441	-8.9	+0.3	+74	+173
	Patient Ward C	-339	-339	-8.9	+0.3	+74	+86

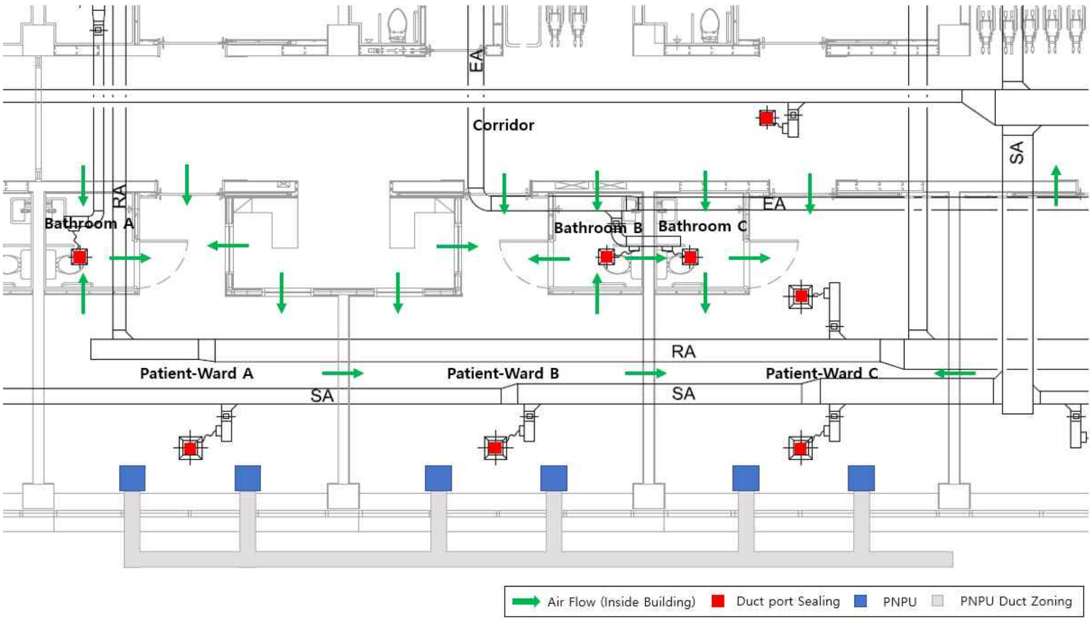
Note: [+: the direction of air supply into the room, -: Direction of exhaust to the outside]



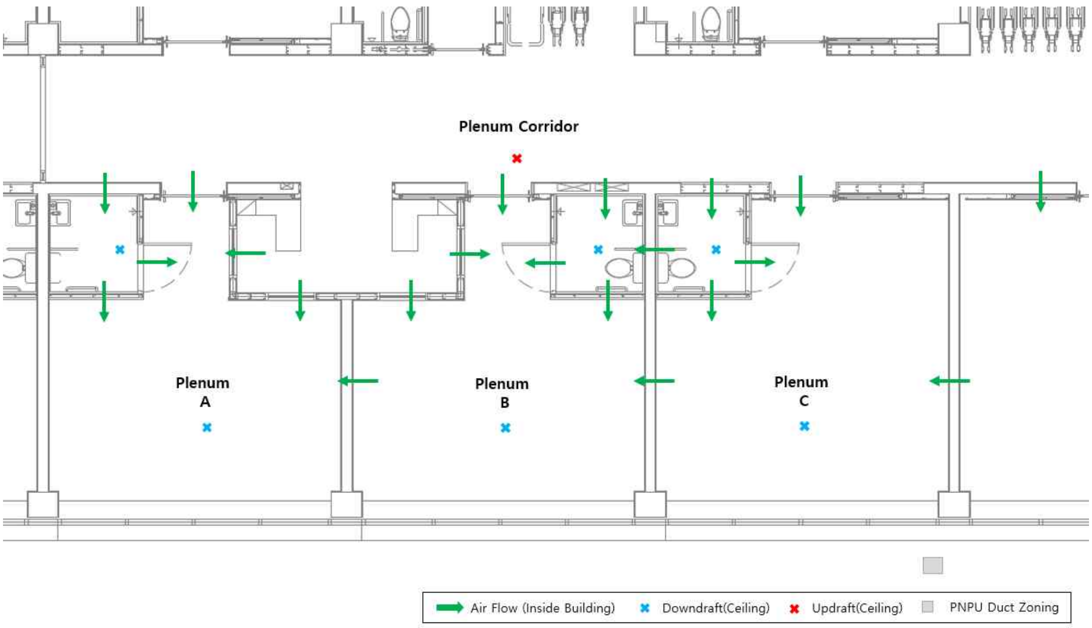
[Figure 4.32] PNPU Air Volume and Room Pressure Differential at Total improvement Model



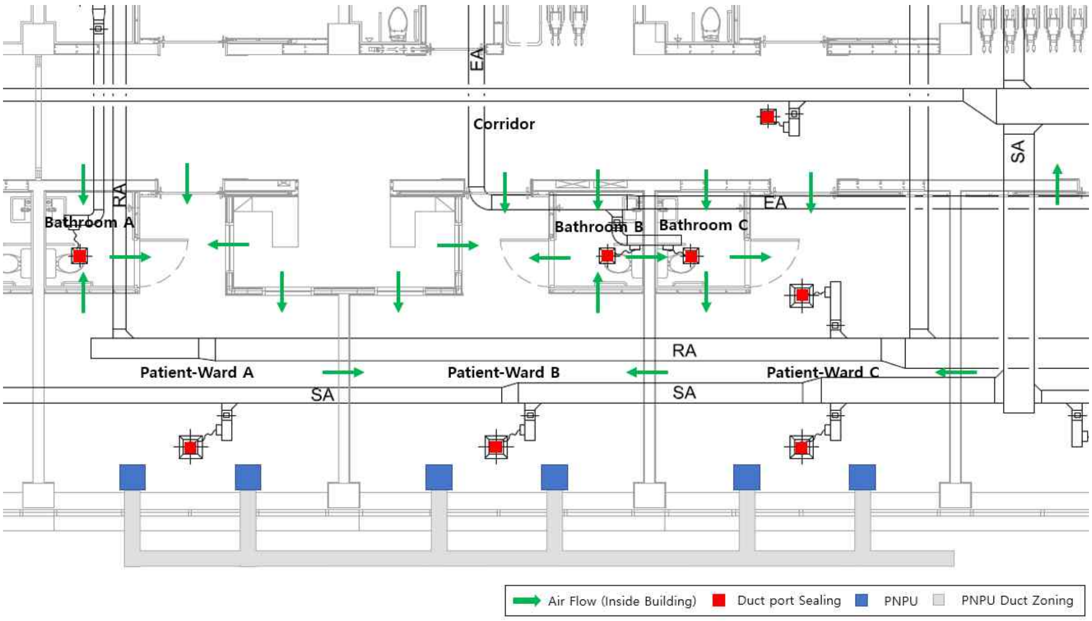
[Figure 4.33] Air Infiltration Rate window and Exterior Wall at Total Improvement Model



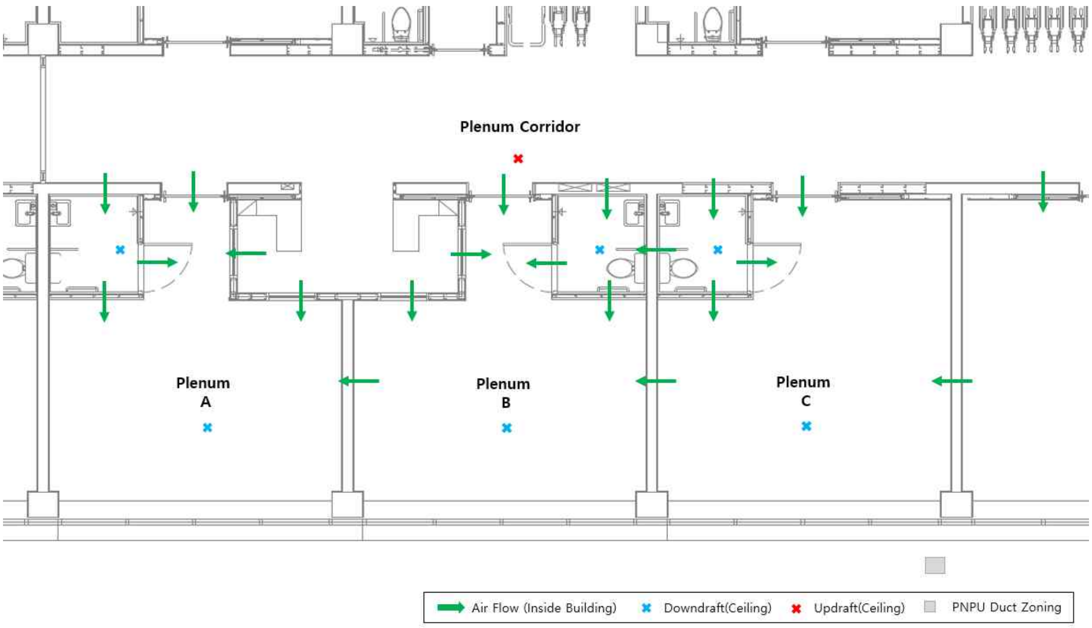
[Figure 4.34] Movement of airflow through Leakage area at Total Improvement 1·2 Model(Floor)



[Figure 4.35] Movement of airflow through Leakage area at Total Improvement 1·2 Model(Plenum)



[Figure 4.36] Movement of airflow through Leakage area at Total Improvement 3·4 Model(Floor)

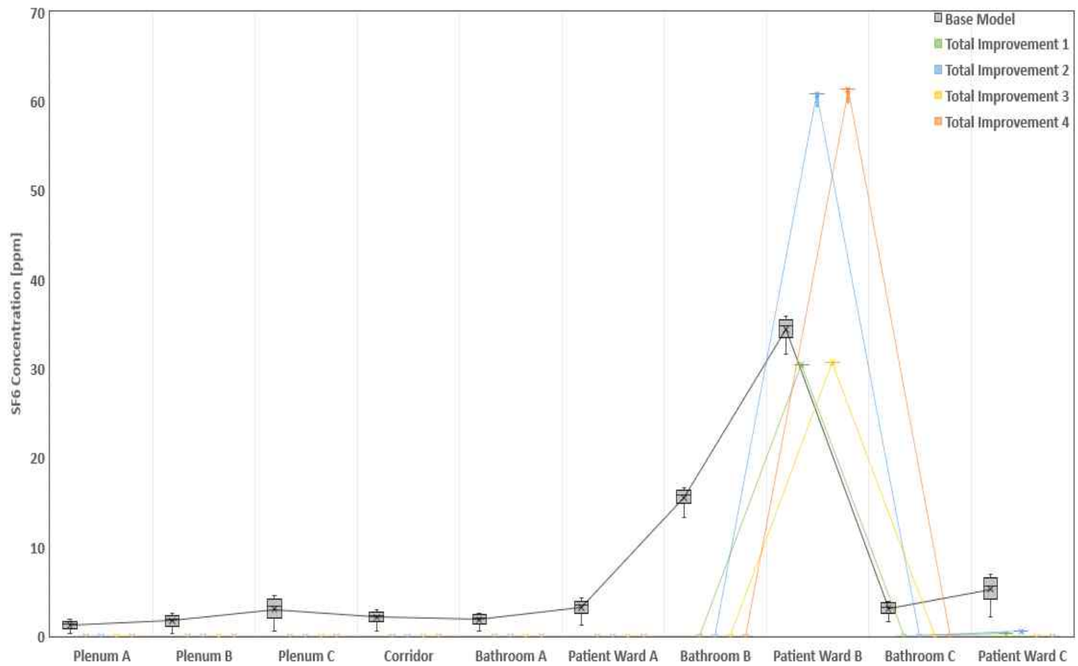


[Figure 4.37] Movement of airflow through Leakage area at Total Improvement 3·4 Model(Plenum)

<Table 4.17> SF_6 Average (relative) Concentration at Total improvement Model

Unit [absolute concentration: $\mu g/m^3$, (relative concentration: %)

		Base	Total Improvement 1	Total Improvement 2	Total Improvement 3	Total Improvement 3
Floor	Bathroom A	1.8(6.5)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)
	Bathroom B	15.5(45.8)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)
	Bathroom C	3.1(10.2)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)
	Patient Ward A	3.2(10.8)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)
	Patient Ward B	34.4(100.0)	30.4(100.0)	60.8(100.0)	30.7(100.0)	61.3(100.0)
	Patient Ward C	5.3(17.8)	0.3(0.9)	0.5(0.9)	0.0(0.0)	0.0(0.0)
	Corridor	2.1(7.3)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)
Plenum	Plenum A	1.3(4.5)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)
	Plenum B	1.7(6.2)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)
	Plenum C	3.0(11.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)



[Figure 4.38] SF_6 Gas Concentration Distribution at Total Improvement Model

4.3 Summary

Based on the results of the actual measurement of the spread of pollutants, the problems occurring in the Emergency Switching Type Negative Pressure Isolation Ward (ESTNPIW) and the simulation results of Architectural improvement, Building Equipment improvement, and Total improvement plan to solve the problem are summarized as follows.

1) As follows, the three problems found in the Emergency Switching Type Negative Pressure Isolation Ward (ESTNPIW) actual measurement were implemented as a base model. ① Diffusion of contaminants through backflow caused by duct pressure imbalance, ② Diffusion of contaminants through non-tight leakage areas, ③ Portable Negative Pressure Units (PNPU) exhaust outlets are adjacent to the exterior wall of the patient ward, causing short circuiting in which contaminants discharged outdoors flow back into the patient ward.

2) It was found that the pressure difference between patients ward was improved when the air leakage area of the Architectural elements was imporved (improved airtightness). If the leakage area of the ceiling is reduced by ½ (improvement of airtightness), the amount of short circuiting air that return into the patient ward among the contaminant air exhausted to the outside through the PNPU increases, increasing the concentration of contamination inside the patient ward. When the air leakage area of the exterior wall facing the outdoor air is reduced by ½ (improved airtightness), the amount of air entering the patient

ward from the outside decreases, so the contamination concentration decreases, but diffusion occurs due to the occurrence of short circuiting. When the air leakage area of the interior wall was reduced by ½ (improved airtightness), the amount of air entering the patient ward from the outside was similar to that of the base model, and the concentration spread due to the pressure difference change was shown rather than the concentration increase in the ward due to short circuiting.

3) As a result of the Building Equipment improvement simulation, when the central air conditioning in the ward is stopped and the duct port is sealed, the bathroom is formed at a positive pressure than the patient ward. Since the port is sealed, backflow due to duct pressure imbalance is prevented, and contaminant diffusion through the duct is prevented. However, in a situation where a short circuit occurs, diffusion from the hospital room to the bathroom can be prevented, but the contaminants spread to the bathroom through the leakage area facing the plenum and corridor among the bathroom areas.Zoning the PNPU exhaust duct was analyzed to be effective in preventing short circuiting and preventing contaminants exhausted to the outside from flowing back into the ward.

4) As a result of Total improvement simulation, which simultaneously improved Architectural elements and Building equipment elements, it was found to be effective in preventing the spread of contaminants in the bathroom and patient ward by preventing short circuiting and solving duct backflow problems. Through the Total Improvement 2 · 4 case, it was found that

sufficient pressure difference was maintained even when the air volume of the Portable Negative Pressure Units(PNPU) was reduced. Through Total Improvement Case 3·4, it was found that the diffusion of contaminants could be prevent if the air volume of the PNPU was adjusted to make the pressure in the ward where contaminants are generated the same or lower than that of the adjacent wards. In addition, in the case of total improvement 4, it was expected that noise and energy consumption would be reduced due to the reduction of PNPU air volume compared to the case of total improvement 3. However, it was analyzed that the concentration of contamination in the hospital room itself increased due to the decrease air exchange rate.

Chapter 5. Conclusion

In this study the possibility of spread of the infectious agent and its route were identified through measurement and analysis of the indoor environment of an ESTNPIW equipped with a PNPU through on-location measurement. Afterwards, in order to improve the problems that appeared in the field measurement through simulation, improvement plans for problems were reviewed through Architectural element, Building Equipment element, Total improvement

It was conducted to provide basic data for the construction and operation of an ESTNPIW by deriving points to be considered when installing a PNPU, and the results of this study are summarized as follows.

First, The indoor environment analysis through on-location measurement of the ESTNPIW to which the PNPU was applied is as follows.

1) Leakage of non-airtight ceilings and plenums can be a pathway for the spread of infectious agents. In addition, leakage acts as a cause of high demand for the air volume of the PNPU when forming the pressure difference between rooms, so airtightness treatment of the leakage area must be preceded in terms of architecture before installing the PNPU.

2) It has been shown that the PNPU can form the necessary pressure difference between rooms and lower the concentration of infectious agents in the patient ward itself. However, the

pressure balance of the existing ducts was broken due to the air volume of the PNPU, and there was a possibility that the infectious agent could spread through the backflowing air. Therefore, even if the central air conditioning system is not in operation, the supply and exhaust port that are not in operation must be sealed to prevent cross-contamination.

3) When pressure differential between adjacent patient wards is excluded and only the pressure differential between the corridor and the patient room is satisfied, Contaminants diffuse through leakage pathways, such as the interior walls of a patient's ward, to the lowest-pressure adjacent ward. Therefore, based on the pressure differential between the corridor and the patient ward, it is expected that each patient ward should maintain the same differential pressure level as much as possible to minimize the spread due to the pressure difference between adjacent wards.

Second, the simulation analysis results are as follows to improve the diffusion problem caused by short circulation, which may occur because the exhaust port of the PNPU is not separated from the Exterior wall, along with the diffusion of contaminants through duct backflow and leakage area.

1) It was found that the pressure difference between patient wards increased when the airtightness of the leakage area of a building such as Ceiling, Interior Wall, and Exterior Wall was improved. When the airtightness of the interior of the building is improved, the air infiltration from the outside for make-up air

increases, resulting in a problem of increased contamination in the ward due to short circuiting. If the airtightness of the exterior of the building is improved, the amount of air infiltration from the outside decreases, resulting in a decrease in the concentration of contaminants, which is also a fundamental problem, short circuiting cannot be effectively prevented, so short circuiting preventing should be be preceded.

2) When the central air conditioning system is stopped and the duct is sealed, the bathroom is formed at a positive pressure compared to the patient ward, preventing the spread of contaminants to the bathroom and the spread through the duct(backflow). but it is not effective in preventing the spread of areas other than the bathroom in the situation of short circuiting. In addition, it was analyzed that zoning a PNPU prevents short circuiting and is effective to prevent spreading contaminants.

3) In the case of a total improvement plan that simultaneously improved Architectural element airtightness and Building Equipment elements improvement, it was found to be effective to prevent the spread contaminants by maintaining appropriate pressure difference, prevent duct backflow and short circuiting problems even if the PNPU air volume is reduced. In addition, when a pressure difference with an adjacent patient ward occurs, diffusion cannot be completely blocked. Therefore, it was found that the diffusion from the contaminated patient ward could be blocked by adjusting the air volume of the PNPU to make the pressure in the contaminated patient ward the lowest or the equal.

4) In the Total improvement, if the PNPU air volume is reduced, the problem of appropriate pressure difference maintenance, noise, and energy usage may be reduced, but the contaminant concentration of the patient ward itself may increase due to the decrease in the Air exchange rate. On the other hand, increasing the PNPU air volume causes problems of increased noise and energy usage, but the Air exchange rate increases, which reduces the contamination concentration of the patient ward itself. Therefore, in order to create a comfortable environment for patients, there is a need for a method that can be solved by considering noise and contamination concentrations at the same time.

This study was conducted only in three consecutive wards, not the entire ward, and has limitations in that external factors could not be controlled because all wards except for the measurement area were being used. In the future, in order to more accurately identify the contaminants spread route and prepare alternatives, it is necessary to conduct additional measurement and simulation analysis of the entire ward along with external factor control.

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국문초록

2003년 SARS(Severe Acute Respiratory Syndrome)에서 2019년 COVID-19(corona virus disease 19)에 이르기까지 5~6년 주기로 새로운 호흡기 감염병이 발병하고 있다. 전염 위험성이 높은 호흡기 감염병은 발생 초기에 격리를 통해 2차 감염을 억제하고 지역사회로의 전파를 방지하고 있다. 격리는 일반적으로 건물 내 공기조화 설비를 이용해 형성된 실간 차압을 따라 공기의 흐름을 오염도가 낮은 준 청결 · 청결 구역에서 오염도가 높은 병실 등의 오염구역으로 유도하는 국가 지정 격리병실(Negative Pressure Isolation Ward)을 설치하여 운영하고 있다.

2019년 발생한 COVID-19 감염병으로 인해 전례 없는 팬데믹 사태가 발발했다. 이로 인해 기존 설치된 국가 지정 음압격리병실의 수용 능력에 한계에 이르게 되었다. 이를 해결하기 위해서 이동형 음압기를 적용해 일반 병실을 음압실로 전환한 긴급전환형 음압격리병실의 설치가 요구되었고, 일반 병실을 음압실로 전환한 긴급전환형 음압격리병실의 실내 환경에 대한 연구가 필요하게 되었다.

따라서 본 연구에서는 일반적인 음압격리 병실과 이동형 음압기를 적용한 긴급 전환형 음압격리병실 기준에 대해 분석하였다. 이후 긴급전환형 음압격리 병실의 실내환경(소음, 이동형 음압기 풍량, 풍속, 실간 차압, 기류 분석, 오염물질 확산) 측정 및 개선방안 시뮬레이션(Base모델, 건축요소 개선, 설비요소 개선, 종합적 개선)을 통하여 오염물질 확산 방지 방안에 대한 효과를 분석했다.

본 연구의 결과를 요약하면 다음과 같다.

현장 실측 결과 이동형 음압기를 가동할 경우 병실은 음압으로 형성되며, 병실 내부의 오염농도를 낮출 수 있었다. 하지만 이동형 음압기 가동은 기존 중앙공조 덕트들의 압력을 불균형하게 만들어 덕트 역류를 발생시켰다. 이로 인해 역류하는 공기를 통해 오염원이 확산될 가능성이

있는 것으로 나타났다. 또한 기밀하지 않은 천장부 및 플래넘의 누기 부위는 오염원의 확산경로로 나타났다.

복도와 병실 간의 차압이 기준을 충족시키는 경우, 기류는 압력이 가장 낮은 병실로 이동하게 되어 병실 내벽 등 누기 부위를 통한 오염원 확산이 나타났다.

현장에 설치된 이동형 음압기의 배기덕트는 외기와 면하고 있어 병실의 이동형 음압기를 통해 배기 된 오염 공기 중 일부가 병실 내부로 유입되는 short circuiting 현상이 발생 될 가능성이 있는 것으로 나타났다.

시뮬레이션 결과 건축적요소(천장, 외벽, 내벽)의 기밀성을 향상시키게 될 경우 병실간의 차압은 증가하는 것으로 나타났다. 건축물 내부 구조체(천장, 내벽)의 기밀성이 향상 될 경우 공급 공기를 위해 외부로부터 유입되는 공기량이 증가하여 short circuiting으로 인한 병동내 오염도가 상승하는 것으로 나타났다. 건축물의 외벽의 기밀성을 향상시킬 경우 외부로부터 유입되는 공기량이 감소되어 병동 내 오염도가 건축물 내부 구조체 기밀성을 향상시킨 경우보다 감소하지만 병동은 오염되는 것으로 나타났다. 건축적요소만을 개선할 경우 short circuiting을 방지할 수 없으므로 효과적인 개선 방안으로 볼 수 없었다.

설비적 요소 중 중앙공조 가동을 중지하고 덕트 급·배기구를 밀폐할 경우 화장실이 병실보다 양압으로 형성되어 화장실로의 오염물질 이동과 덕트 역류로 인한 확산을 방지할 수 있는 것으로 나타났지만 short circuiting이 발생하는 상황에서는 다른 실로의 오염물질 확산과 복도·천장과 화장실이 면한 누기 부위를 통해 복도·천장에서 화장실로의 오염물질 확산을 일어나는 것으로 나타났다. short circuiting 방지를 위해 이동형 음압기의 배기 덕트를 조닝 할 경우 short circuiting이 방지되어 병실 내 오염원 확산을 차단하는데 효과가 있는 것으로 분석되었다.

건축 및 설비적 개선방안을 동시에 진행한 종합적 개선방안의 경우 덕트 역류 및 short circuiting으로 인한 오염물질 확산 방지에 효과적

인 것으로 나타났고 음압기의 풍량이 감소되더라도 일정한 차압이 유지되는 것으로 분석되었다. 그리고 음압기 풍량을 조절해 오염원이 발생되는 병실의 압력을 가장 낮게 형성할 경우 오염된 병실로 부터의 확산을 차단 할 수 있는 것으로 나타났다.

음압기 풍량을 감소시킬 경우 적정 차압 유지, 소음, 에너지 사용량은 줄어들 수 있지만 환기 횟수 감소로 인한 병실 자체의 오염도는 증가하는 것으로 분석되었으며, 음압기 풍량을 증가시킬 경우 차압 유지, 소음, 에너지 사용량이 증가하지만 환기 횟수 증가로 인해 병실 자체의 오염도는 감소시킬 수 있는 것으로 나타났다. 환자의 쾌적한 실내 환경을 조성하기 위해서는 소음과 오염도를 동시에 고려한 해결 방안이 필요하다.

본 연구는 측정 구역 외의 병실이 이용 중인 점과 병동 전체가 아닌 연속된 세 개의 병실에 한하여 진행되었다는 점 등 외부 요인을 통제할 수 없었다는 점에서 한계를 가진다. 향후에 보다 정확한 감염원 확산경로 파악과 대안 마련을 위해서는 외부 요인 통제와 함께 병동 전체에 대한 측정 및 시뮬레이션 분석 등이 추가로 진행될 필요가 있다.

주요어 : 이동형음압기, 긴급 전환형 음압격리병실, 현장측정, 확산실험, 개선방안 시뮬레이션
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