A hygiene ventilation renovation

Systematic partial engineering control for small sharing room with ceiling mixing ventilation for “corona-proof”

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Content

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Glossary

Air Change Hourly (ACH) - abbreviated ACPH or ACH, or air change rate is a measure of the air volume added to or removed from a space in one hour, divided by the volume of the space. If the air in the space is either uniform or perfectly mixed, air changes per hour is a measure of how many times the air within a defined space is replaced each hour.

Air age - the resistance time of indoor air after being supplied into the ventilation zone and before being exhausted out of that ventilation zone.

Air change efficiency - is a measure of how quickly the air in the room is replaced in comparison with the theoretically fastest rate with the same ventilation air flow.

Acceptable infection risk - an achievable infection risk calculated by Wells-Riley calculation in the sample room with two occupants indoors can ensure that the majority of healthy people will not be infected by COVID-19 based on the extensive measurement data from US schools.

Air recirculation rate – a measure of the recirculated air volume locally resupply to a space in one hour, divided by the volume of the space.

Breathing zone - the breathing zone in this research is the zone in the centre of the room where the meeting table is and the occupants sit around at the height of 1.1-1.3 m.

Contaminant removal efficiency - is a measure of how quickly an air-borne contaminant is removed from the room. It is defined as the ratio between the steady state concentration of contaminant in the exhaust air, and the steady state mean concentration of the room.

Computational fluid dynamics (CFD) - a branch of fluid mechanics that uses numerical analysis and data structures to analyse and solve problems that involve fluid flows, especially the ventilation airflows, human body airflows and respiratory airflows in the small shared rooms in this research.

"corona-proof" - an engineering performance to prevent or reduce the risk of indoor infection for ventilation design in this research.

Coanda effect – the tendency of a fluid jet to stay attached to a convex surface. the tendency of a jet of fluid emerging from an orifice to follow an adjacent flat or curved surface and to entrain fluid from the surroundings so that a region of lower pressure develops.

Ceiling level - the ceiling level in this research is the zone in the centre of the room where the ceiling supply opening is from 20cm below the ceiling to the ceiling height.

Efficient opening area – efficient opening area is based on the theory of nature ventilation to calculate the different area of top and bottom openings to solve the air flow pressure due to the height difference. In this case, there is the pressure drop caused by the fan coil in the indoor end unit, the introduction of efficient opening area is to remove the pressure difference caused by the opening area at the end of the opening, calculated by $\frac{1}{A_{eff}^{2}}=\left(\frac{1}{A_{bottom}^{2}}+\frac{1}{A_{top}^{2}}\right)$.

Filtration control - engineering design, installation and maintenance of the integrated end equipment within the ventilation pattern design that has the capacity to remove or inactivate the virus nuclei laid airborne particles.

General control - also centralized control in in the mechanical ventilation system of commercial high buildings (no less than 16 m), including the air handling unit for the whole building and outdoor units in VRF ventilation system for multiple ventilation zones.

General ventilation distance – the linear distance between the supply opening and exhaust opening in the general local ventilation.

Individual control - different from partial and general controls, the individual control is for the ventilation facilities provided by the individual user are independent of the ventilation system of the building.

Medium-scale environment - an indoor environment, like the small shared room, with a spatial scale between macro and micro climate and equipped with only one indoor ventilation unit showing the direct relationship between single indoor end unit of a HVAC system and the micro-climate around human body.

Mixing level – the homogenization of indoor air quality due to mixed ventilation is reflected, calculated by the standard deviation of indoor contaminant concentration minus the absolute value of the mean divided by the mean indoor contaminant concentration

Mapping logics – Like the synonym for a function in mathematics, in category theory, a map may refer to a morphism, which is a generalization of the idea of a function to build up an academic language system among the three disciplines, theoretical ventilation design, infectious disease pathology and practical systematic control.

Partial control - to distinguish from centralized control or individual control in the mechanical ventilation system of commercial high buildings (no less than 16 m), mainly are the single ventilation end unit for each ventilation zone, like indoor end units.

Purifiers - any end equipment integrated in the ventilation pattern design that has the capacity to remove or inactivate the virus nuclei laid airborne particles.

Recirculation distance – the linear distance between the resupply opening and air return opening in the local air recirculation pattern.

Thermal plume - A plume is a substance which moves from a source into its surrounding area, such as a plume of smoke. A thermal plume is a plume that is specific to temperature alone. Therefore, a thermal plume involves a part of a particular substance such as water or atmosphere which is of a different temperature, usually an elevated temperature which is proceeding from a source and has not yet dissipated into the surrounding substance and equalized temperature. In this research, the thermal plume is the airborne particle from human and particularly dissipates in and above the breathing zone.

1. Introduction

The thesis focuses on the economic renovation of the existing ventilation system of the sample public commercial space, a small meeting room in Kuijpers, Leiden, to decrease airborne transmission of respiratory infectious diseases. More specifically, the partial ventilation for optimal synergic impacts on filter effects at the end unit of ceiling mixing ventilation pattern in VRF ventilation system in Dutch offices.

1.1 Context

The coronavirus pandemic (COVID-19) is an infectious disease caused by a newly discovered coronavirus(SARS-CoV-2).The highly variable symptoms of COVID-19 make the virus spreading hard to control (Huang et al., 2020). COVID-19 has an incubation period of up to two weeks. In the incubation period, the infected already shows a high infectivity (McMichael et al., 2019). And up to 2.2% of people with asymptomatic infections can infect anyone else, compared to 0.8%-15.4% of people with symptoms(Burke et al., 2020). As of 6 January 2021, more than 86.4 million cases have been confirmed, with more than 1.86 million deaths attributed to COVID-19 in the world ("WHO Coronavirus (COVID-19) Dashboard", 2021). A 3.4% Mortality Rate was estimated by the World Health Organization (WHO) as of 3 March 2020. The death rate was 1.43% in the Netherlands as of 6 January 2021 (COVID-19 mortality rate by country | Statista, 2021). The death rate decreased to half (0.76%) after the public has been widely fully vaccinated in the Netherlands as of 24 September 2021 (COVID-19 mortality rate by country | Statista, 2021). The old and those with underlying medical problems are more likely to develop serious illness. The further injuries, like permanent lung damage, heart muscle damage and stroke risks on brain, can last a lifetime in severe patients (Carfì et al., 2020).

Except for its physical impact on human bodies, people faced emotional impacts due to coercive insulation among infected and healthy family members. Because of the unexpected affinity and alienation in the short time caused by city lock-down, family relationships tend to be polarized. Due to COVID-19-related external stress, the likely harmful dyadic processes undermines couples' relationship quality. The further harmful psychological impacts include attachment insecurity and depression (Pietromonaco & Overall, 2020)

The epidemic has brought a new round of economic crisis all over the world. The economic recession can be caused by: pressure on weak health care systems, loss of trade and tourism, dwindling remittances, subdued capital flows, and tight financial conditions amid mounting debt (Kose et al., 2020). People cast their eyes on electronic information industry in succession like We Media, online shows, e-shopping etc. The lock-down policy decreases personnel mobility and freight transportation. Public social places, schools and restaurants are closed, which changes the social interaction pattern, working mode and education methods.

As for the built environment, the requirement of indoor living environments has become higher. For example, when buying a house, people want to have an independent yard and a fully-equipped apartment. The indoor working areas also draw extra attention for an independent working place for every family member. Previous architectural design, Small Office & Home Office becomes popular again in the construction market.

From the state to social groups to individuals, various levels of society have taken different levels of epidemic prevention measures. The Dutch government has introduced restrictions on the size of groups, social distance limits and the closure of non-essential business premises. The TU Delft has organized an TU Delft COVID-19 Response Fund and initiated research related to the COVID-19 like 3D printed components to make snorkel masks and the development of an emergency ventilator ("TU Delft COVID-19 Response Fund", 2021). Individuals learn indoor disinfection measures, such as a separate washbasin. For the management of educational spaces, TU Delft created one-way routines, labeled the available seats with safe distance control and real-name checking in-and –out system to track every building user. The opening hours, daily occupancy and accessibility of education places are strictly controlled by TU Delft.

COVID-19 changes everyone’s daily life from all aspects. Every individual is alert for any risky exposure and try to protect their families. All societies are desperate for a series of solutions to improve the public safety of epidemic prevention. Everyone hopes to minimize the impact of the epidemic on people's daily life.

Based on the observation of social changes in people's social behaviour, this building technical research will discuss the public spaces that of high social value in the corona times. The research scaled down the topic from the indoor infectious disease transmission type and the space type to its geometry scale to its indoor activities to its ventilation system to its indoor end unit.

1.2 Indoor epidemic prevention

Buildings are manmade environments to meet human’s living needs. More than 80% of human activities are done indoors. People spend 90% of our time indoors on average (Figure 1) Interior spaces are the direct material carriers for production and living, some of which for long-stay purposes need to meet relatively high requirements on living, comfort, durability and economy. The engineering methods for corona-virus defense faces with different challenges, standards and requirements. For examples, the unfixed layouts of residential buildings bring with challenges. The high hygiene standards in hospitals also ask for a higher air change standard. The dynamic movements of students in school have special requirements for high occupant density (L. Morawska et al., 2017).The indoor conditions also play an essential role in the prevention of COVID-19. If a building preserves natural resources, prioritizes good ventilation, uses efficient and green energy and uses non-toxic sustainable materials, it can generally reduce the harmful particles in the air which virus and bacteria can attach to and help ward off corona-virus in an extensive view.

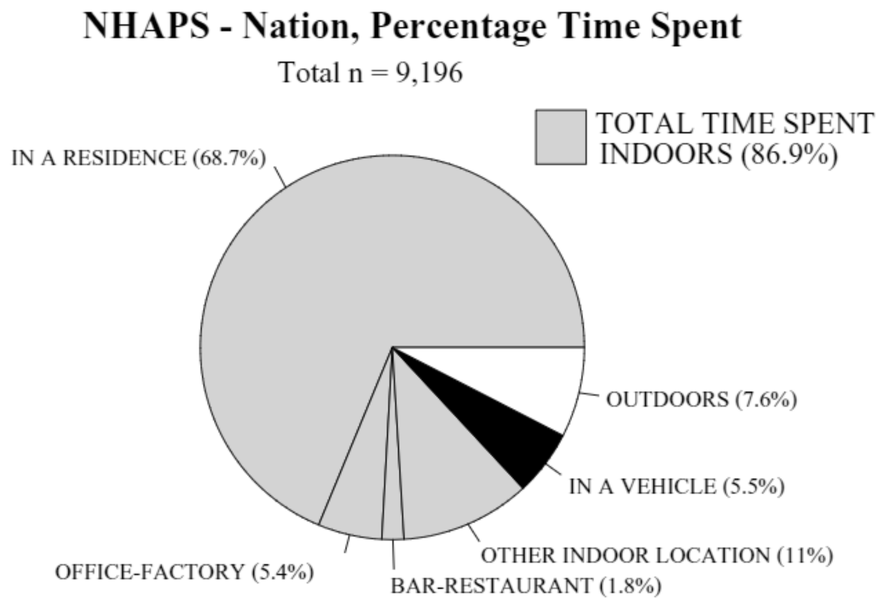


Figure 1 The mean percentage of time on the diary day from The National Human Activity Pattern Survey (NHAPS) (Klepeis et al., n.d.)

Airborne transmission is one of the three commonly accepted transmission modes for person-to-person respiratory infectious diseases, like COVID-19 (Hoseinzadeh, Safoura Javan, et al., 2020) (see Figure 2). The other two valid transmission routes are direct contact with virus-laden surfaces and exposure to the respiratory droplets from effected people (Lidia Morawska et al., 2020). These two transmission methods can be cut off by personal hygiene protection, like washing hands frequently, keeping safe social distance and wearing masks ("COVID-19 Clinical management: living guidance", 2021). Most buildings have already provided self-disinfection plots and separated in and out movement routines. But as for airborne transmission, it is hard to predict the airflow or make personal protection. And in wide cognition, the most influential engineering method for the general public to decrease the infection risks is ventilation (Lidia Morawska et al., 2020).

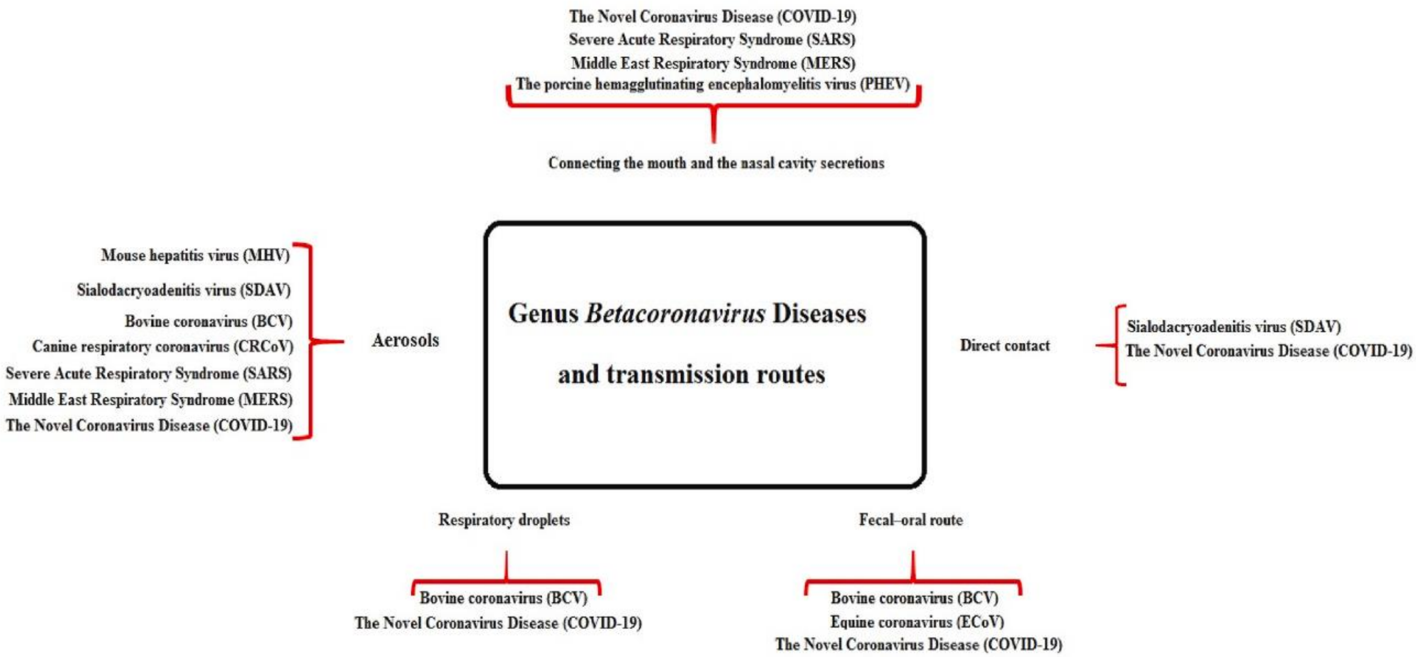


Figure 2 Betacoronavirus diseases and their transmission paths (Hoseinzadeh, Javan, et al., 2020).

As real social connection is of vital importance for individual physical and psychological health, family bonds and local developments, the epidemic prevention in public places is important. The ventilation design for public buildings could be best solution to maintain the essential social activities, like meeting, shopping and group works, and protect people from high-risk exposure.

1.3 "Corona-risk-decreased" ventilation

Building system engineering can help decrease the risk of being infected by the aerosol which containing the virus-laden droplet nuclei. Many techniques in building system can help decrease the concentrations of particles. The six currently practical building engineering technologies are**: ventilation, mechanical air filters, UV lights, bio-polar ionization generators, ozone Generating air cleaners and electrostatic precipitator (EPS)** (Nafezarefi, F; Joosten, 2020). Based on the traditional infection control pyramid adapted from the US Centers for Disease Control ("Hierarchy of Controls | NIOSH | CDC", 2021), the six technics are ranked based on the infection control engineering efficiency (see Figure 3). The most effective way to control the indoor airborne transmission of COVID-19 is ventilation flow design, especially in the open public indoor spaces for general protection.

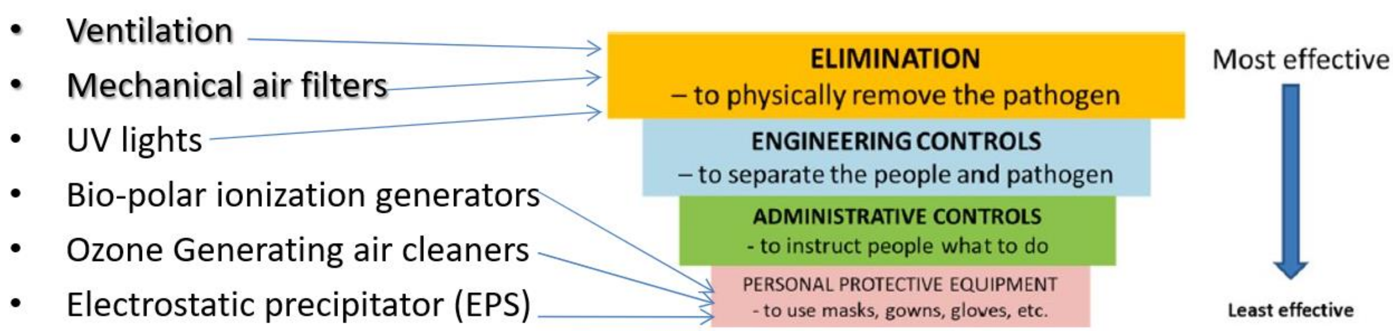


Figure 3 Traditional infection control pyramid adapted from the US Centers for Disease Control ("Hierarchy of Controls | NIOSH | CDC", 2021) & author.

The corona-risk-decreased ventilation is to decrease risks for exposed healthy occupants of being infected COVID-19 via airborne transmission. Currently, there are not much specific ventilation designs for public buildings for uninfected general healthy people, like offices, schools, theaters, supermarkets and airports. From a general spatial scale, the main elements for the existing ventilation control are **outside air fractions** and **air change hourly rates (ACH)**. Scientist suggested that **the air recirculation should be avoided under COVID-19 crisis** (Lidia Morawska et al., 2020). From an individual human-body scale, the ventilation control is to well organize the ventilation flow, human body boundary layer flow and respiratory flow (Arsen K. Melikov, 2015). The dynamic design elements include layout of the room, indoor activities and breathing modes. **The manageable design elements are room air distribution pattern, air supply mode in HVAC system and ventilation flow rate.** The two mean parameters to evaluate whether a ventilation design achieves decrease the infectious risk are **the local mean age of the air** and th**e mean concentration of particles**.

The ventilation strategy design is to have a general control of the indoor air flow dynamics, and thus, focusing on the airborne transmission, which has a larger spatial impact and is more influenced by indoor ventilation than droplet transmission and direct contact transmission. The particle movement driven by the ventilation flow is the core of the airborne transmission at a macro level. Droplet nuclei, where the corona virus attached, are fine air particles that remain airborne for a considerable length of time. Thus, the adhesion to different particle sizes and the pathogenicity at different concentration rates of corona virus influence aerosol transport at a microscopic level.

1.4 Clean room technology for corona-risk-decreased

For different hygiene standards and building functions, the requirements for indoor cleanliness are different. Compared to the public commercial buildings, like supermarkets, restaurants, shopping malls and theaters, the hygiene requirements for kindergartens, nursing centers and hospitals are higher. In clean rooms, the hygiene quality can be maximized. Clean rooms are already applied in many fields, including semiconductor manufacturing, biotechnology, the life sciences, and other fields that are very sensitive to environmental contamination. Air clean technology is a new technology, starting from mid-1950s. HEPA filter air clean technology is the most basic and the most necessary means for air clean technology. Other clean room design details, including the position of supply and exhaust openings, dilution efficiency, air quality monitors and air quality smart control, are also important in high-hygiene ventilation design. The clean room ventilation, standing for the highest cleanness level in the built environments will inspire the ventilation strategy design for epidemic prevention in shared space.

Kuijpers is a company with years of experience in technical installations in buildings. The services of Kuijpers include design, construction and maintenance. The company pays special attentions to a healthy working and living environment. Kuijpers is also the clean room contractor for Johnson & Johnson's Dutch vaccine plant. The company actively responding to the Dutch epidemic prevention request and try to explore COVID-19 related epidemic prevention researches.

The theoretical knowledge of clean rooms and practical installation experience of Kuijpers will support the promotion of a higher hygiene ventilation strategy for prevention and control of infectious diseases in public space for commercial purposes.

1.5 Problem statement

Public spaces are important for people’s daily life and social economic developments. Most countries cannot execute the extreme lock-down policy to ban all the social behavior as China did. Asymptomatic people are already capable of spreading the disease. And the indoor airborne transmission is one of the three main ways for COVID-19’s cross-infection. A lot of researches an indoor airborne transmission have been done for expiratory infectious diseases. It has been proved that indoor ventilation design is the most effective way to generally control the expiratory infectious diseases, like COVID-19. To decrease the infectious risks, it is recommended to increase the air exchange rate, enlarge the outside air fraction and avoid indoor air recirculation. But the small ventilation suggestions may bring about uncomfortable experience and large cost. For example, most offices in the Netherlands are using the hybrid mixing ventilation pattern with air-recirculation indoor end unit, because such type of HVAC system is economic, efficient and comfortable at the same time. The limitation from current research in understanding the indoor infectious disease transmission, the deep gap between practical installation and theoretical proposal, and the huge capital input for building system renovation make it impossible to immediate totally switch the current dismal indoor infection condition.

The idea is to find a ventilation strategy to **control or at least reduce the risk of respiratory infections via airborne transmission** and meet the requirements of indoor comfort and reasonable economic costs in **a typical meeting room** based on the widely applied ventilation system in Dutch offices (which is using **the fan-coil air-recirculation indoor end unit** under **hybrid ceiling mixing ventilation pattern**), in this case, the meeting room in the Kuijpers office, Leiden. A lot of airborne transmission researches have been conducted in an ideal small-scale steady-state clean room with only two manikins insides, but not enough attempts has been done for a small-scale room based on the realistic common ventilation system in commercial buildings of general healthcare standard for general public yet. The authority suggests **no air recirculation** to avoid cross infection caused by the possible secondary pollutant from it. Most public buildings in the Netherlands apply mixing ventilation for indoor comfort and economic considerations. **In this system, the room air is already homogenized when supplying the indoor air to occupants**. The room air is partly reused at the indoor end unit of air recirculation mode (see Figure 4) Such kind of indoor end unit is the mainstream products for ventilation system in offices, which is to be avoided under the COVID-19 crisis, bringing about an obvious dilemma between policy and market.

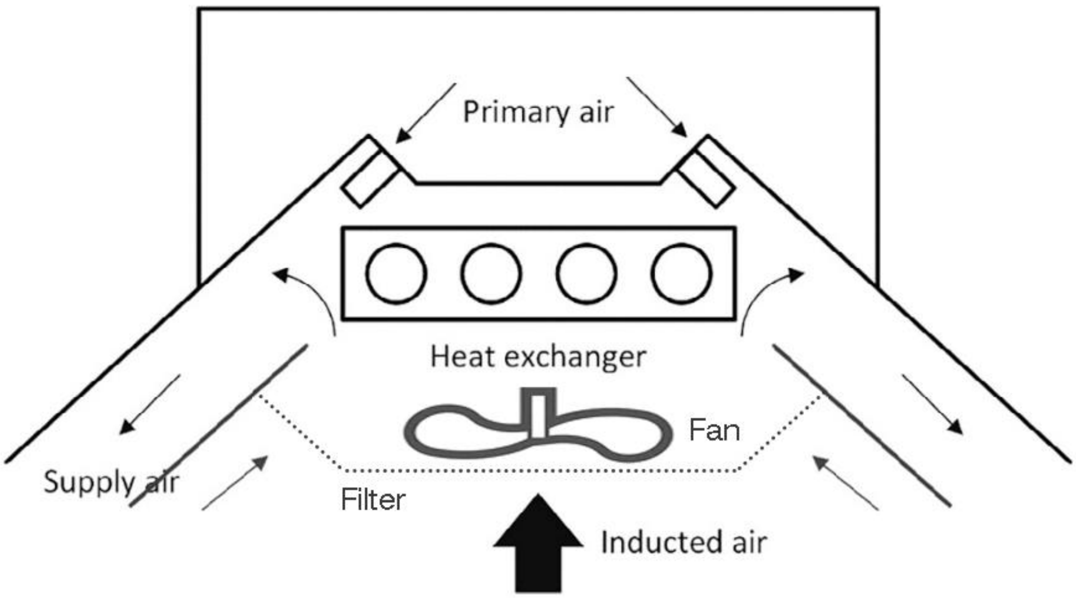


Figure 4 A typical multi-split air-conditioning indoor end unit for ceiling mixing air distribution (by author).

There is potential in the integration of theoretical airborne transmission research results in the small-scale steady-state rooms with the realistic small meeting room in the typical Dutch offices where people are concentrated and stay at a quiescent state for a certain time. The movements, positions, breathing modes and postures of people are unpredictable and dynamic factors in reality but in uniform certain status in design. The only variant is on or off air-circulation mode in one ventilation indoor AHU to an unit enclosed area. **There is no definite conclusion for the official recommendation that "no direct indoor air circulation" helps decreasing the infectious risk via airborne transmission in a standard ceiling-mixing-ventilation meeting room. What would be different performances of airborne transmission control between on or off air-recirculation mode in one ventilation indoor end unit? If the recommendation is applied, what will be the series of adjustments in ventilation parameters and HVAC system to maintain a high ventilation efficiency and indoor comfort? What methods can be applied afterwards to improve the possible uncomfortable experience and extra energy cost?**

Thus, the problem focuses on **implementable performance-based renovation strategy to decrease COVID-19 infectious risks via airborne transmission for small-scale meeting rooms in Dutch offices, where the current ventilation prefers direct air recirculation for indoor comfort and energy efficiency and is contrary to Indoor epidemic prevention recommendations.** Cutting off the air circulation at the indoor end unit seems to be a one-step change, but as the end of the dynamical system, it can cause a series changes in the ventilation system and indoor micro-climate. All the possible impacts need to considerate, such as the air flow patterns, air exchange rate, supply air flow rate, temperature distribution, draught and other installation indicators. The renovation strategy will provide a systematically interactive ventilation design, aiming at micro-climate scale, which is switchable for exceptional circumstances like COVID-19 when adjusting air recirculation at the end unit is necessary.

1.6 Objectives and restrictions

The main objective of this project is bridging the gap between theory and practice by intersecting knowledge base of **indoor airborne transmission**, **anti-epidemic ventilation researches** and **technical ventilation installation** within a specific typical design case, an **air recirculation and filtration control strategy** in the end part of mixing ventilation system for the small meeting room in Kuijpers, Leiden.

This research offers a substitutional operation model when facing with infectious expiratory diseases for the public commercial buildings, like offices, with medium hygiene requirements but sometimes high occupant density in small groups for low-activity-level long staying. The interdisciplinary research dismantles the main object into three aspects: **theoretical ventilation design, infectious disease pathology** and **practical systematic control**.

The sub-objectives of this research have been scaled down to:

- **Infectious disease pathology**
  Clarify the design constraints for the **infection risk** via airborne particles (COVID-19 virus-laid droplet nuclei) of **airborne transmission.**
- **Theoretical ventilation design**
  Measurement and evaluation of the current **indoor comfort** and **ventilation efficiency** of ceiling-mixing air distribution methods with the air-recirculation indoor end unit in the small shared room.
- **Practical systematic control**
  Evaluation of the **possibility** of **secondary pollution** caused by the air recirculation mode in ceiling-mixing indoor end unit in the small meeting room in Kuijpers, Leiden, within the smart building system.

The expected main products of this work are:

- An **optimal ceiling mixing ventilation pattern** for small meeting room in Kuijpers, Leiden, under the current COVID-19 scenario.
- An **evaluation matrix in engineering design parameters** that indicate a low-infection-risk ventilation performance in small shared rooms.
- A **design workflow or production chain** (production, installation, regulation and maintenance) for the hygiene ventilation renovation products for the construction market.

Because of the dynamic design elements, like layout of the room, indoor activities and breathing modes, the ventilation design may not suitable for all the small public communal spaces, but will provide a neoteric and practical view for them and other public spaces. This project bridges the gaps among **theoretical ventilation design, infectious disease pathology** and **practical systematic control**. With the long-term consideration to adapt the design into the developing construction market, the project has two phases:

- Firstly, in response to the **on-going outbreak**, rapid analyses will provide actionable advice for health care professionals, crisis managers, and logisticians responding to the Covid-19 epidemic.
- In a second phase, the project will focus on tying together the learning from this outbreak and develop **a suite of open-source tools and methodology** to prevent or mitigate the effects of (future) epidemics and pandemics outbreaks.

In general, the ventilation design will help optimizing the indoor hygiene quality of public commercial buildings.

1.7 Research questions

This research takes two main parts of ventilation system at different levels of the design into consideration:

- General indoor airflow distribution pattern;
- Mechanical mode of indoor end unit in common Dutch offices.

The hypothesis is that fully running the air recirculation at indoor end unit will enhance the ventilation efficiency of mixing ventilation and thus decrease the risk of cross-infection of corona virus in small meeting rooms. Starting from a small meeting room with 2 occupants, the hypothesis is that an efficient air-recirculation unit end with middle standard filter and effective air exhaust opening position to increase the **air mixing level** and reduce **the average virus concentration**, thus to reduce the infectious exposure risks and ensure a comfortable indoor environment and economic costing at the same time, and further **optimally synergize** the performance of additionally installed **purifiers**.

Thus, this graduation project aims to answer the main research question:

*What is renovation on **partial control** level in **air-recirculation** mode of indoor end units in Dutch standard meeting rooms with **hybrid ceiling mixing ventilation system** to decrease the COVID-19 infectious risk by integrating **clean-room techniques** with indoor comfort and feasible construction considerations?*

For this question to be answered, other sub-questions also need to be taken into account and will also be answered throughout this project. There are three technical aspects (see Figure 5) in the research that interacting each other and impact the final research results: **theoretical ventilation design, infectious disease pathology** and **practical systematic control**.

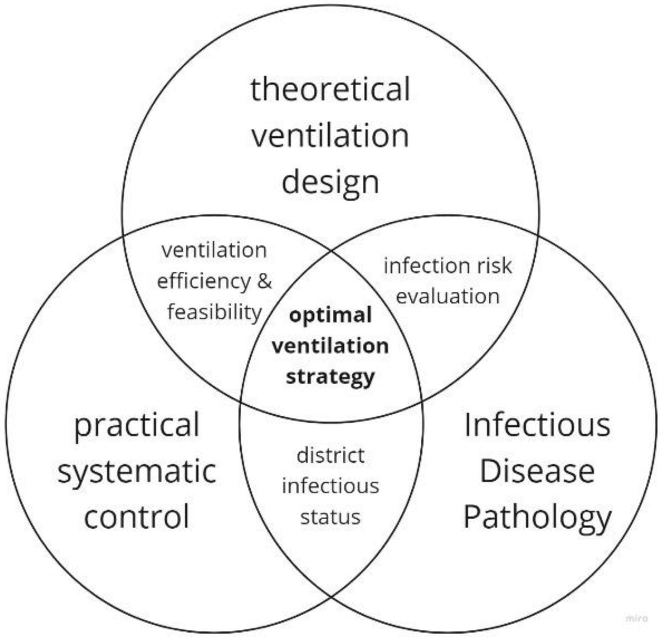


Figure 5 Interdisciplinary relationship in this research (from author).

In the aspect of the **theoretical ventilation design**, the airflow distribution pattern is impacted by the specific geometry of the sample room, the air recirculation mode, the location of the ventilation end facilities and brings about the following sub-research questions:

A. What would be the positive impacts from **partial ventilation controls** that practically help decreasing the infection risks indoors?
    a. What is role of air-recirculation mode at ceiling mixing HVAC end unit in general ventilation efficiency in the small meeting room?
    b. What is the impact of air recirculation that may cause the **secondary pollution** in airborne transmission in the small meeting room?
    c. What is the feasible renovation based on the general office ventilation system in the Netherlands?
    d. What partial changes in the ventilation ends would help enhancing the virus removal performance of normal purifiers or filters?

The hypothesis is based on a practical renovation context for coronavirus crisis, an existing meeting room of frequent usage even under COVID-19. When facing with the ideal design and practical achievement, there is always limitation in practice. The limitation between the theoretical design and realistic production raise the series of subsequent influences in different scales:

B. What is the **infectious disease pathology** for the airborne transmission in the small meeting room based on existing anti-epidemic policy?
    a. What is connection between built environment engineering and epidemiology for practical epidemiological control?

   b. What is the ventilation design reference from the current understanding of COVID-19 epidemiological control?

C. What is the epidemiological performance of current building system in the small meeting room of a typical Dutch office building?
   b. What is the mechanical logics of current ventilation system from the central level to the end level of the system to supply clean air?
   c. What are the main parameters in ventilation engineering that essentially impact the indoor infection risk via airborne transmission?
   d. What clean-room techniques can be applied in the middle-end HVAC system to decrease the infection risk via airborne transmission, and at the same time achieve requirements from indoor comfort and installation feasibility?

1.8 Approach and methodology

The experimental ventilation design is based on a compromise between experimental resources, airborne transmission theories, the current ventilation system and operation mode of a real room. The main efforts will focus on the corona-virus exposure rate of occupants under current anti-epidemic policies. The five main phases and its time distribution in the research program for the ventilation design are as shown in Figure 6):

- Knowledge Phase:
  Literature research of airborne transmission, traditional efficient ventilation design and clean-room ventilation design;
  - To scale down the space typology to small shared room (area < 30m2; height < 2.8m);
  - To scale down the infectious scenario to airborne transmission which matches the Poisson distribution;
  - To scale down the design product to a mixing ventilation distribution pattern which optimizes the performance of filters or purifiers installed in future.
- Experiment Phase:
  - Onsite experiment and analysis of current ventilation conditions in the meeting room in Kuijpers, Leiden;
  - Experimental test of the possible secondary pollution at the indoor end unit through air recirculation mode;
- Simulation Phase:
  - Computational simulations of current ventilation conditions in the meeting room in Kuijpers, Leiden;
  - Setting a standard case with the well-mixing and symmetrically distributed airflow pattern as the initial reference for the infection risk calculation and evaluation;
  - Predictive computational simulations of ventilation conditions with different air-recirculation setting and total airflow routes on the ceiling level in the meeting room in

Kuijpers, Leiden, to sketch out the essential engineering parameters for epidemiological ventilation design;

- Design Phase:
  - Strategy design referring to clean-room techniques and other advanced building engineering to improve the anti-epidemic performance;
  - Renovation design based on optimal ventilation parameters with the maximum feasibility for commercial purposes;
  - Detail adjustments for the indoor comfort under the maximum operation of the existing whole ventilation system when applying the conclusive strategic renovation design.
- Test Phase:
  - To roughly prove the validity of the ventilation design;
  - A purifier-integrated prefabricated ventilation ceiling modular production chain design.

This research is based on human health, thus, epidemic prevention and indoor comfort are the design priorities. While, the renovation efficiency and construction costs are of third or fourth importance. They will be taken into consideration based on the marketing experience and experimental results.

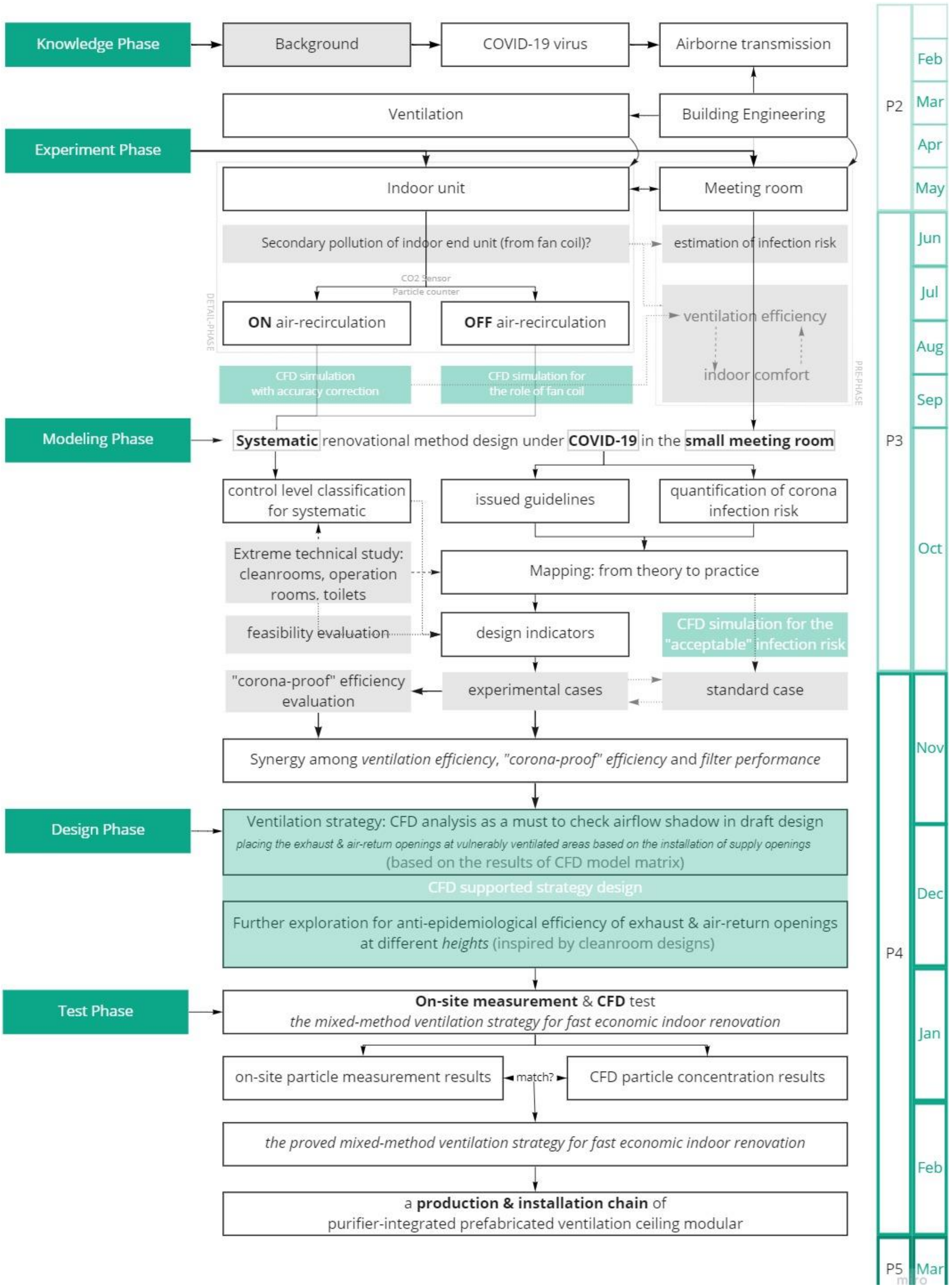


Figure 6 Graduation plan scheme (by author)

2. Knowledge

The knowledge phase is divided into three aspects: **theoretical ventilation design, infectious disease pathology** and **practical systematic control.** To bridge the gaps among the three aspects, the cross information comprehension follows the basic knowledge base of each aspect, see Figure 5 in chapter 1.7:

- **Pathology ←→ Building technology**: from virus (chapter 2.1.1) to particle (chapter 2.1.2) to airborne transmission (chapter 2.1.3) to distinguish the infection risk focused in this research is airborne transmission risk only, which is also the only transmission route that can be controlled via building engineering (chapter 2.2.3).
- **Building technology ←→ Engineering practice**: from the three air flow in micro-environment (chapter 2.2.1) to air distribution pattern in the room (chapter 2.2.2) to the anti-epidemic performance of existing HVAC engineering (chapter 2.2.3) to distinguish the spatial scale in this research is a small shared room between micro and macro scales (chapter 2.3.1) with a complex parameter system but without clear evaluation system for hygiene ventilation.
- **Engineering practice ←→ Pathology**: from the choice of medium-scale environment in Kuijpers, Leiden (chapter 2.3.1) to its HVAC system for general control (chapter 2.3.2) to its indoor end unit for partial control (chapter 2.3.3) to possible introduction of cleansers (chapter 2.3.4) to distinguish the research and design object is the indoor end unit with purifiers.

To comprehend all the fundamental knowledge from these three different disciplines, a **dynamic parameter system** (chapter 2.4) is established for the further design and test phase.

2.1 Infectious disease pathology

Starting from theoretical micro aspect, the first level is about corona virus, particles carry microorganisms and respiratory airborne transmission. The pure scientific theoretical knowledge elaborates the propagation characteristics of COVID, which provides the design premise for subsequent ventilation product design.

2.1.1 COVID-19 virus

A series of acute atypical respiratory infections ravaged the Wuhan city of Hubei province of China in December 2019. The pathogen responsible for these atypical infections was soon discovered to be a novel coronavirus belonging to the family Coronaviridae and was named as the severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2). It was seen to be **highly homologous to the SARS** coronavirus (SARS-CoV), which was responsible for the respiratory pandemic during the 2002–2003 period. The respiratory illness caused by this virus was termed as coronavirus disease 2019 or simply COVID-19 by the WHO, and brought sequent breakout throughout the world (Parasher, 2021).

The virus is transmitted via **respiratory droplets and aerosols from person to person**. Once inside the body, the virus binds to host receptors and enters host cells through endocytosis or membrane fusion. The coronaviruses are made up of four structural proteins, namely, the spike (S), membrane (M), envelop (E) and nucleocapsid (N) proteins (see Figure 7) (Knowlton, 2019). The S protein is seen to be protruding from the viral surface and is the most important one for host attachment and penetration.

ACE-2 has been identified as a functional receptor for SARS-CoV and is highly expressed on the **pulmonary epithelial cells**. It is through this host receptor that the S protein binds initially to start the host cell invasion by the virus. Postmembrane fusion, the virus enters the pulmonary alveolar epithelial cells and the viral contents are released inside. The viral N protein binds the new genomic RNA and the M protein facilitates integration to the cellular endoplasmic reticulum. The virus Completes RNA transcription and translation in the host cell and forms new viral particles to invade the adjacent epithelial cells as well as for providing fresh infective material for community transmission via respiratory droplets (see Figure 7 and Figure 8) (Parasher, 2021).

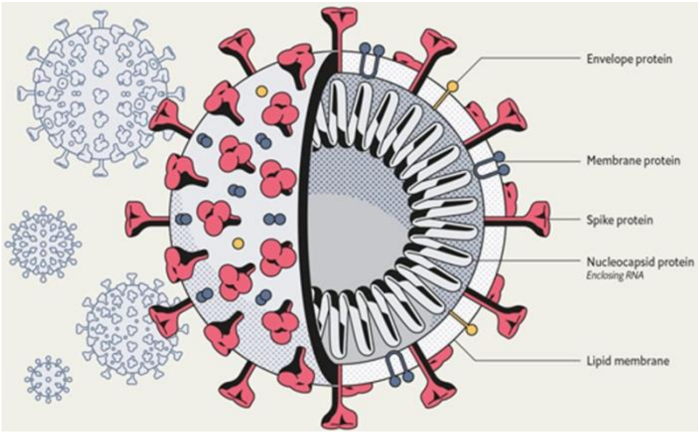


Figure 7 The shape of COVID-19 virus (Parasher, 2021)

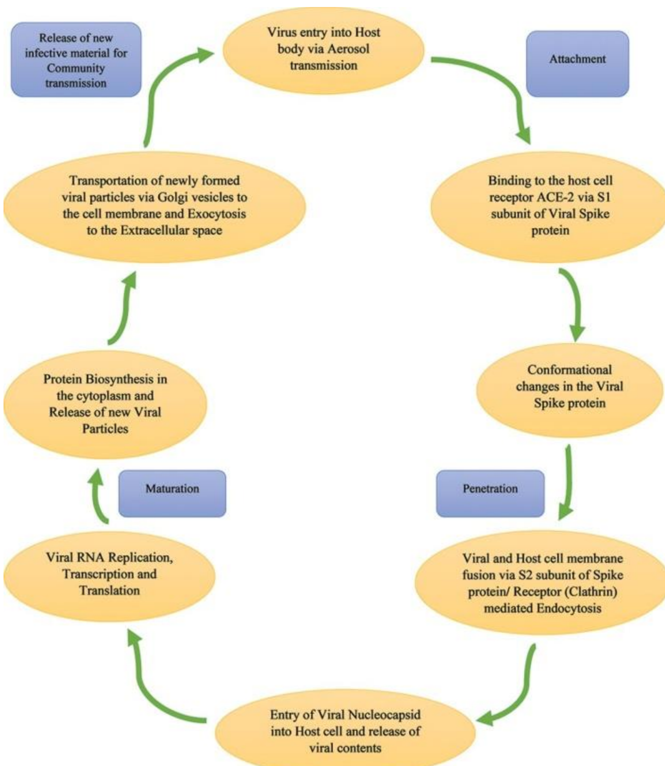


Figure 8 The pathology of COVID-19 virus (Parasher, 2021)

Infection can be spread by **asymptomatic, pre-symptomatic, and symptomatic carriers.** The average time from exposure to symptom onset is 5 days, and 97.5% of people who develop symptoms do so within 11.5 days. The patients of COVID-19 belong mostly to the 40–70 years age group, and most commonly present with fever, body aches, breathlessness, malaise and dry cough, although patients may present with asymptomatic, mild, moderate or severe disease. Patients already have infectivity during asymptomatic phase and reach **maximum during the symptomatic phase** via cough and vomiting (Wiersinga et al., 2020).

Depends on different environments, temperature and humidity, the survival time for corona virus is different. According to researches on repertory infectious virus, like transmissible gastroenteritis virus (TGEV), mouse hepatitis virus (MHV) and Middle East Respiratory Syndrome (MERS-CoV), inactivation was more rapid at higher temperature than at lower temperature at all humidity levels, but the relationship between inactivation and RH was not monotonic, and there was greater survival or a greater protective effect at low relative humidity (20%) and high relative humidity (80%) than at moderate relative humidity (50%) (Pyankov et al., 2018) (Casanova et al., 2010). Since influence of temperature and humidity on the survival time of virus is obvious in the extreme environment conditions, in the built environment, the temperature and humidity are always controlled in a certain domain for indoor comfort. **The survival time differences caused by the extreme temperature and humidity levels can be ignored.**

SARS-CoV-2 remained viable in aerosols throughout the 3-hour duration. This reduction was similar to that observed with SARS-CoV-1. The half-lives of SARS-CoV-2 and SARS-CoV-1 were similar in aerosols, with median estimates of approximately 1.1 to 1.2 hours and 95% credible intervals for both SARS-CoV-2 and SARS-CoV-1 (Taylor et al., 2020).

2.1.2 Virus nuclei-laid particle

Electron Microscope (TEM) to be 60–140 nm, which averages to **100 nm**(Zhu et al., 2020). As the virus can be attached to particulates less than 100 nm, the smallest size for the COVID-19 and its carrier (droplet or particle) can still be about 100 nm(Leung & Sun, 2020).

Particles of various sizes are produced during coughing and sneezing. Pathogens capable of surviving in small droplet nuclei (<5 µm in diameter) then become airborne. To be capable of surviving in small droplet nuclei, the pathogen must be durable and resistant to drying. (Wong & Leung, 2004)

Studies of cough aerosols and of exhaled breath from patients with various respiratory infections have shown striking similarities in aerosol size distributions, with a predominance of pathogens in small particles (<5 µm).

Since the speech droplet has been widely accepted as the main transmission method of respiratory diseases. The droplets produced via conversational speech is a wide range (submicron up to diameter 100 µm). And the majority of aerosol particles in exhaled breath are <5 µm (Fennelly 2020). However, the relationship between the viral load and different aerosol sizes is unaware, which makes the estimation of infectivity principally hard. Human exhalation contains a large amount of water, and the rate of evaporation depends on the size and composition of the droplets and the relative humidity and temperature of the air (Redrow et al. 2011). Compared the evaporation time and resulting nuclei sizes of model sputum saline solution and water droplets (see Figure 9). Thus, the virus nuclei is a spectrum scale from 0.005 um to 0.3 um. Virus nuclei can be minimally attached to particles as large as they are. Thus, the virus nuclei-laid particle is about 0.01 – 0.5 um, which is the airborne particle size discussed in this paper.

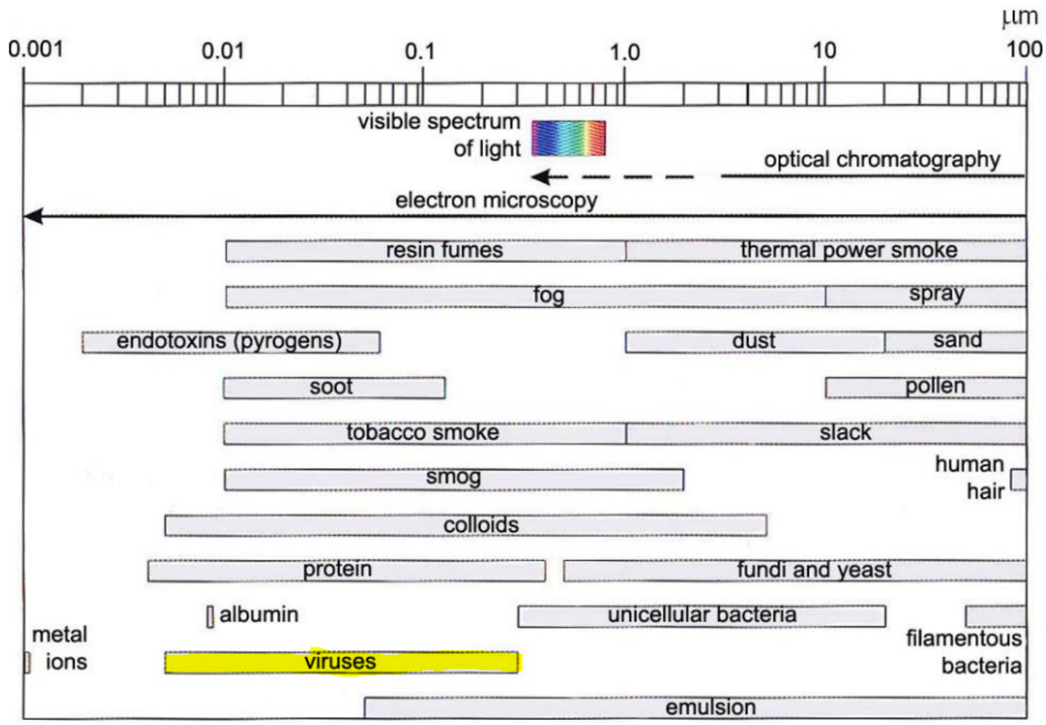


Figure 9 Nature of air contamination (Whyte, 2001)

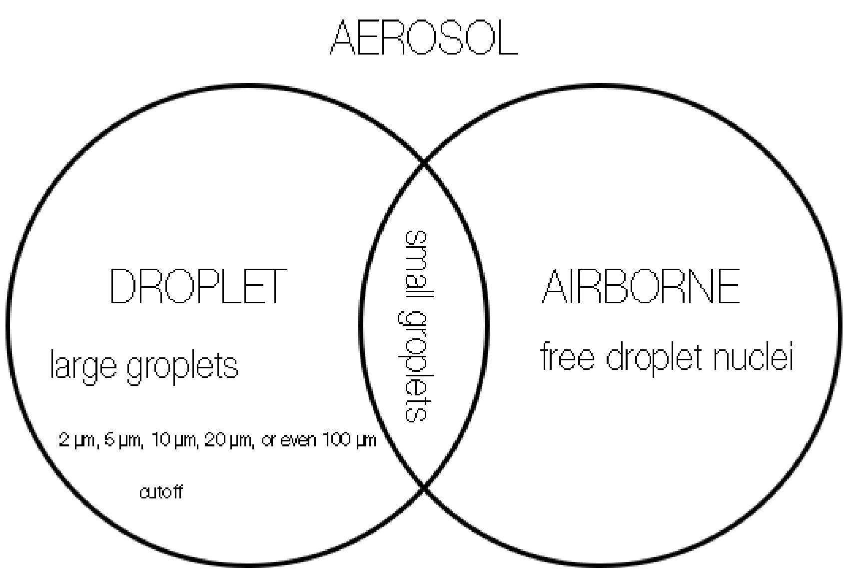


Figure 10 the definition of the size of droplet and airborne particles (from the author)

Respiratory particles are formed during any respiratory activity such as coughing, sneezing, talking and breathing. Once the particles are released into the surroundings, the mechanisms in-which they flow and settle depend on the fluid dynamics of the particles and the conditions in the vicinity. Fluid dynamics can characterize the evaporation rate of the particles which allows the determination of the prevalence of small droplets and nuclei droplet transport. COVID-19 belongs to the beta CoVs pathogen group and has a spherical or ellipsoidal. Particle trajectories depend primarily on approximate diameter of 60-140 nm. The shape of the virus can be their size and the balance of various forces acting on the particle in the air. Gravitational and aerodynamic forces are the two primary forces acting on such particles, where the latter force dictates the flow behaviour of the particle. Figure 11 shows the trajectories for particles of various sizes ranging from 0.01 um to 100um. Stokes law explains the frictional force relation exerted on spherical objects with very small Reynolds numbers in viscous fluid. The resistance coefficient may decrease with increasing diameter, but the **drag force increases linearly with the diameter**. However, since the gravitational force increases with the mass, it increases with diameter cubed, thus, more rapidly than the drag force as the diameter increases. Therefore, larger particles have the tendency to settle. This phenomenon helps to explain why smaller particles are more likely to be airborne (Lipinski et al., 2020). Thus, the airborne particle movement is expansive, and shows high similarity as the tracer gas, CO2, which is widely applied in the air quality evaluation.

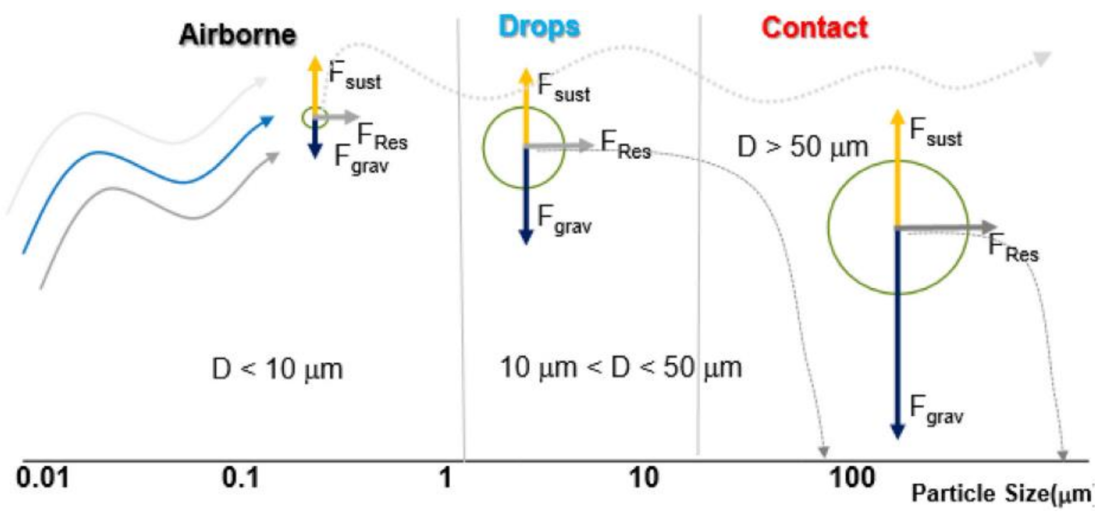


Figure 11 Trajectories of particles with various sizes (Lipinski et al., 2020).

The main source of the virus nuclei-laid particles are: respiratory and bodily secretions, like sweat and dandruff in a steady state whose transmission can be 5m in a short time, sneezing and cough in a sudden state whose transmission can be 1.5m in a short time (see Figure 12).

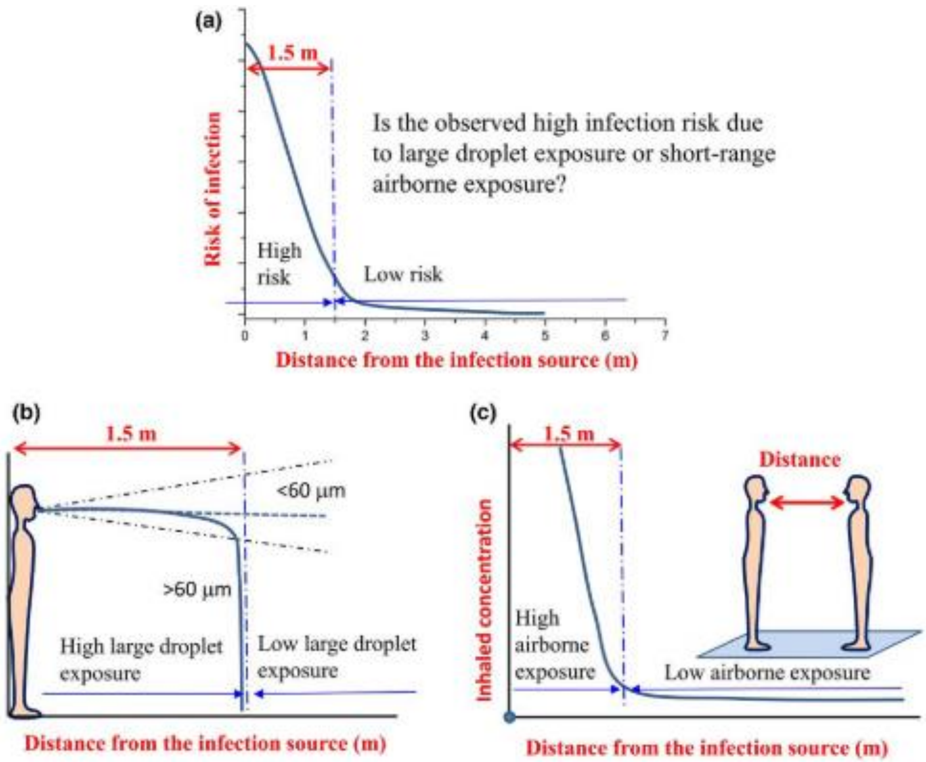


Figure 12 Droplet transmission condition from distance from the infection source (L. Liu et al., 2017)

2.1.3 Airborne transmission

During corona times, the governments almost all over the world applied a series of basic anti-epidemic rules to avoid the direct contacts and droplet transmission. For example, the anti-epidemic rules published by Dutch government in January 2022 (see Figure 13) avoided the direct contacts via less social communicational activities and frequent hand cleaning, and cut off the droplet transmission via safety distance (an efficient and valid method proved by chapter 2.1.2) and wearing mask (Lidia Morawska et al., 2020). For indoor airborne transmission, the of basic anti-epidemic rules only suggest opening the windows for direct nature fresh air, which is hard to achieve in most Dutch public commercial buildings.

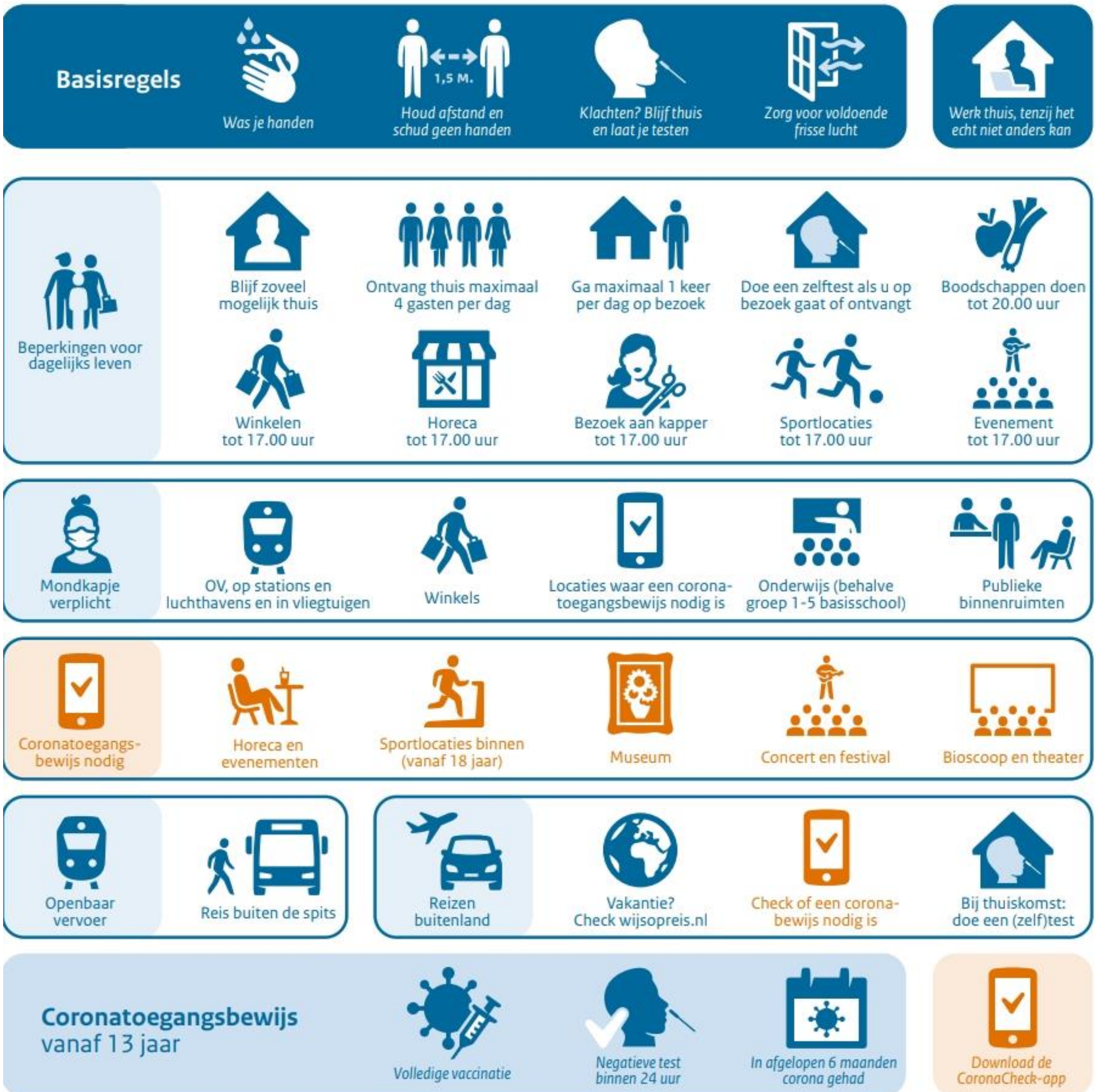


Figure 13 the anti-epidemic rules published by Dutch government in January 2022 (from RIVM)

From chapter 1.2, the conclusion can be draw as: airborne transmission is one of the three indoor infection transmission routes. The special attention is paid on the indoor transmission because:

1) indoor environment is where most people spend their most life time in (as mentioned in chapter 1.2);
2) the unpredictability of infectious diseases from potential patient's representation may allow the infected but unaware stay longer time within the healthy crowd and has a potential high risk in airborne transmission rather than the direct touching nor droplet transmission, both of which are based on the infected symbol, cough (as mentioned in chapters 1.2 and 2.1.1); and

3) the at-least 3-hour survival time of the majority of corona virus is three times longer than the air change rate standard for most long-stay commercial buildings, which indicates the inevitability of existence of airborne transmission in the corona times.
4) The high mechanic similarity of the airborne particle movements as CO2 is the precondition for the CFD simulation of airborne transmission indoors, which makes this topic researchable.
5) Wells-Riley calculation is a reliable method to analyse the infection risk of airborne transmission in the room.

2.2 Theoretical ventilation design

The second level is about the three air flow in micro-environment to air distribution pattern in the room and HVAC building system engineering.

2.2.1 Three indoor air flows

When in the steady long-staying mode, the three indoor airflows (see Figure 14) - **body air flow, respiratory air flow and ventilation air flow** - have interactional influence with each other and are difficult to control in human microenvironments.

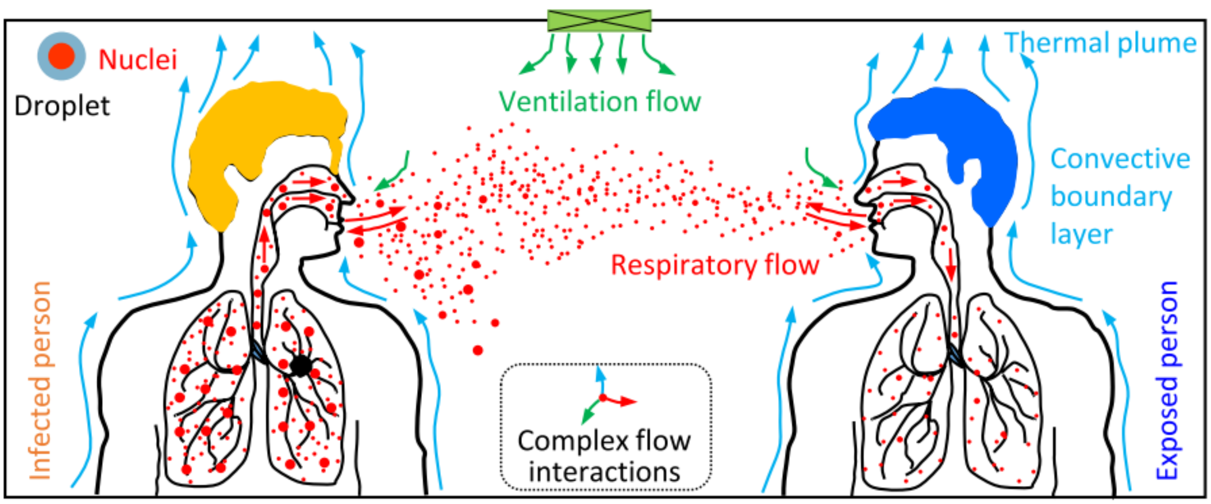


Figure 14 Complex flow interaction in the micro-climate surrounding human body(Ai & Melikov, 2018).

Human thermal plume refers to the constantly rising airflows around the boundary layer of human body due to persisting temperature gradients between the body surfaces and the ambient air, including the respiratory flow and body airflow. Ample evidence indicated that the thermal plume controls the dispersion and transport of aerosols in the human microenvironment. Given that in calm indoor environments most air inhaled by human comes from the boundary layer where thermal plume flows through constantly, the role of thermal plume needs to be scrutinized to predict the diffusion of droplets, aerosols and other airborne carriers of the novel coronavirus around the human body for prioritizing infection control strategies. The key variables in the formation of thermal plume in indoor environments include **ambient temperature, human posture and type of clothing**. Researches indicate that the human thermal plume should facilitate the airborne transmission of COVID-19 in enclosed spaces by elevating small droplets and airborne particles into the breathing zone from lower regions and ascending respiratory droplets from the sources into the upper atmosphere. By drawing attention to aerosol transport dynamics in the human microenvironment, these insights may be useful for understanding COVID-19 transmission in enclosed spaces, especially those intended for public use.(Sun et al., 2021)

The human microenvironment constitutes the critical last step for airborne transmission to effectuate. Generated by body-to-air temperature gradients, human thermal plume creates persistent uprising airflows along the human boundary layer, typically as a laminar-to-turbulent flow with varying thicknesses from 2–4 mm to 200 mm and a maximum velocity of 0.2–0.3 m/s, which is comparable to the designed air velocity in various buildings with mixed ventilation under the current design criteria. Being a constant source of directional airflows and thermal buoyancy, in a clam indoor environment thermal plume plays a significant or even dominant role in the aerosol trans- port dynamics in the human boundary layer where most inhaled air comes from. Existing evidence shows that thermal plume has significant influences on the diffusion and transport of volatile compounds, exfoliated human skin scales and airborne microplastics into the human breathing zone in typical indoor environments. Meanwhile, thermal plume promotes the dispersion of human respiratory droplets from the source by ascending them along the boundary layer and into the upper atmosphere. Based on the mechanisms and key variables in the formation of thermal plume (e.g., ambient temperature, body posture and type of clothing), several precautionary measures may be put in the place to reduce the risks associated with thermal plume and its induced aerosol transport in the human microenvironment (see Figure 15). The recommendations in **thermal plume control** are **eliminating the sources** of indoor particle emissions, maintaining **natural ventilation**, **moving body closer to desk** and **wearing long and loose clothing** can reduce the magnitude or influences of thermal plume and the resultant risks of inhaling virus-laden droplets and particles rising from lower regions in indoor spaces. Given that people spent most of their time in various indoor environments and there is an increasing trend of adopting sedentary lifestyles in the global population, it is of significance to further study the roles of thermal plume and the human microenvironments in the airborne transmission of COVID-19 and other human respiratory pathogens, especially in enclosed public spaces.

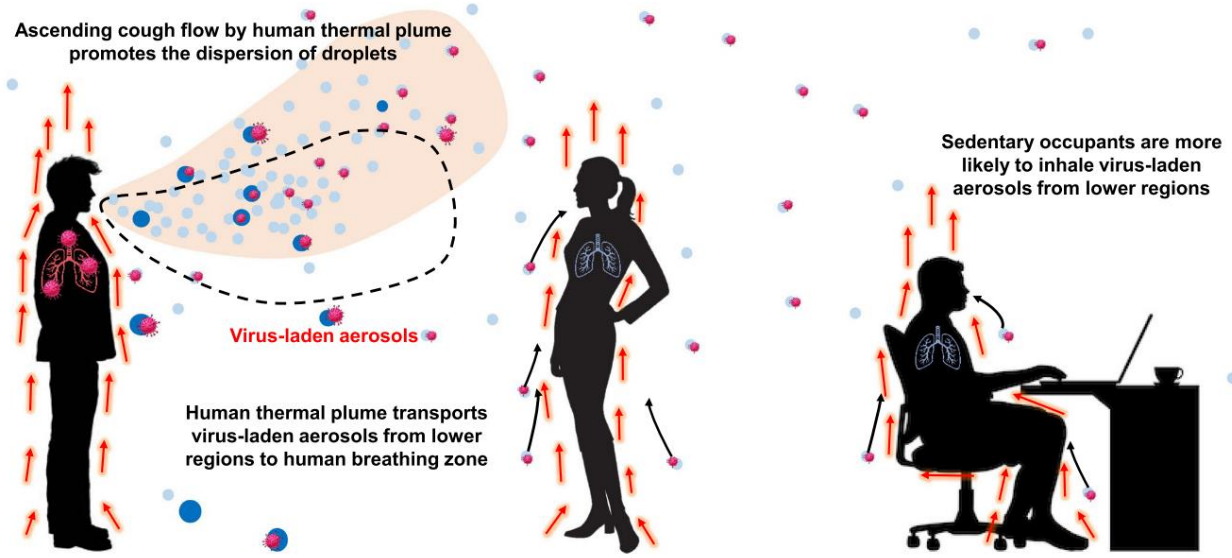


Figure 15 Potential influences of human thermal plumes on airborne transmission of COVID-19 (Sun et al., 2021)

2.2.2 Air distribution patterns

Mixing and displacement room air distribution are the main principles of total volume mechanical ventilation that are applied today in buildings (Muller et al., 2013; Skistad et al., 2002) & (A. K. Melikov, 2016). Understanding of the mechanical logics is of vital importance for the strategy selection. The advantages and disadvantages of different ventilation air distribution patterns for indoor comforts, ranges of application and COVID-19 anti-epidemic performance.

There are influences of mixing ventilation (MV), displacement ventilation (DV), and under floor air distribution (UFAD) in the transportation of bio-aerosols from human respiratory activities (see Figure 16). An Eulerian modeling for real offices investigated the spatial concentration and temporal evolution of exhaled and sneezed droplets that fall within the size range of 1.0 − 10.0μm in these three ventilation patterns. The important conclusions of this study are as follows:

1. Under steady-state conditions, the exhaled droplets from normal human breathing can become trapped at the human breathing height in DV and UFAD, thereby increasing human exposure and risk of infection.

2. In DV and UFAD, the distribution characteristics of particulate matter generated from a surface with convective heat versus those from a human nose are entirely different. A trapped layer appears when pollutants are released from the latter.

3. The transient dilution of sneezed/coughed droplets is dominated primarily by the indoor air velocities in the breathing zone. The higher velocity with MV results in a faster-mixing droplet cloud in the ventilated air than with DV and UFAD. Thermal stratification combined with a lower air velocity at the middle-room-height can result in a longer residence time for respiratory droplets in the human breathing zone and thus potentially increase human exposure and infection risk (Gao et al., 2008).

The research generally prove that **spatial height**, **air change rate** decides the performance of air distribution patterns, especially for distribution ventilation and mixing ventilation: the large distance between the air supply opening and the working area and the low air supply rate may result in a high degree of mixing of fresh air before it reaches the working area, resulting in similar ventilation performance for DV and MV. And spaces higher than **2.8m** are less efficient for displacement ventilation installation than mixing ventilation (Z. Xu & Zhou, 2014). For the places where installed with DV, there is very likely short circuit in the space, and thus, less anti-epidemic efficient even than normal MV. The well mixed can increase the exposed rate of each occupant in the room. But mixing ventilation is still the most popular choice in the construction market, even used in cleanrooms and hospitals (A. K. Melikov, 2016).

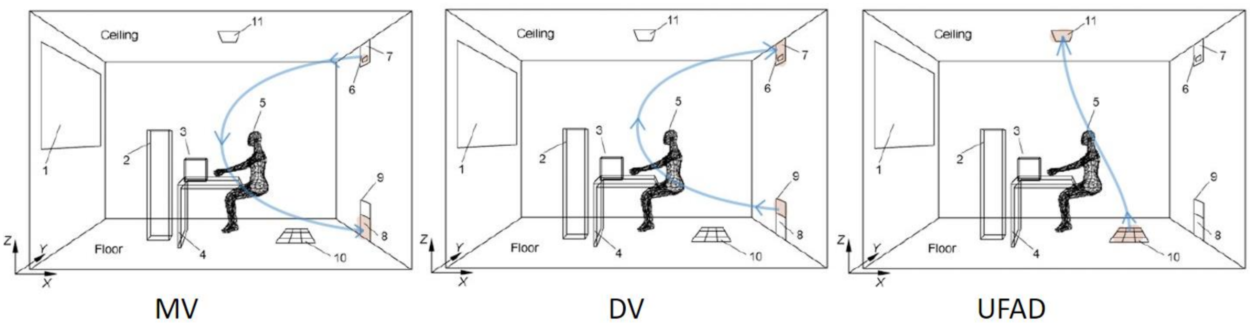


Figure 16 Three room air distribution patterns (Gao et al., 2008) & author

Mixing ventilation is a popular air distribution pattern that has been applied in a large number of commercial buildings for its high prospects in terms of thermal comfort. A good ventilation efficiency is the most direct and efficient way to decrease the infectious risks in any kind of air distribution pattern. There is no regulation for the specific ventilation efficiency in any construction code yet. The two parameters, CO2 concentration rate and particle removal rate, can be used as the clues to evaluate the ventilation efficiency in the practical engineering control. Compared to the distribution ventilation, an official recommended option, the mixing ventilation actually is more efficient in particle removal for the whole space, because this system can provide uniform pollutant distribution at best (Behne, 1999). The displacement ventilation shows strength in local particle removal efficiency.

2.2.3 Anti-epidemic control of HVAC system

And when discussing about the indoor engineering control for airborne transmission, the current research shows the limitations in current economic HVAC system in public constructions (Lidia Morawska et al., 2020):

- ventilation and the control of airflow directions in buildings can demonstratively control the transmission and spread of infectious diseases;
- The minimum ventilation requirements for healthcare and educational buildings still need specification and quantification;

- Such kind of multidisciplinary study need environmental and pathological studies with technical helps from molecular biology test methods and the new computer modeling and experimental methods for investigation building ventilation.

The **official suggestions** for COVID-19 infectious prevention for HVAC system are (see Figure 17) (Butt, 1979):

- To increase the existing **ventilation rates** (outdoor air change rate) and enhance ventilation effectiveness - using existing systems.
- To eliminate any **air-recirculation** within the ventilation system so as to just supply fresh (outdoor) air.
- The extra installation and following maintenance of **air cleaners, purifiers or filters** in the existing economic HVAC system is of vital importance.

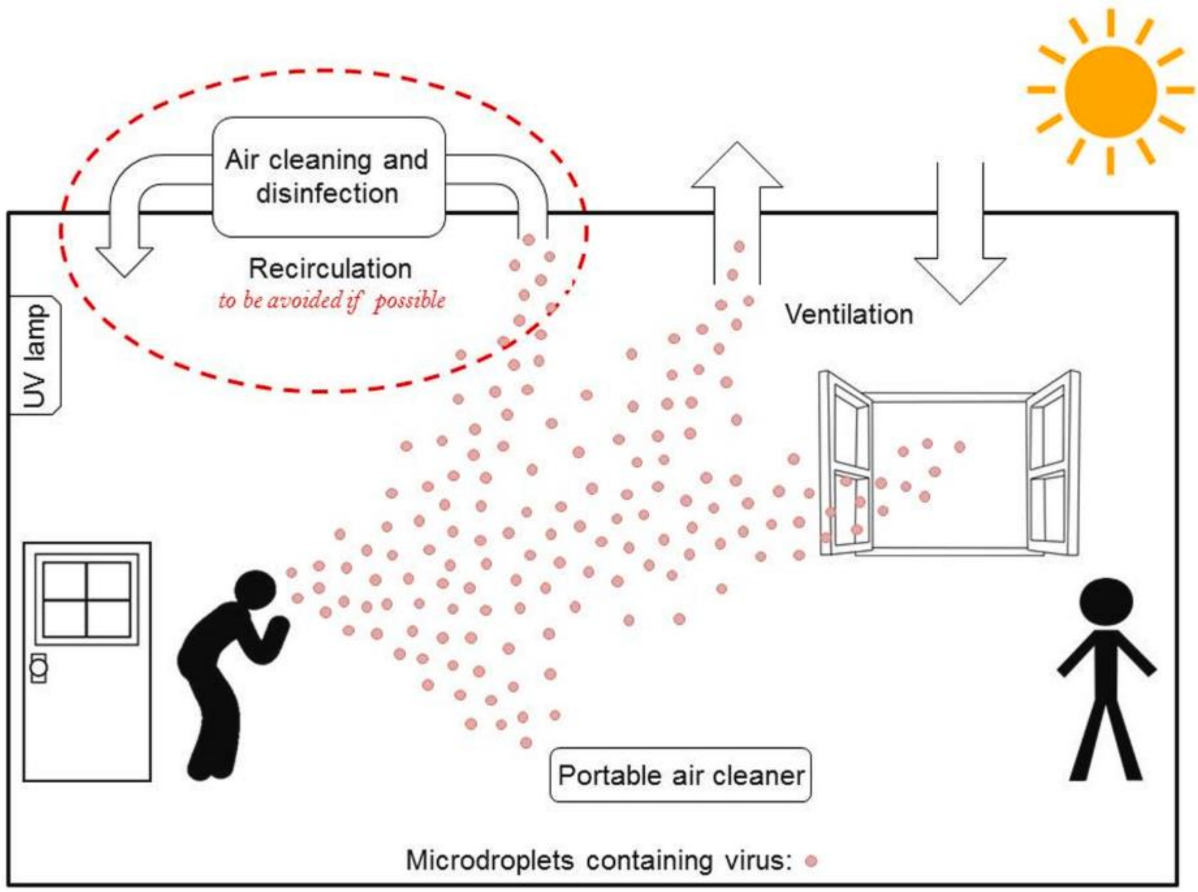


Figure 17 Engineering level controls to reduce the environmental risks for airborne transmission (Lidia Morawska et al., 2020)

2.3 Office building engineering for corona prevention

Heating, ventilation, and air conditioning (HVAC) system is an essential part for the indoor physical comfort, especially for thermal comfort and indoor air quality. This chapter, strongly back up by the realistic engineering practice, is about the office HVAC system, indoor end units and integration of ventilation with other building engineering methods with consideration of the techniques applied in cleanrooms.

2.3.1 Medium-scale environment context

Before the pandemic, offices are believed as a critical element for the company's productivity, culture, and winning the war for talent. Companies competed intensely for prime office location in the bustling city centers. Densification, open-office designs, hostelling and co-working were the battle cries. But during the pandemic, a large number of people gain unexpected high productivity by distant working mode at home and other forms of digital collaboration and gradually accepted this home working style.

As a result, even after the COVID-19 crisis, the role of offices is changing. Individual tasks are more flexible and do not ask for sharing spaces. The offices will be transformed into sharing spaces in a large portions. According to current distant working experience, lectures and large-scale meetings with less commutations or interaction can be well replaced by online meeting, but special tutoring, group discussions and activities needs direct feedbacks and high-frequency interaction cannot be well replaced by distant meeting. Thus, small-scale meeting rooms are quite needy in COVID-19 crisis and future role of offices, where necessary collaboration happens.

The geometry layout of the small meeting room (see Figure 18) is usually a standard rectangular or square space with an occupancy capacity of 4-6 persons. There should be at least one clean wall for screening and the furniture should be removable to create an open place for any possible activities. At the sight height level, there should be no obscure to cut off direct eye contact among speakers or watching the screen. There usually only one ventilation unit in this scale of space. Because of the long-staying requirement, the requirements for indoor comfort are higher than the other function places in offices.

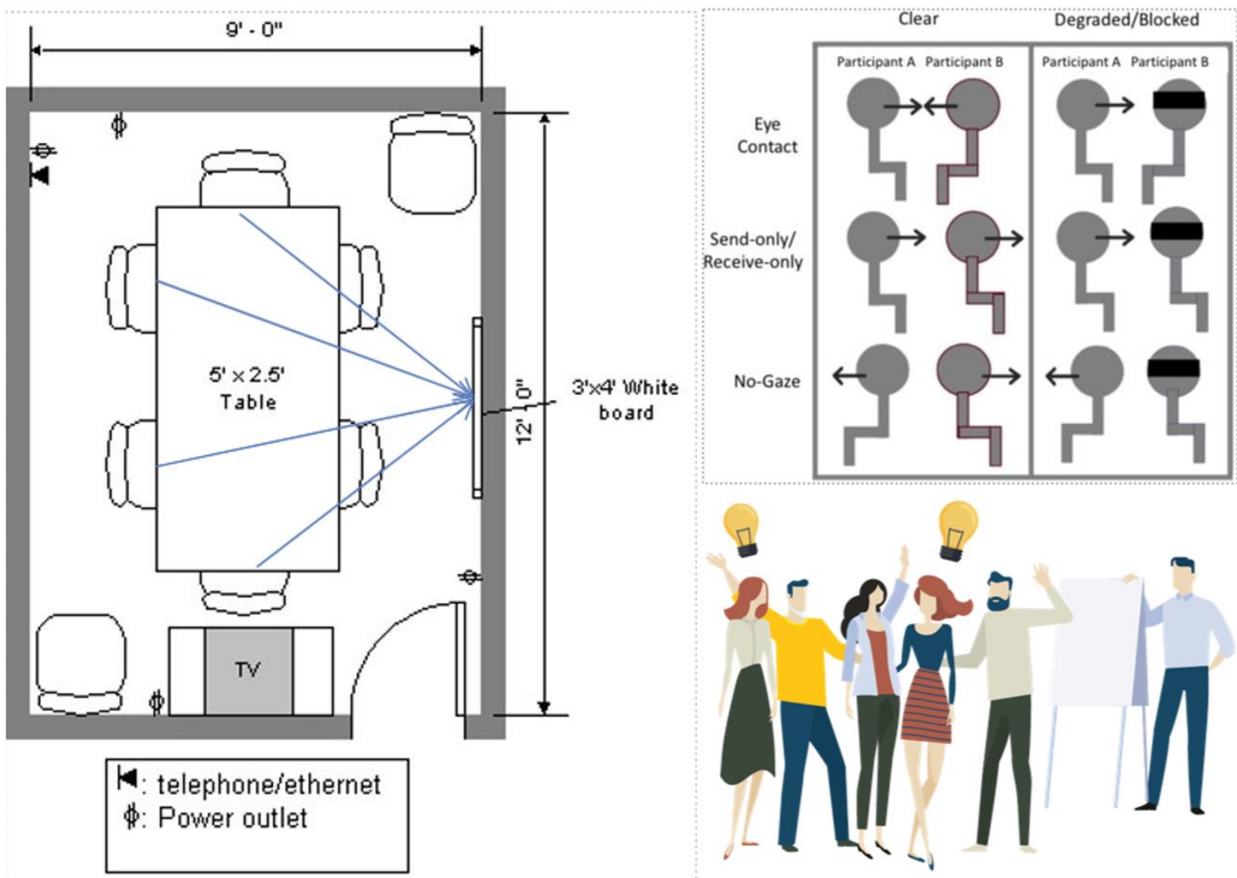


Figure 18 The common characters of small meeting rooms (by author)

The indoor comfort indicators related to ventilation include temperature, local air renewal rate, air velocity, CO2 concentration, controllability, acoustic impacts from HVAC.

According to the Bouwbesluit:

- Temperature:

Indoor dry bulb temperature should be 23.5-25.5 [°C] for summer and20-23[°C]for winter according to the heat balance of human body evaluation for normal Dutch offices. But there's no law for temperature domain in working places.

- Local air renewal rate:
  Facility for ventilation with a capacity of at least 0.7 dm^3/s per m^2 floor space with a minimum of 6.5 dm^3/s per person for meeting rooms and offices, 7 dm^3 / s for toilet room, 14 dm^3 / s for bathroom, 21 dm^3 / s for an installation space.

- Air velocity:
  The supply of fresh air causing an air velocity in the long-stay area that is no greater than 0.2 m/s.

- CO2 concentration:
  The comfort boundary of CO2 concentration is 1000-1500 ppm. The recommended level is 600-1000 ppm.

- Controllability:
  Natural supply of fresh air to be adjustable in the range of 0% to 30% of the capacity in addition to the lowest position of at most 10% (for offices) of that capacity and a position of 100% of that capacity, at least two control positions in the control area that differ by at least 10% (10% for offices) in capacity.
  Mechanical supply of fresh air has a closed position, is adjustable in the range of 10% to 100% of the capacity, in addition to the lowest position of at most 10% (for offices) of that capacity and a position of 100 % of that capacity at least one control position in the control area.

- Acoustic control:
  A mechanical device for air exchange, heat generation or heat recovery causes a characteristic installation noise not exceeding 30 dB(A).

- Humidity:
  Optimum humidity levels are between 40% and 60% and not extend 30% - 70%. Humidity levels below 40% will begin to cause problems for workers with conditions such as sinusitis. (Advice: from the CSA Standard CAN/CSA Z412-00 (R2005) and ASHRAE Standard 55 - 2010)

For such spatial scale, there is only one indoor ventilation unit in the majority of these room cases. Thus, this **medium-scale environment** between macro and micro, larger than micro-climate, smaller than the gathering halls, where body air, respiratory flows and ventilation flows effect the whole space, directly illustrate the relationship between single indoor end unit of a HVAC system and the micro-climate around human body. The sample meeting room in Kuijpers, Leiden, is chosen as a typical medium-scale environment in this research.

The sample room chosen for the research is in a standard geometry layout, 4.52m*5.60m*2.80m(h), a small meeting room for 6-8 people before corona time. The room is a typical shared space for group work. The normal activity state is sitting and talking at the same time, which is of light level. There is one exhaust opening and one indoor unit with a separated control panel in that space. The exhaust opening is a 0.6m*0.6m perforated aluminium panel. The indoor unit is PLFY-P20VLMD-E by Mitsubishi. The only control panel in this room controls the indoor unit of this room only, though this system allows one control panel controlling multiple indoor units in one zone at the same time. The only possible way for passive ventilation an Inward-opening bottom-hung windows, which is closed all the time. During the corona time, the space is only available for 2-4 people at one time.

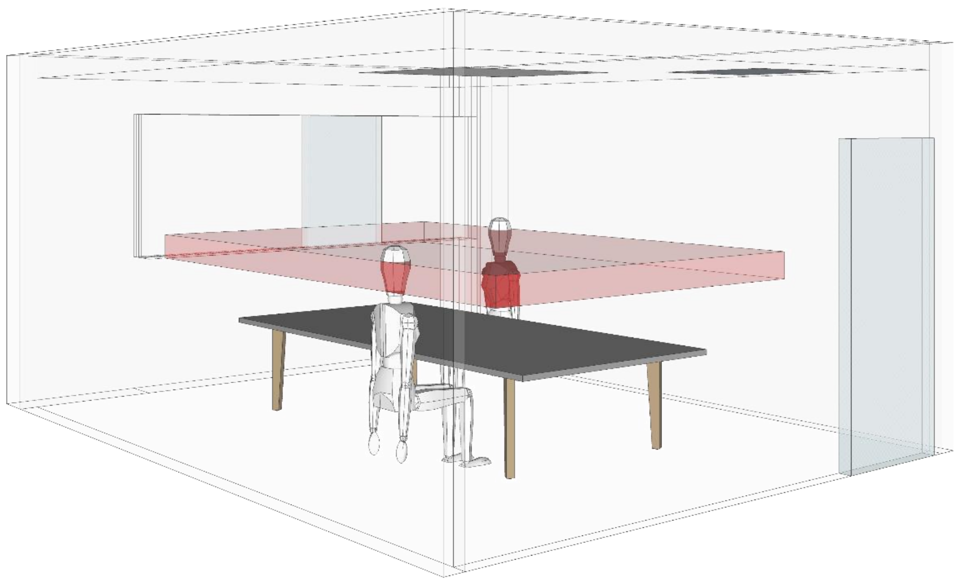


Figure 19 the perspective of the meeting room in Kuijpers, Leiden, as the typical medium-scale environment (by author)

a) indoor end unit ceiling surface. b) the single exhaust opening

Figure 20 the only one pair of indoor end unit in the sample room (photos from author)

2.3.2 HVAC system in Kuijpers, Leiden

The building is the precondition for the research, as it is where all the story happens. Different buildings of different attributes are equipped with different systems for different functions and different scales. The research aims at the engineering control of indoor climate of **medium-scale environment**.

a. Building information

The experiment object is the room based on that specific HVAC system applied for that joint office building. The building is regarded as the standard Dutch office building, because of its standard development mode, construction year and energy label (https://www.fundainbusiness.nl/kantoor/leiden/object-40507628-haagse-schouwweg-6/):

- Development mode: the attribute of the building is office for rental as the initial development purpose. The further operation is based on Model ROZ (Raad voor Onroerende Zaken).
- Construction period: 1981-1990, a period of Dutch public building boom.
- Energy label: B 1,21 of generally good standard.

b. Building engineering for indoor air quality

The building engineering for indoor air quality in the sample building is totally based on mechanical ventilation, HVAC system, by processing and transmitting the fresh and removed the polluted air. The total mechanical ventilation shows the advantages in human intervention from all aspects:

1. Good control of the ventilation capacity; no dependence of the outdoor weather conditions and despite possible noisy environment
2. The possibility of extracting heat from the exhaust air and use it to preheat the fresh air supply (heat recovery)
3. The possibility of preheating and pre-cooling of the air supply
4. The possibility of humidify and dehumidify of the air supply
5. The possibility of cleaning the air by an air filter or supplying the air from a relative clean site of the building

The total mechanical ventilation is the precondition for the analysis the impacts and possible solution from HVAC system.

Currently the building system design follows the concept, smart building, which is based on building automation system (BAS) or building management system (BMS) to automatic centrally control a building's HVAC, electrical, lighting, shading, access control, security systems and other interrelated systems, and at the mean time shows the flexibility for individual adjustments on a certain level. As HVAC system is under this smart building system, to understand the control basis is important for the variant control of the further experiments.

Such indoor air quality control methods are popular in Dutch construction market. There are quite some offices in the same condition and construction context as the sample space chosen in this study.

c. Detail information about the HVAC system of Kuijpers, Leiden

For offices, cooling load usually takes a larger energy consumption than heating load in building system. In the case of this research, the meeting room of Kuijpers Leiden is located on the 5th floor of a joint office building for lease, Haagse Schouwweg 6 (see Figure 21). To understand the building system is to classify the control level of the HVAC system, and thus, to figure out an optimal control level which is economic for fast renovation and can efficiently and effectively decrease the indoor infection risk via airborne transmission to achieve a hygiene ventilation renovation.

Figure 21 The perspective of the office building of Kuijpers, Leiden (from Google Map).

The building system consist of Variable Refrigerant Flow (VRF) System and standard commercial air conditioning system with an indoor air handling unit (AHU), see Figure 22. The external air comes in the system through the intake grille and preheated by the heat exchanger. Then, it will heated or cooled by water based system, boiler or cold water chiller in the AHU, or by the primary heat exchanger in outdoor units. The air is transferred to every floor by the primary air supply ducts at a specific temperature, which is 14 ℃ in Kuijpers case. The primary air is well mixed in the fan-coil indoor units by direct indoor air recirculation or at the ceiling level by mixing ventilation. Fan coil plays the main role in providing the kinetic in the whole mechanical ventilation system. At the end of the return ducts, there is also a heat exchanger to make full use of the heat in the waste gas for preheating the fresh inlet air.

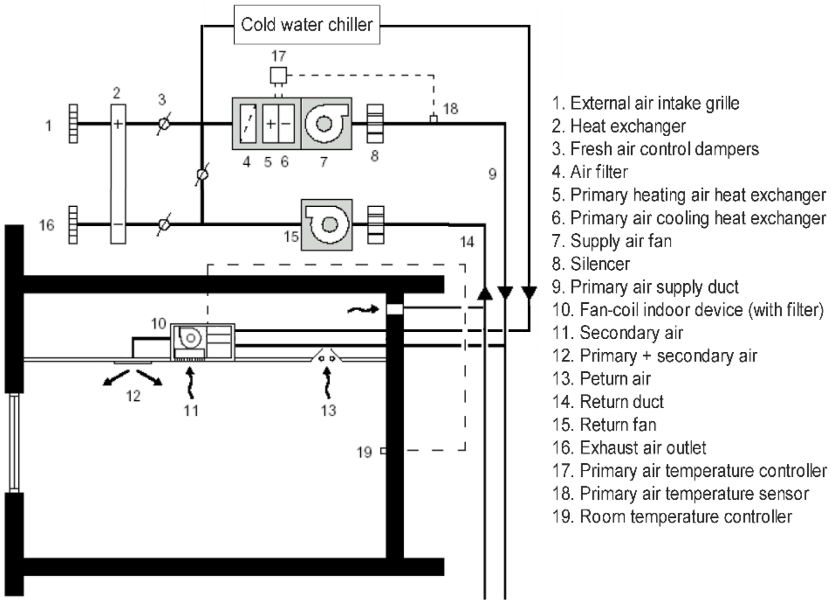


Figure 22 The building system scheme (by author).

VRF System is part of the HVAC system, which allows a high flexibility for customized adjustments in different spaces (see Figure 24). All the VRF part of the HVAC system (including the outdoor units and the indoor units) is supplied by Mitsubishi. Every outdoor unit connects with a certain number of indoor units (see Figure 25) for certain domain of the building by refrigerant. And the air handling unit is supplied by Carrier (see Figure 23). This HVAC system is that it is a total mechanical supply & exhaust ventilation with heat recovery. The mechanical system will be turned off only in the weekends.

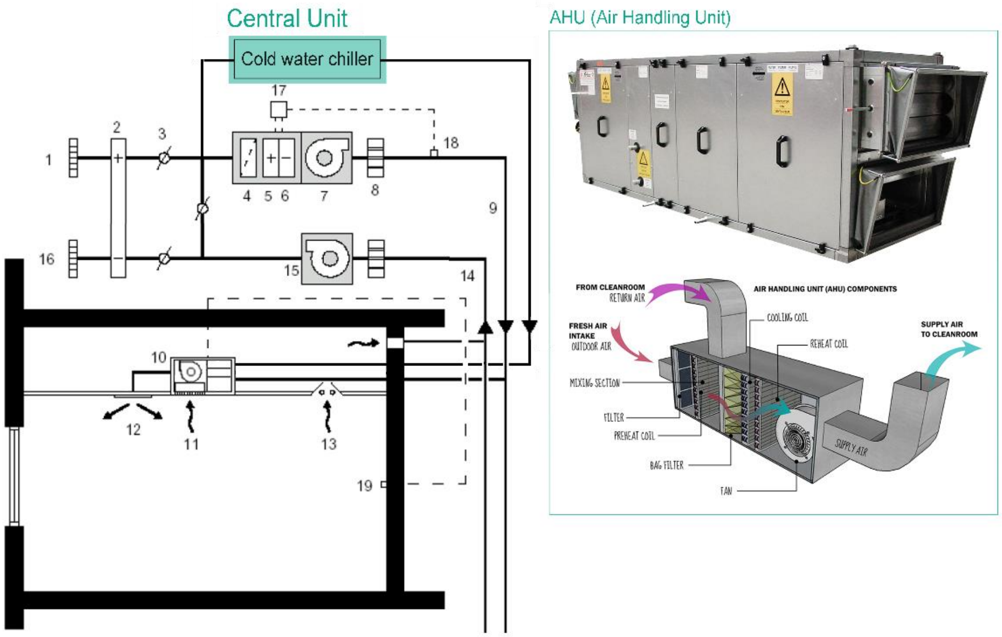


Figure 23 Detail of the central air handling unit (by author).

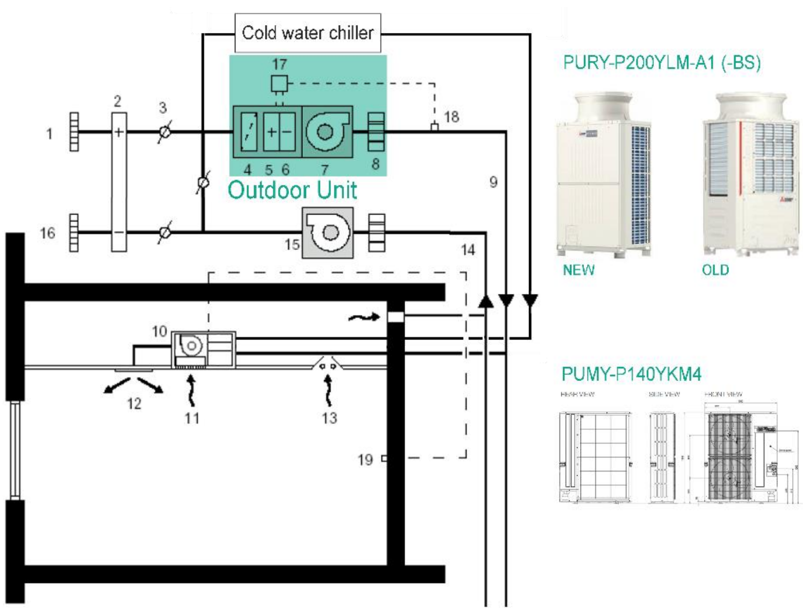


Figure 24 Detail of outdoor units from VRF ventilation system (by author).

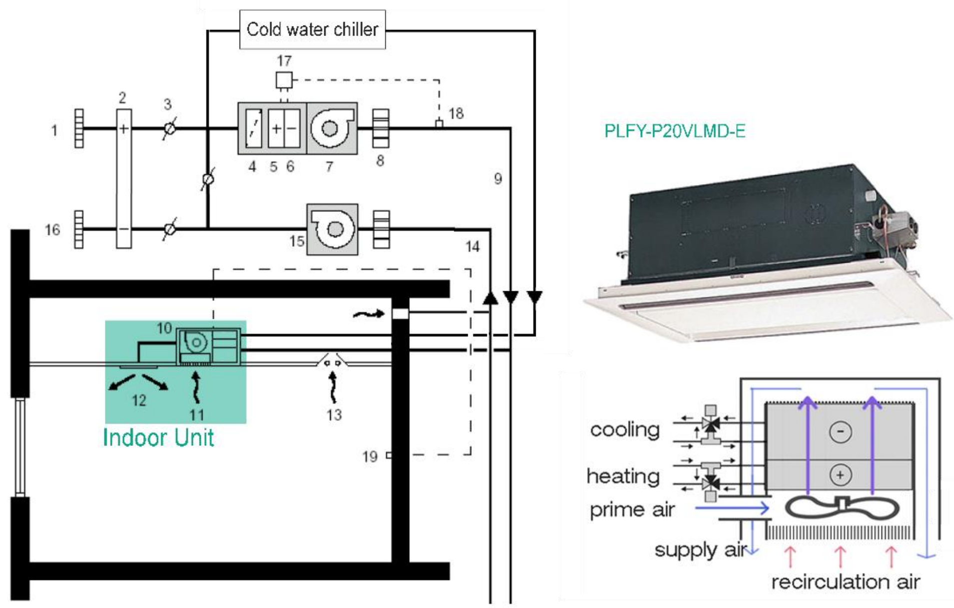
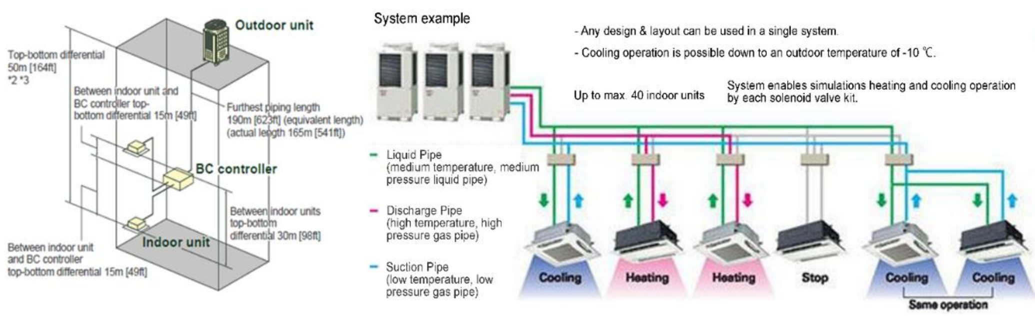


Figure 25 Detail of indoor units from VRF ventilation system (by author).



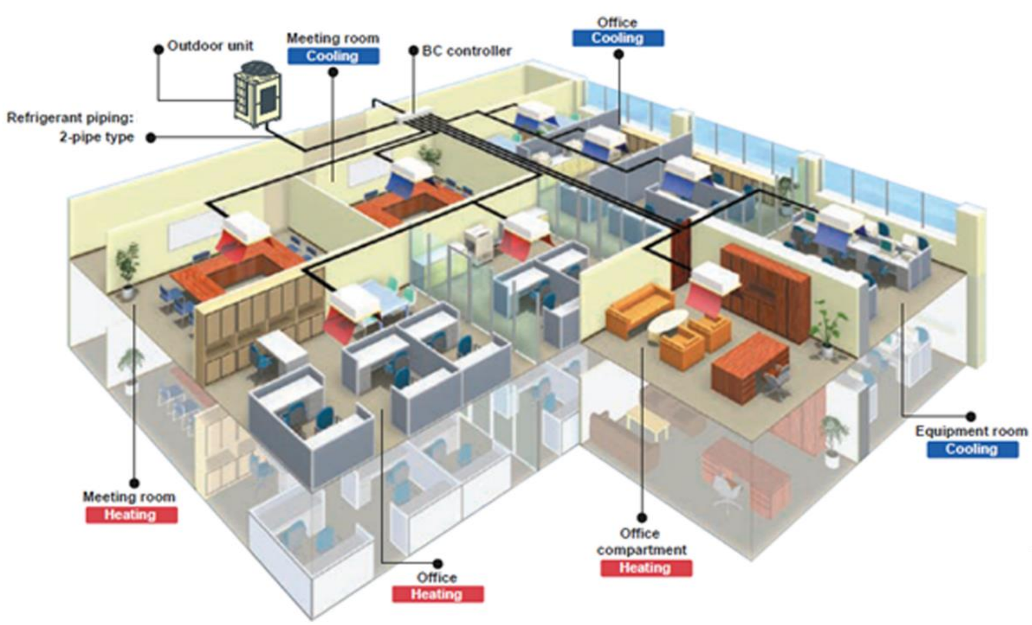


Figure 26 The characters of variable refrigerant flow (VRF) system (Mitsubish City Multi VRF Introduction Book, 2020)

The HVAC system is based on variable refrigerant flow (VRF) (see Figure 26) to control the indoor temperature by mechanical supply & exhaust ventilation with heat recovery. The HVAC system that applied in the whole building is **Variable refrigerant flow (VRF)** system. Because this office is a sharing building and designed to rent to different companies on different floors, the building system with an open and flexible plan is well equipped in every floor for any possible working place design based on different culture and workflow of different companies. With VRF system, the air-conditioning (AC) system is able to control the amount of refrigerant flowing to the multiple evaporators (indoor units) for multi-functional zones. VRF system usually have high flexibility in local ventilation controls but shows a higher total energy consumption and initial costs compared with other HVAC systems.

The HVAC system consists of two parts, a standard water cooled indoor air handling unit and a VRF system including air cooled outdoor units and indoor units. The VRF system is parallel to the traditional HVAC system which is only based on air handling units. The scheme and the position of the HVAC system is shown in Figure 23 and Figure 24. In this building system, the application of VRF system allows the variable temperature control in different zones. The VRF system is based on refrigerant for the thermal exchange and transmission between outdoor and indoor units. And the VRF system can provide simultaneous heating and cooling. But the current HVAC system is temperature based for fresh air supply. The adjustable indoor temperature domain is 15 – 27 ℃.

The detail product information in the HVAC system:

- Outdoor unit: PURY-P200YLM-A1 (-BS)*9 + PURY-P200YLM-A1 (-BS)*2 + PUMY-P140YKM4*2
- Central Air handling unit (chiller): SDK65 FOS400 ANS manufactured by j.e.stock ventilatoren b.v.
- Indoor unit: PLFY-P20VLMD-E*25 per floor

The control system is temperature-based with a reaction domain of lower than 20 degree and higher than 26 degree. According to the measurement, the indoor temperature is well controlled around 21 degree in the meeting room in this case. In the reality, it is not an all-air system, which includes radiator along the exterior walls beneath the windows, but, the radiator in the sample room is always turned off, the medium-scale environment in this research is simulated into an all-air ventilation system.

The VRF as a sub-ventilation system for the high flexibility in open working space design, which is also widely recommended by a lot of architects and real estate managers. The flexible open working place shows a higher interaction and of a higher value for investment. Thus, the building system body is complex and mass, every change can be an essential pattern in the dynamic system alternative. But VRF is not the only technique applied by the Dutch offices like Kuijpers, Leiden, another important technique is the smart building control system, which can automatically adjust the working mode of the electric systems, including lighting system, security system, HVAC system and internet system via the sensors in each control zone to realize the instant occupation condition. *The experiment about the current situation* (see chapter 3.1) observed one-week integrated working patterns to well understand the smart building control logics and then classify the control levels in the ventilation system based on the smart building mechanical system.

This research focus on the airborne transmission, thus, the second aspect mentioned in the three principles introduced in the Chapter 2.5.1, cutting off the transmission path. Infectious disease control methods targeting for individual, like masks, one-to-one ventilator or individual air purifiers, as discussed in Chapter 1.3 as the low engineering control efficiency, are out of discussion in this research. The **engineering control levels** in the ventilation system are classified as general control and partial control. In the ventilation system of the sample building, the general control is the engineering methods that are above the specific room, while the partial control is the derivate ventilation end units or facilities based on the whole system (see Figure 27)

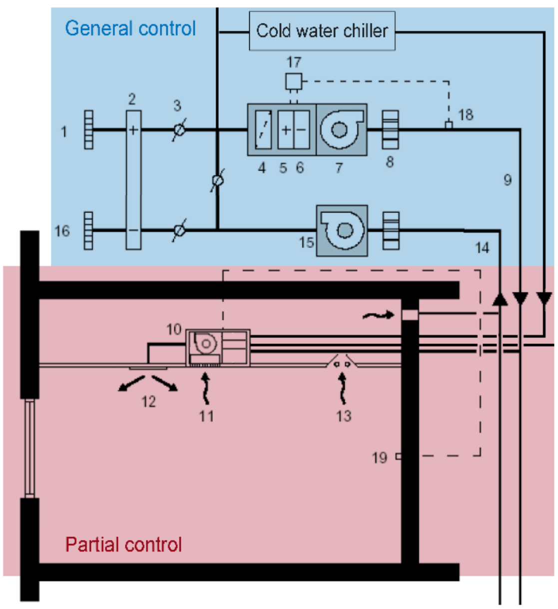


Figure 27 The classification of the ventilation system

2.3.3 Indoor unit

Mixing ventilation is the only ventilation pattern for this research, and the multi-supply fan-coil indoor end unit is the secondary equipment of the building system under this ventilation pattern. The impacts of this type of unit on the whole indoor environment tightly relate to the general air processing system in the building and the overall air distribution pattern applied in the room. Thus, there are two levels of the fan coil end unit worth discussing in the indoor infectious disease prevention via airborne transmission. And the two elements in this end unit that worthy for hygiene ventilation design are the filter for the virus nuclei laid particle removal and fan coil for the ventilation efficiency performance. In the experiments and CFD modelling, the impacts of the indoor unit is further discussed for the mechanic impacts of these two elements on the local contaminant removal rate.

There is always a high risk of short circuiting where the room air rising at the heat sources, when applying the cooled ceiling. The role of air recirculation in the mixing ventilation end unit is to completely mix the indoor air and the primary air. The mechanical process will not absorb or produce CO2, but may impact the sedimentation of the suspending particle in the air. And the mechanism of mixing ventilation to control the density of indoor pollutants is by bringing in enough outdoor air to dilute emissions from indoor sources uniformly. In this logics, the mixing level of the primary air and the indoor air decides the ventilation efficiency. And the air recirculation mode is an efficient method to maximize the mixing of fresh air with room air at the air supply outlets. In this way, to improve the mixing ventilation efficiency, the mixing level of the primary air and room air plays an important role in this context.

The decentralized indoor unit is a fan coil unit with a fan and design in direct expansion form for thermal exchange with the conditioned fresh air.

According to the measurements, the recirculation rate can achieve 12.3. There is a separated control panel for the only indoor end unit in the sample meeting room.

Indoor unit production information

The indoor unit is the core component in direct the supply airflow direction, airflow speed (if the air exchange rate is the same, then this term directly relates to the air-recirculation rate and mixing level), mixing level and air exchange rate.

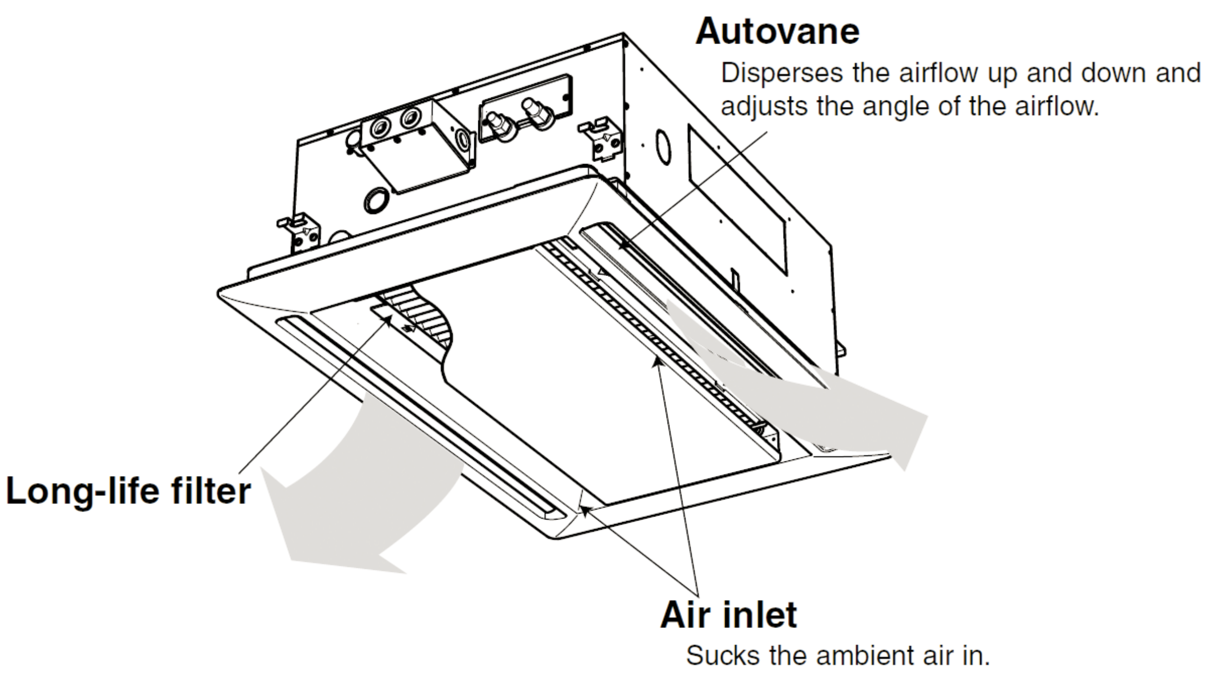


Figure 28 The indoor unit

- Filter
  The filter applied in this indoor unit is a long-life filter made by PP Honeycomb fabric (washable). It removes the sucked-in dust and dirt. The product manual suggests the filter should be cleaned

at the beginning of air-cooling and heating seasons.

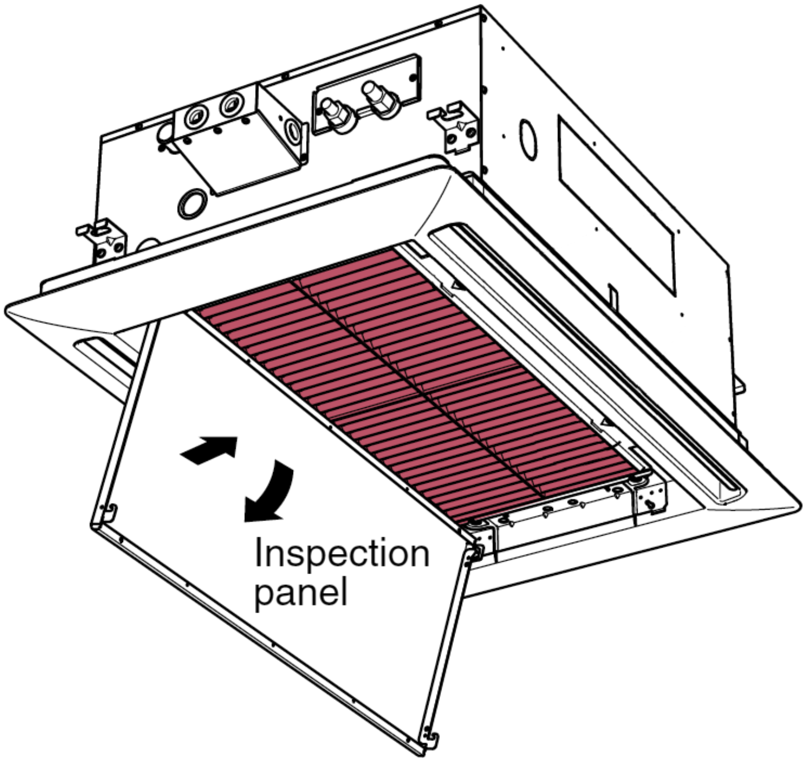


Figure 29 the filter

- Fan coil

  There are 4 levels of fan speed on the control panel, while only 2-4 levels are available for manual setting, as shown in the table, Low-Mid-Hi. The information about the fan coil is listed in the below table:

Fan	Type*Quantity		Turbo fan x 1
	Airflow rate *2 (Lo-Mid-Hi)	m3/min	6.5-8.0-9.5
		L/s	108-133-158
		Cfm	230-283-335
	External static pressure	Pa	0

Table 1 product information of the fan coil

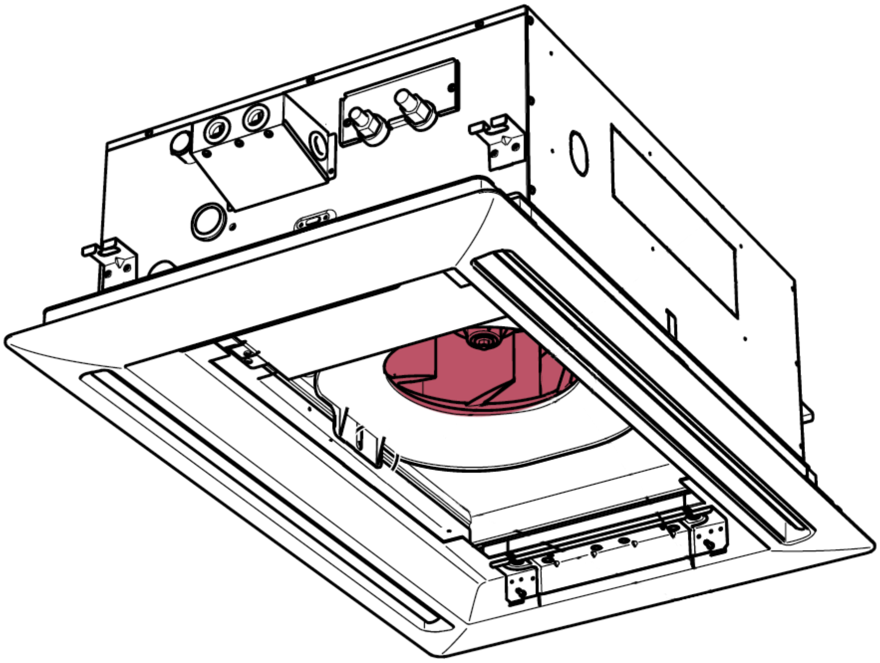


Figure 30 the fan coil

The mechanism of the indoor unit is shown in the scheme: the recirculated air first goes through the filter for coarse particles, and mixes up with the prime air before fan coil. By the air pressure offered by the fan coil, the mixed air will be heated or cooled by the cross fin heat exchanger in the unit as the secondary procedure. Later it will be transported to the supply opening and be supplied to the space at an angle of 15°. The detail information and geometry layout is shown in the product drawing. The two supply openings are 800mm*50mm with a vane in each to adjust the air flow direction at the angle 10° - 20°, mostly at 15°.

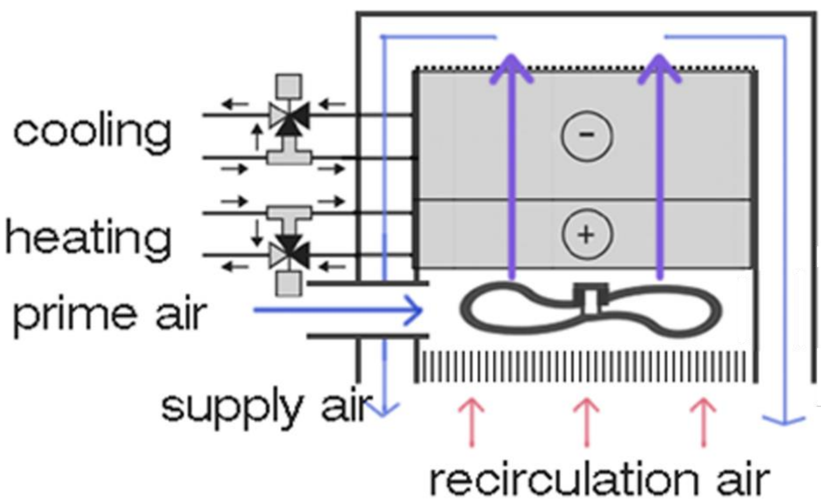


Figure 31 the mechanical scheme layout of the indoor unit

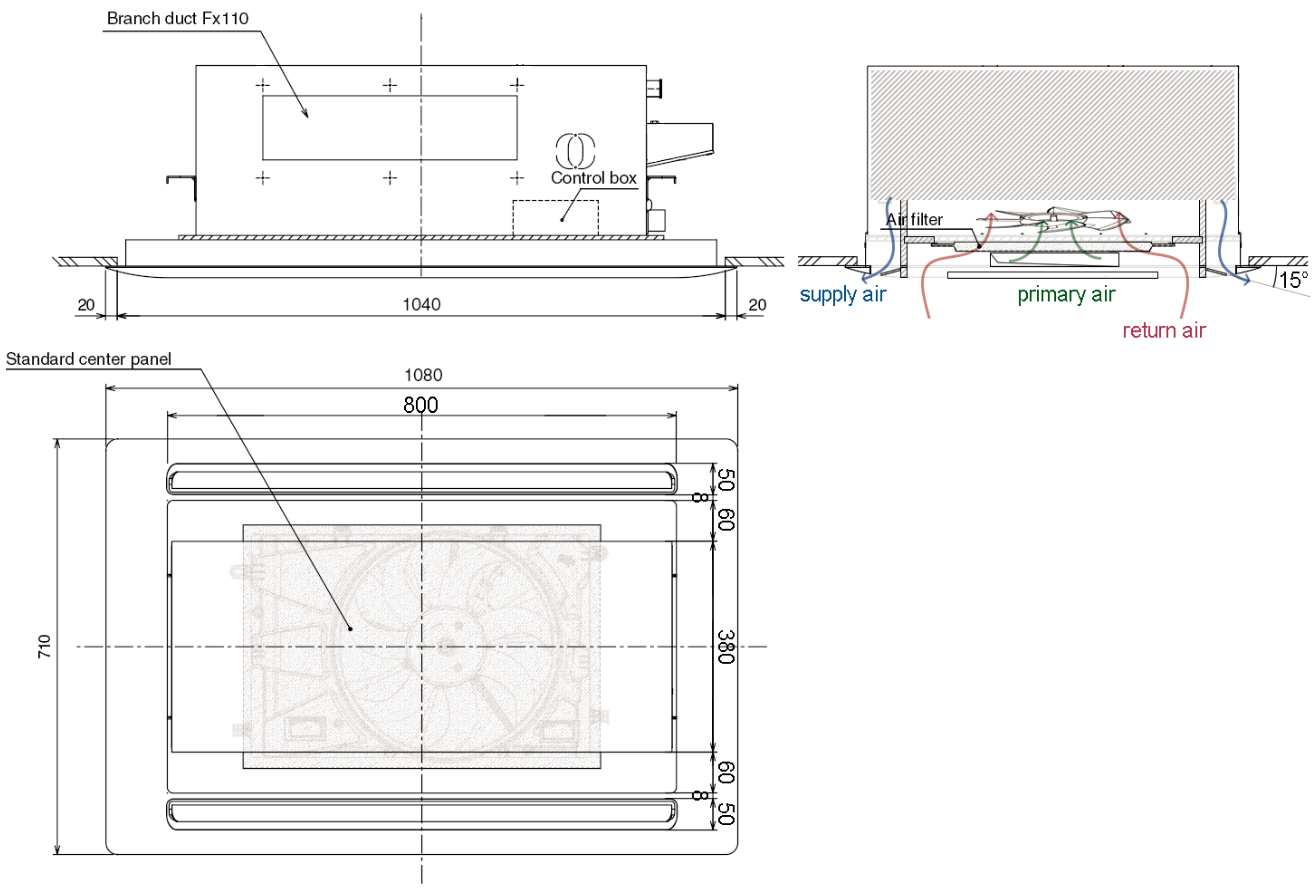


Figure 32 The technical drawings of the indoor end unit

2.3.4 Purifier technics for indoor end unit

As the research of the anti-epidemic condition of current economic HVAC system (see chapter 2.2.3) and CFD analysis in this research suggest: extra installation and following maintenance of **air cleaners, purifiers or filters** in the existing economic HVAC system is worthy of discussion for later product design.

HEPA filters

Studies have confirmed the superiority of filtration over increased ventilation at reducing transmission risk of airborne viruses. However, permanent air filters usually are not easy to install in exciting systems. Therefore if it is not possible, portable high-efficiency air filtration (PHEAF) can be an alternative solution. HEAF device is another type of filtration option where a portable HEPA or ULPA filtered fan units with options for internal UV lights is used. They can be used in all projects to recirculate the highly filtered and UV treated supply air in large areas such conference rooms, cafes, nursing stations and in corridors. But the HEPA filters for virus nuclei laid particles needs high-speed air flow to pass through and provide sufficient fresh air to meet the air change rate for meeting room. This could be applied in the new-built building for a new established HVAC system, but not for the most existing HVAC office system, because all the ducts need to upgrade larger ones. This proposal may not be the best choice for meeting rooms and schools, because the large amount of air flow rate in the ducts produce noises which can affect normal communication.

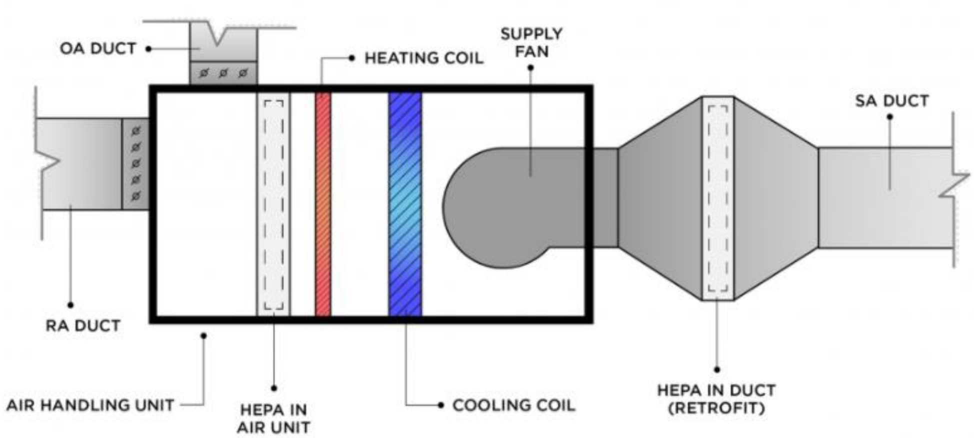


Figure 33 Use of HEPA filter in HVAC system (from (Schafer, 2020)*)*

UV lights

If air is circulated in the HVAC system, the air can be sterilize as it that passes through with a UV lamp. This kind of air sterilization system with UV installed in the air duct was used in a newly built hospital in the 60s. Sterile air was supplied to the operating room, delivery rooms and etc. It After period of two years it was reported that the infection rate among surgical cases was nearly 10 times less in comparison than another hospital without application of such sterilization system. The Advantages of such system is that it is applicable and available both for use with central (ducted) HVAC systems and for non-ducted spaces. There are many novel applications of UV sterilizers specific to almost every application, including stationary lights or portable devices mounted on robots for off hour surface sterilization *(Schafer, 2020)*.Although such a system extinguish pathogens like bacteria and viruses it does not filter all impurities. Therefore, it can be extremely effective at both capturing and destroying contaminants if it is combined with other filtration systems such as HEPA filter *(Schafer, 2020)*. Based on the beta-HCoV-OC43 results, continuous far-UVC exposure in occupied public locations at the current regulatory exposure limit (~3 mJ/cm2/hour) would result in ~90% viral inactivation in ~8 minutes, 95% in ~11 minutes, 99% in ~16 minutes and 99.9% inactivation in ~25 minutes (Submitted et al., 2021). The application of this technic needs a long duct routine for the radiation process, the droplet and installation space problems are hard to handle in the reality.

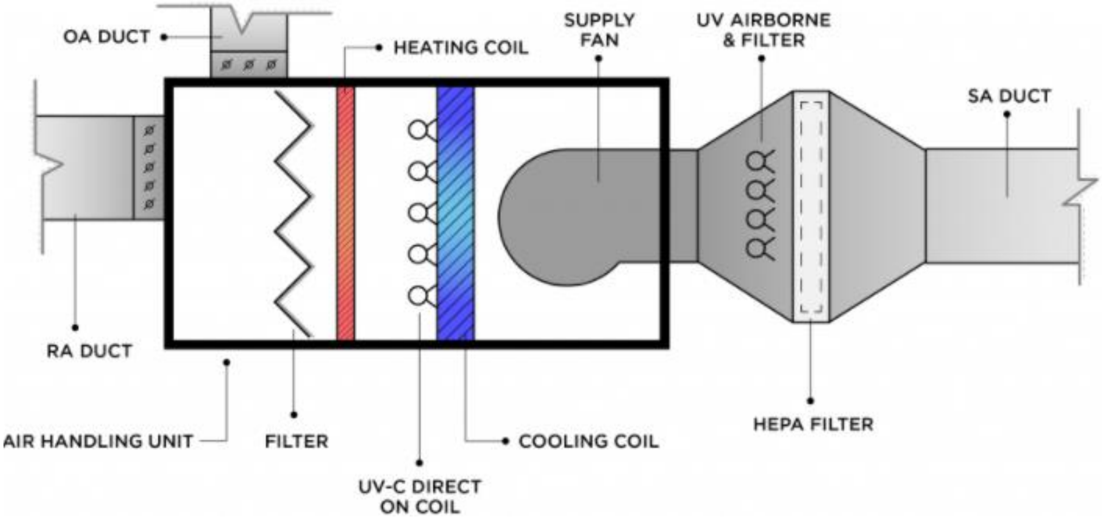


Figure 34 Integration of UV light into HVAC system(from (Schafer, 2020)*).*

Biopolar ionization generators

Bipolar ionization is created when an alternating voltage source (AC) is applied to a special tube with two electrodes. Production of both positive and negative ions purify the air. The generated charged ions bind to contaminants in the indoor air, either causing them to drop out of circulation in the room or to be captured by a mechanical filter within an air handling unit. Bipolar ionization systems can reduce dust and mould, capture odoris, reduce volatile organic compounds, and reduce viruses and bacteria in the air. The advantage of this technology is that the existing HVAC system dose not to be re-engineered. It does not rely on contaminants passing through the unit to be cleaned, the bi-polar ionization process allows for air cleaning to occur within the desired space treating a larger volume of air within the breathing range. The disadvantage is that it only captures particles from the ducted air – not within the space and has potential to **create ozone** by-product *(Schafer, 2020)*.

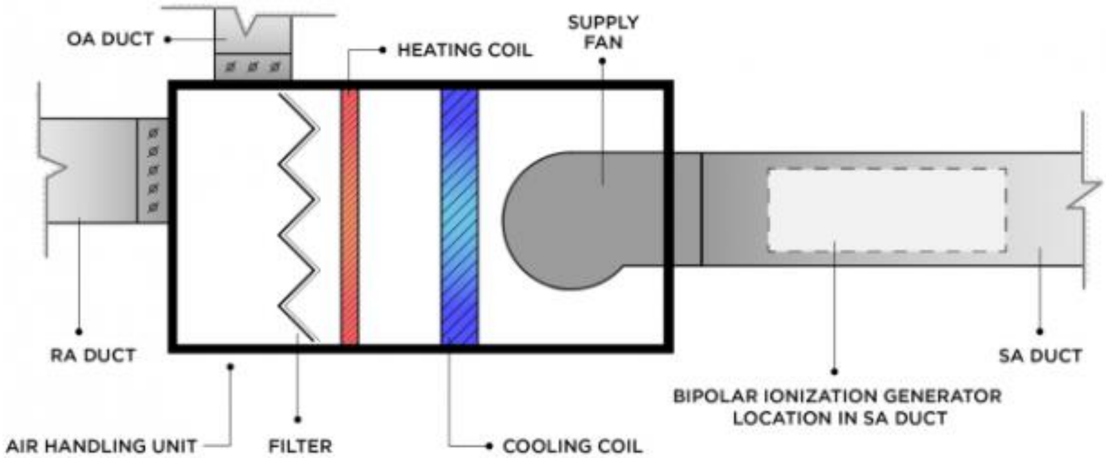


Figure 35 Use of Bi-Polar Ionization Technology in HVAC system (from (Schafer, 2020)*).*

Ozone Generating air cleaners

They are devices that intentionally produce high concentrations of ozone to clean the air in a room. Ozone kills micro-organisms by breaking down their protein structure. It neutralizes pathogenic and non-pathogenic germs as well as many organic and inorganic odoris, both gases and small particulate. Research shows that indoor secondary organic aerosols do form from ozone reactions in residential environments, and can contribute to human exposure to such particles when ozone generators are used indoors. Because of its effects on human health and therefore no federal government agency has approved these devices for use in occupied spaces. ASHRAE's Environmental Health Committee issued an emerging issue brief suggesting "safe ozone levels would be lower than 10 ppb. Ozone Generating air cleaners should only be considered for disinfection on unoccupied spaces and never be used in occupied spaces. Use of the at concentrations that do not exceed public health standards, ozone is generally **ineffective** in controlling indoor air pollution.

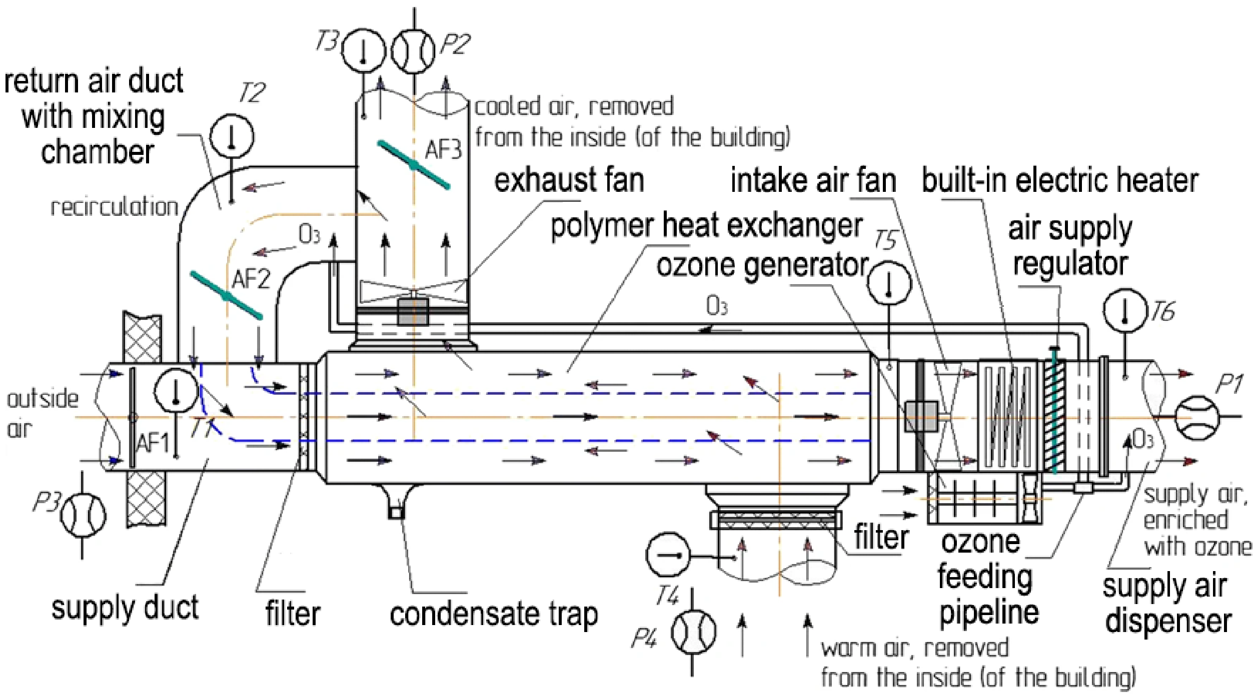


Figure 36 Use of Bi-Polar Ionization Technology in HVAC system (by author).

Electrostatic precipitator (ESP)

ESP ionizes the air by applying high voltage to the electrodes. Dust particles are charged by the ionized air and collected on the oppositely charged collecting plates. They can handle the *dry* collection of valuable materials or *wet* collection of fumes and mists. The ESP are less efficient in removing PM, but are easy to clean and less costly to operate compared to HEPA filtration. Utilizing an ESP upstream of a HEPA filter can substantially reduce the pressure drop resulting from particle accumulation on the HEPA, and can also reduce operating costs by extending the lifetime of HEPA filters.

This proposal will bring about new indoor comfort problems caused by humidity control.

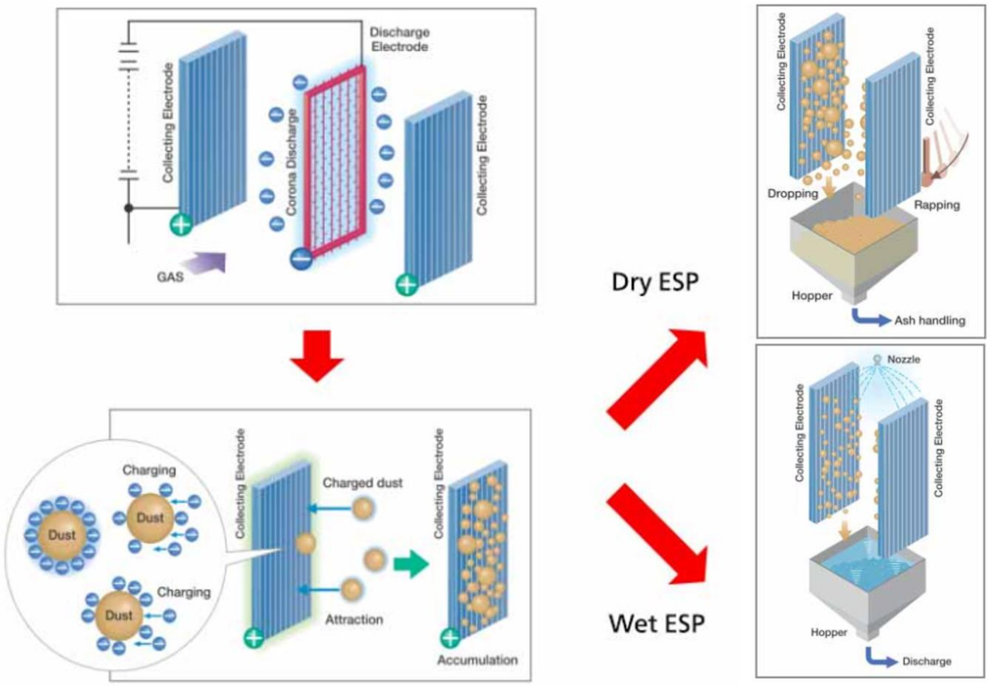


Figure 37 Mechanic logics of ESP

Conclusion

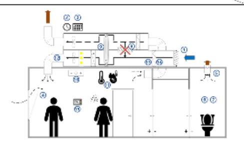
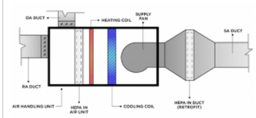
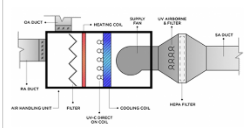
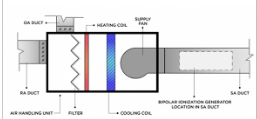
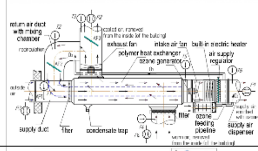
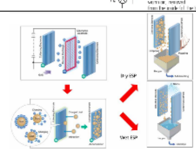
Engineering strategies	Criteria / Scheme / weight	Virus-removal efficiency	Comfort impact	Economy		Energy	Adjustability	Overall rating
				First cost	Maintainance			
		30%	20%	10%	10%	15%	15%	
Ventilation		10	8	5	9	8	10	8.7
HEPA filter		9	9	4	8	9	6	8.0
UV lights		4	10	10	10	10	10	8.2
Biopolar ionization generators		8	6	7	5	10	5	7.1
Ozone Generating air cleaners filter		6	6	6	6	10	7	6.8
Electrostatic precipitator (ESP)		8	7	9	8	8	9	8.1

Table 2 the comparison among different building technologies (by author)

The credits and the weigh values given are based on the comprehension from the author though the massive reading and realistic installation practice. Electrostatic precipitator, UV lighting and HEPA Filter are developed technique in HVAC system to meet hygiene requirements. In conclusion, the strength and shortages for the practical installation are:

Electrostatic precipitator (ESP) – low requirement in installation room. It can also achieve as high ePM 1 particle removal rate as the HEPA filter with small pressure drop. The possible leakage of toxic ozone and NOx with unclear safety standard. The cleaning maintenance process is messy.

UV light - Inability to deactivate 100% of the viruses that pass through, kill rate/technical difficulty/system modification level/energy consumption.

HEPA filters – nearly 100% safety margin can be achieved without efficient and low noise end fans, extended recirculation paths, centralised purification at the rear of the system, local air pressurisation and noise control. The initial cost of the high-standard filter for airborne particle is high. The dense filter can become "production sinks" for many harmful forms of bacteria.

2.4 Dynamic parameter system

There are three aspects in the literature study for the dynamic parameter :

- For engineering practice: official ventilation guidelines for construction market;
- For building technology integration - variant control for CFD modelling;
- For pathologic evaluation – the adaptability of Wells-Riley formula.

The official ventilation guidelines is to figure out the necessary indicators for the ventilation design. The variant control analysis is a comprehensive consideration of the indicators that can be applied in the sample room as a fast efficient renovation based on the existing ventilation system. The design value of the infection risk, also the acceptable infection risk is the design goal for ventilation design.

2.4.1 Official ventilation guidelines

There is already an update in the guidelines from various institutions, as the table shows below. The guidelines promote a series of engineering controls based on the principle logics of ventilation system (see Table 3).

	ASHRAE	REHVA, ECDC	CCIAQ, PHO	ASC, NHC	SHASE	ISHRAE
Outdoor air and airflow pattern	1. Increase outdoor air volume as much as possible. 2. Disable DCV systems. 3. Arrange exhaust air inlets away from pedestrian areas. 4. Open windows. 5. Hourly air exchange rate of three is recommended.	1. Switch AHUs to 100% outdoor air. 2. Disable DCV systems. 3. Open windows for 15 minutes before entering a room. 4. Direct airflows should be diverted away from occupants. 5. Use CO_2 as indicator of indoor air quality.	1. Inspect HVAC systems before use. 2. Maximize outdoor air volume and avoid air recirculation. 3. Disable DCV systems. 4. Use CO_2 as indicator of indoor air quality. 5. Optimize layout of exhaust air inlets as well as air supply outlets, and eliminate dead zones.	1. Check sources of outdoor air. 2. Maximize outdoor air volume and reduce air recirculation. 3. Check balance of airflow in each area. 4. Inspect function of antifreeze protection of outdoor air systems in the cold and severe cold zone. 5. Avoid airflow short-circuiting. 6. Open windows and doors.	1. Outdoor air ratio of 100j% is recommended. 2. Hourly air exchange rate of three is recommended. 3. Avoid airflow short-circuiting. 4. Eliminate blockage of air supply outlets and exhaust air inlets.	1. Provide adequate ventilation. 2. Open windows regularly for buildings without mechanical ventilation systems. 3. A minimum outdoor air volume of 8.5 m^3/(h•person) is recommended.
	ASHRAE	REHVA, ECDC	CCIAQ, PHO	ASC, NHC	SHASE	ISHRAE
Temperature and relative humidity set-points	1. Relative humidity should be set between 40% to 60%. 2. Temperature should be set between 18 °C to 26 °C in summer and winter, respectively.	1. Effects of temperature and relative humidity are limited.	1. Relative humidity should be set between 40% to 60%.	1. Increase and decrease temperature of supply air in winter and summer, respectively.	1. Relative humidity should be set between 40% to 70%. 2. Temperature should be set between 17 °C to 28 °C in summer and winter, respectively.	1. Relative humidity should be set between 40% to 70%. 2. Temperature should be set between 24 °C to 30 °C in summer and winter, respectively.
Operation schedules of HVAC systems	1. HVAC systems operate extra 2 hours before and after a building is occupied. 2. Ventilation systems and relevant exhaust systems should operate for cleaning crews or maintenance workers.	1. Ventilation systems should work at a nominal speed at least 2 hours before the building opening and set to a lower speed 2 hours after the building usage time. 2. Ventilation systems should run at nights and weekends at a lower speed.	1. Ventilation systems operate extra 2 hours before and after a building is occupied.	1. Ventilation systems operate extra 1 hour before and after a building is occupied.	1. Ventilation systems operating around the clock is suggested.	1. HVAC systems should operate around the clock. 2. Air recirculation mode should be switched on during weekends and holidays.
	ASHRAE	REHVA, ECDC	CCIAQ, PHO	ASC, NHC	SHASE	ISHRAE
Countermeasures for the specific spaces	1. Exhaust air systems should be accommodated to keep negative pressure for bathrooms, process areas, custodial areas and commercial kitchens.	1. Ventilation systems of toilets should operate 24 hours per day, and windows in toilets should not be opened. 2. Occupants should flush toilets with lids closed. 3. Water seals should be checked every three weeks.	1. Install special exhaust systems in high-risk spaces such as washrooms and rooms containing confirmed cases, and exhaust systems should operate 24 hours per day.	1. Regularly disinfect critical areas such as kitchens and toilets. 2. Regularly check water seals. 3. Exhaust air systems in toilets and hot water rooms as well as ventilation systems of underground garages should operate 24 hours per day. 4. Pressure of toilets and disposal rooms should be negative.	1. Toilets, bathrooms and kitchens should be controlled with negative pressure. 2. Airflow route should run from clean areas to polluted areas.	1. Exhaust airflow being diverted from toilets to other occupied zones is prohibited. 2. Exhaust fans in toilets and kitchens should be kept in operational mode. 3. Pressure of isolation wards should be negative and the hourly air exchange rate of wards containing confirmed cases should be twelve.
	ASHRAE	REHVA, ECDC	CCIAQ, PHO	ASC, NHC	SHASE	ISHRAE
Application of auxiliary equipment	1. MERV-13 filters and UVGI systems are recommended. 2. Make sure HVAC systems are capable of meeting indoor thermal comfort requirements and pressure differential after upgrading filters. 3. Heat recovery devices can be utilized for leakage is acceptable.	1. Changing outdoor air filters is not necessary. 2. Air cleaners and UVGI systems can be applied in the short term. 3. Replacing air filters and cleaning ducts as normal schedules is enough. 4. Common measures for respiratory protection should be taken during replacement and maintenance work. 5. Heat recovery devices can be utilized for leakage is below 5%.	1. Take advantage of stand-alone air filtration, humidification and dehumidification equipment according to increased ventilation rates and outdoor air conditions. 2. Filters should be upgraded to MERV-13 or better, and HEPA filters can be applied. 3. UVGI systems can be used in healthcare to purify contaminated air. 4. Cross contamination between outdoor air and exhaust air should be avoided with the application of heat recovery devices.	1. Air filters can be upgraded to HEPA filters, and portable air cleaners can be used. 2. UVGI systems are not recommended for installation in HVAC systems. 3. Cleaning, disinfecting and replacement of air filters in air supply outlets, exhaust air inlets and ducts should be done every week. 4. Rotary heat exchangers should not be applied.	1. Medium-efficiency filters can be adopted in offices, and HEPA filters can be applied in operating theatres. 2. Portable air cleaners are efficient. 3. Maintenance of air filters can be executed according to normal schedules when HVAC systems operate in 100% outdoor air mode. 4. Heat recovery devices can be utilized for leakage is below 5%.	1. Air filters should be upgraded to MERV-13 and the capacity of fans and motors should be able to adapt to increased pressure drops. 2. UVGI systems and HEPA filters are recommended. 3. Portable air cleaners should be selected according to room size. 4. Rotary heat exchangers should not be applied.

Table 3 comparison of guidelines issued by virous institution (from (Zheng et al., 2021) *)*

The guidelines include engineering improvements from both general and partial control level. The suggestion seems too general and unrealistic for practice on some level:

1. DCV system
   Since the smart building system widely applied in most commercial buildings, especially office, turning off the DCV system is possible but may not be widely accepted or notified by the clients.
2. Air recirculation
   Air recirculation can happen on two levels of the ventilation system, centralized process of the whole building and the local process in the end unit in one room. The impacts of centralized process on corona virus laid nuclei airborne particles, like inactivation, adsorption, accumulation and sedimentation, are unknown, but it increase the exposure risks for those rooms room which are originally free of viruses. As the previous experiments proved, the local air recirculation in one room is an essential part in mixing ventilation, which helps increase the mixing level and enhances the ventilation performance in mixing ventilation air distribution pattern.
3. CO2 as the indicator for indoor air quality
   The difference of attributes between CO2 and airborne particle cannot be ignored. Though in computational simulation, the pollutant particle and CO2 are being simulated in the same logics. In practice, though the indoor movement of CO2 is very similar to that of airborne particles, there are still unavoidable differences in their physicochemical properties, like inactivation, adsorption and sedimentation.
4. Fresh air amount
   A sufficient fresh air amount is required via different scalars, like hourly air exchange rate and minimum outdoor air volume per person, but enlarging the fresh air amount cannot directly promise a lower indoor corona infection risk. For different geometry layout of the room, the fresh air amount may need a further evaluation of the indoor activities and occupation situation.
5. Thermal comfort
   Thermal comfort includes indoor temperature and humidity. With different local climate background, the preferred temperature and humidity are different from place to place. The comfortable indoor temperature (around 20℃) and relative humidity (around 40% - 60%) for human beings have an inhibitory effect on the survival of corona viruses. Effects of temperature and relative humidity are limited.
6. Extension of HVAC system operation schedule
   At least 1-hour operation extension before and after the occupation of commercial buildings is required. Different ventilation efficiency of different HVAC system can hardly promise a safe hygiene indoor environment. The regulation should be based on characters of HVAC system, like intensity, frequency and duration, and the attributes, ventilation efficiency and particle removal efficiency of the space.

The official ventilation guidelines recommends are weak for ventilation practice in reality. Further exploration about these design parameters and practical ventilation performance is needy.

The possible modelling variants mentioned in the formal guidelines and the practical worth for them to be modelled are shown in the table below:

	Is it a prerequisite?	*personalised controlability*	*relationship to engineering*	*Influenced by spatial geometry*	*indicators*		***How worth is it for ceiling mixing ventilation in modelling & design phase?***
					for dessign	*for evalucation*	
Temperature	no	high	high	medium	temperature [°C] [°F]	temperature [°C] [°F]	low
Humidity	no	high	medium	medium	relative humidity [%]	relative humidity [%]	low
Fan speed	no	medium	high	low	airflow velocity [m/s] [m^3/s]	airflow velocity [m/s] [m^3/s]	low
Outdoor air portion	no	low	high	low	outdoor air amount/recycled air amount from the whole system [%]	outdoor air amount/recycled air amount from the whole system [%]	medium
Air exchange rate	no	low	high	high	hourly air exchange rate [times per hour]	hourly air exchange rate [times per hour]	**high**
Airflow pattern	yes	low	high	high	none, directly related to the location of supply and exhaust openings and indoor end unit types	none, indirectly illustrated by direct airflow divertion and mixing level of the supply air	**high**
Working hours	no	medium	low	low	hours, tensity	hours, tensity	none
Maintenance	no	medium	medium	low	frequency, maintance scale	frequency, maintance scale	none

Table 4 comparison for parameter system (by author)

The research feasibility analysis is based on the existing ventilation system frame, including VRF HVAC system, mixing ventilation air distribution pattern and none-DCV system (based on the official guideline but achievable in this smart building system). To optimize the existing ventilation condition for a lower corona infection risk, the modelling research mainly focuses on the variants that are of high capital cost efficiency and low renovation time costs.

The prerequisite variant allows certain levels of adjustments but no large innovation. Variants, like temperature and humidity, are directly impacted by the objective feelings from occupants, are impossible for subjective engineering control.

In the engineering design phase, different engineering system directly determines the flexibility and domain of temperature, fan speed, outdoor air portion, air exchange rate and airflow pattern. The indoor humidity is impacted by the engineering system, the supply air temperature and mostly the occupation of that space (human is the main source of indoor humid). While, working hours and maintenance depend more on the building management strategy.

In small shared rooms, the spatial geometry directly impact the air exchange rate and the air flow pattern. The temperature and humidity are the secondary variants based on the air exchange rate and airflow pattern. There are less impacts for temperature and humidity in small rooms than those in large spaces.

The indicators that are consistent in design and evaluation phases can be scaled down to a certain standard domain to see whether the space meets the ventilation requirements for epidemic prevention or not. But the impacts from airflow pattern are complex and can only be indirectly illustrated by the ventilation efficiency, particle removal efficiency and mixing level of room air. Especially, the airflow pattern is effectively impacted by the partial control methods. Further modelling is needy to help understand the its relative impacts on airborne transmission in such small shared rooms.

2.4.2 Variant control for modelling

As the literature discussed above, air exchange rate and airflow pattern are the two variable elements of high worth for further research in modelling. The accessary optimal local engineering method, enhancing the filter standard in the end unit, is an additional method that help achieve a low indoor infection risk and need further discussion about the efficiency in this specific case.

The relationship among variants in ventilation control

As the ventilation levels have already defined in previous studies, there are two levels for ventilation controls: **general** and **partial** levels. In the end unit of the room, the **supply air** form the opening includes primary and recirculated airs. The **primary air** is directly from the air handling unit based on the settled air exchange rate, which is a type of general control. And the **recirculated air** is directly from the room air based on the **recirculation rate** according to the customized indoor condition and a secondary thermal treatment is based on the VRF system setting. The **supply airflow velocity** can determine the supply air path and distribution. The engineering reference for these impacts, for direct controls, are **airflow speed** and **recirculation rate** (by the fan speed level), and for air distribution designs, are **direct supply airflow path through the room** and **the distance between supply and exhaust opening**. For the indoor air distribution, the mixing will be at the **supply opening** and its infectious impacts will be in the **breathing zoom**. After the ventilation design and installation, airflow velocity, air age, CO2 concentration and particle concentration are the main indicator to evaluate the indoor air quality, ventilation efficiency and comfort (like, draught risks). Filter, as effective additional facility, can be applied in any engineering control levels, but faced with different technical problems, and the application of filter in the indoor end unit for air recirculation is the only type this research discussing about. In general, the indexes, **feasibility in practice**, **ventilation efficiency** (including **air change efficiency** and **contaminant removal efficiency**), **infection risk** and **indoor comfort** to evaluate the ventilation renovation quality under COVID-19 crisis. The infection risk is a probability of micro-climate accident. Disregarding the pathologic differences from receptors and ligands, the local virus concentration is the main scalar quantity for the infection risk and also impacted by the ventilation condition. The feasibility in practice includes capital limitation and local codes, and the ventilation strategy will be based on the parameter matrix as shown in the graph. In this research context, the design will focus on the partial reconstruction, which is the air recirculation pattern in the indoor unit, to optimise the air distribution pattern based on the existing ventilation system.

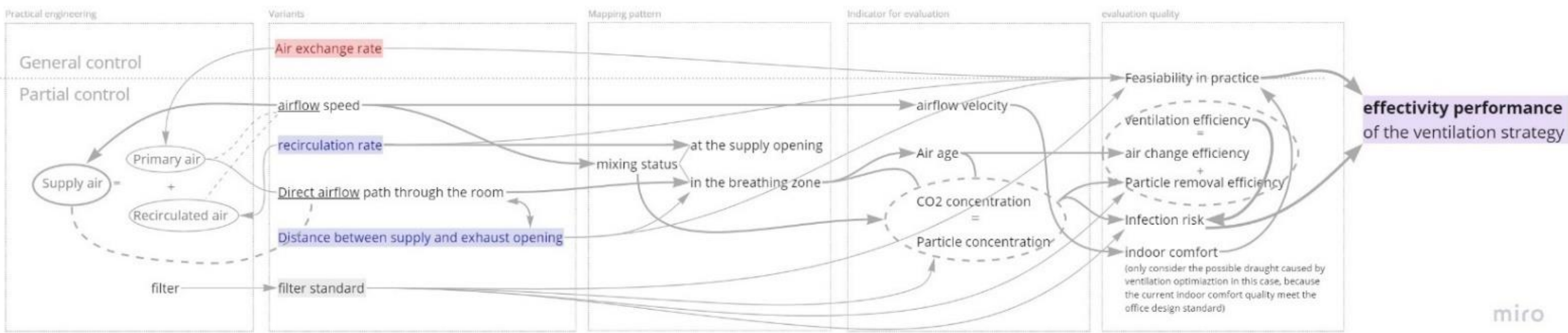


Figure 38 the relationship mapping of the parameters in theoretical ventilation design, infectious disease pathology and practical systematic control (by author).

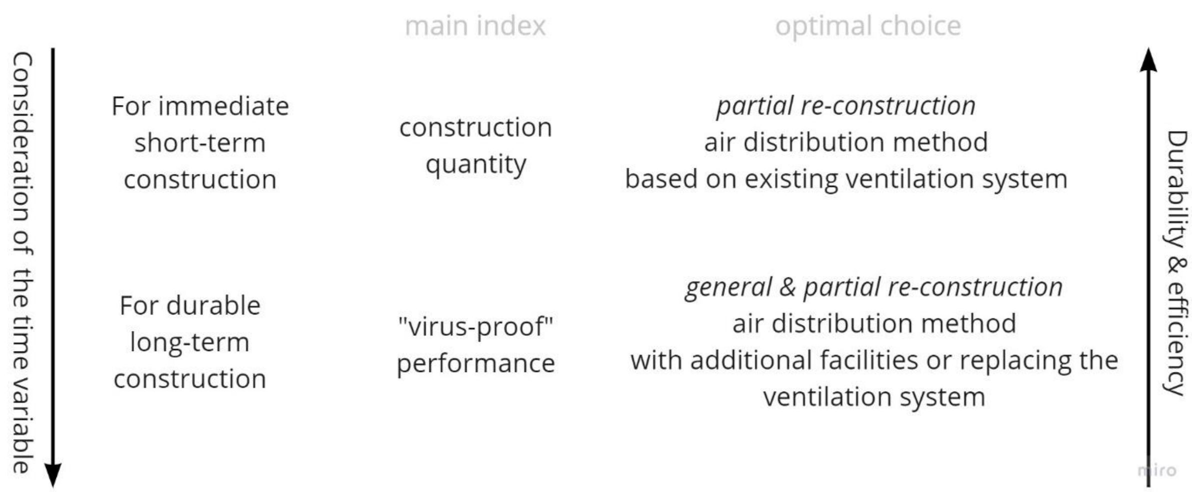


Figure 39 the marketing purposes for hygiene ventilation (by author)

The relationship among different variants in ventilation control

- Airflow pattern

  The variants about airflow pattern under the ceiling supply mixing ventilation air distribution pattern, include the **air recirculation rate**, **supply airflow velocity**, **the distance between the supply opening and the exhaust opening**. The turbulence-level and induction rate are also very relevant parameters, they are related to the air velocity, surface condition and diffuser design. They are the secondary parameter to be looked into and more about detail design level. In this research, they are temporarily avoided for further researches due to the lack of knowledge base and experiment control methods. All these inclusive variants directly impact the mixing status in the room. The mixing level of the room air and primary air at the supply opening and the deviation of ventilation performance for epidemic prevention in general whole space and the local seats consist of the mixing status of the whole room air. The mixing status also shows a deep relationship with the ventilation efficiency, particle removal efficiency and air age, thus, these variable relationships need to be sorted out by the advanced modelling method.

- Filter
  The filter alternative is regarded as an additional method to explore the optimal effective ventilation design. The filter type should not cause obvious pressure differences between both side to ensure the same efficiency of the fan coil unit in the end unit. The filter replacement should not impact the upper engineering level of the building system neither. A higher standard pre-filters for common indoor multi-split air conditioning units would be preferred. Currently, it is M5, to remove 1 um particle, the filter should update to F7 at least.

Classificeringstabel							
PM1		PM2,5		PM10		Coarse	
ISO ePM1 95% ISO ePM1 90% ISO ePM1 85% ISO ePM1 80%	F9	ISO ePM2,5 95% ISO ePM2,5 90% ISO ePM2,5 85% ISO ePM2,5 80% ISO ePM2,5 75% ISO ePM2,5 70% ISO ePM2,5 65%	F7	ISO ePM10 95% ISO ePM10 90% ISO ePM10 85% ISO ePM10 80% ISO ePM10 75% ISO ePM10 70% ISO ePM10 65%	M6	ISO Coarse 95% ISO Coarse 90% ISO Coarse 85% ISO Coarse 80% ISO Coarse 75% ISO Coarse 70% ISO Coarse 65% ISO Coarse 60%	G4
ISO ePM1 75% ISO ePM1 70%	F8						
ISO ePM1 65% ISO ePM1 60% ISO ePM1 55% ISO ePM1 50%	F7	ISO ePM2,5 60% ISO ePM2,5 55% ISO ePM2,5 50%	M6	ISO ePM10 60% ISO ePM10 55% ISO ePM10 50%	M5	ISO Coarse 55% ISO Coarse 50% ISO Coarse 45%	G3
						ISO Coarse 40% ISO Coarse 35% ISO Coarse 30%	G2
Minimaal 50% efficiency-graad in onbehandelde en in ontlade toestand.		Minimaal 50% efficiency-graad in onbehandelde toestand. Geen eis met betrekking tot ontlade toestand.		Minimaal 50% efficiency-graad in onbehandelde toestand. Geen eis met betrekking tot ontlade toestand.		Geen eis met betrekking tot ontlade toestand.	
Fijnfilter		Mediumfilter				Groffilter	

Table 5 the filter classification in the Netherlands (from Kuijpers)

The controlled variants in this modelling

- Air exchange rate
  The **hourly air exchange rate** is an effective indicator that shows a directly positive feedback relationship with ventilation design for epidemic prevention. The higher the hourly air exchange rate, the lower the particle concentration indoors. Because of the requirements of indoor comfort in long-stay spaces and the limits of **mechanical system capacity**, like duct system and fan power, the optimization from hourly air exchange rate has a limit value in different ventilation design.

Figure 40 the central air handling unit type applied in the Kuijpers office, Leiden (from carrier)

25668m3/h

The HVAC system in this study case shows obvious limitation for increasing the hourly air exchange rate from 1.1 to 3 (the recommended value from the guideline). Currently, the indoor air handling unit is the mean air supply unit. The capacity of all the possible products are as shown below:

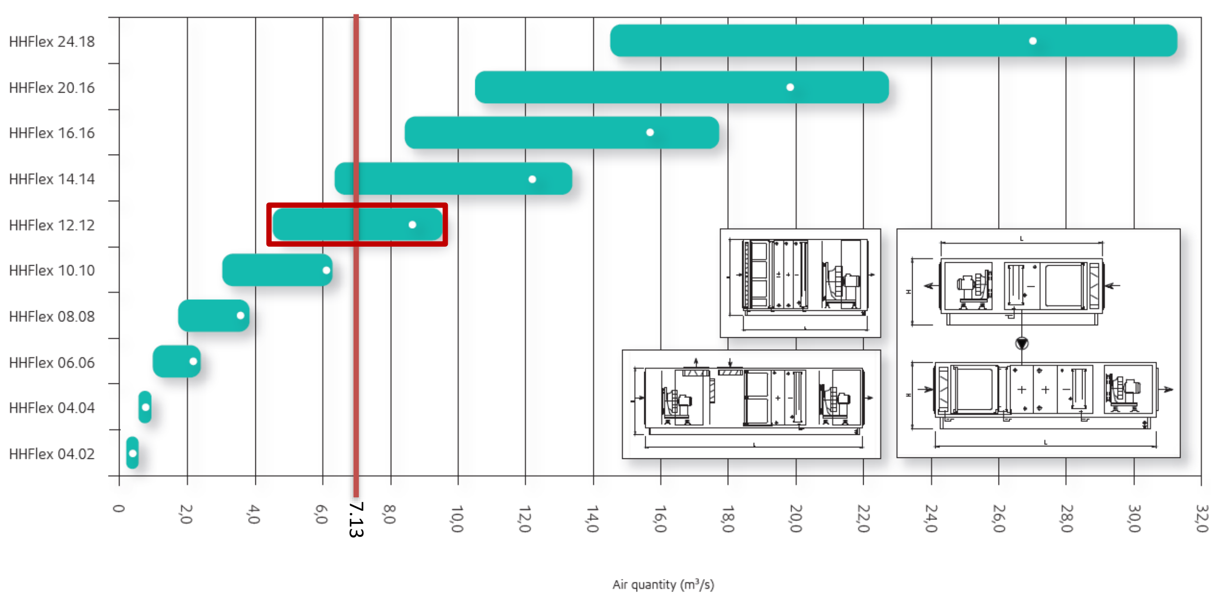


Table 6 Quick selection table of air handling unit for supply (from carrier)

More specifically, the design ventilation power of the air handling unit in the sample building is 7.13 m^3/s, which is Flex 12.12 as shown in the figure. The maximum ventilation would be 1.3 times of the design value, which is 1.4 times per hour in the sample room.
Generally speaking, according to the existing product list for the air handling unit that applied in the building, the design capacity for all the products are about 2 times of the minimum design capacity and the maximum standard design values are the white points. Neither of the differences between maximum and minimum values or the allowable domain for the design value cannot achieve an hourly exchange rate as 3 times per hour for each standard rooms. The air exchange rate in this building can only be maximized to around 1.15 times of the current design value. And the air exchange rate is always recommended to be as high as possible, the maximum design value in this case would be 1.3, which will not cause a large change in airflow rate as those from the recirculated airflow. The maximum alternative domain for the air handling unit of these types in commercial buildings would be 1.15 – 2 times of the design value. The hourly air exchange rate, 1.4, will be applied in the last product design phase, but not in the modelling experiments for this air distribution design discussion. In this experiment, for an obvious comparison, the hourly air exchange is settled as **1.1**, which is the same value as the current existing condition.

- Thermal comfort
  The constant same temperature and relative humidity are to simulate an ideal indoor environment where there is a stabilisation of cooling and heating process. The ventilation may only focus the refresh the indoor air rather than temperature maintenance.
- Off DCV mode
  The opposite results based on particle and CO2 from the on/off air recirculation experiment are caused by the demand control ventilation (DCV). Since the current ventilation is temperature based smart control, once the sensed indoor temperature achieve the required amount, the ventilation will decrease or stop working. When the DCV mode, CO2 concentration will show a higher consistency as the airborne particle concentration, and thus, more reliable for the infection risk analysis from a theoretical-practical perspective. DCV should be off, which is also mention in ventilation guidelines issued ASHRAE, REHVA, ECDC,CCIAQ, PHO.
- Biomass related variants
  Human and pathogen related variants, including the indoor activity, positions, breathing mode and epidemiological transmission pathology would be based on the same research background information that has already applied in many existing researches, to focus on the impacts from ventilation strategy only.

2.4.3 Adaptability of Wells-Riley

Precondition for application of Wells-Riley Model in the scenario

Since having been discussed in the literature study of this report already, there is no direct mathematical method to connect the indoor pathology with the detail ventilation engineering. The Wells-Riley Model is still the most ideal mathematical tool to illustrate the infection risk of a space on general. The methodology applied in this research focus on the optimization by the partial ventilation adjustment on the breathing level, which is of medium spatial and engineering scales, compared to the individual ventilation applied in the micro-climate surrounding a person and the general air exchange rate control for the room as a whole.

To tell the improvement of the alterative in ventilation engineering details, a standard case with an ideal mirror-symmetric ventilation pattern with all the variants same as the existing real case. In this way, under the same variants, the standard case achieve the maximum mixing level of the sample room as the start point of coordinate evaluation axis. Further comparisons of the CO2 concentration of different cases at breathing height with that of the standard case will indicate the changes of local infection risk.

The precondition for Wells-Riley model still being the main reference of infection risks in all experimental cases is that all the cases (including the simulation of the real situation) meet the well-mixing ventilation pattern. Thus, the airborne virus nuclei-laid particle distribution meet the independency and stochasticity required by the Poison model. The distance between the seats is always more than 1.5 m, which promises the airborne transmission scenario and also the independency and stochasticity for independency and stochasticity of an individual in both seat getting infected by the other. In this way, the difference caused by the distribution of infectious and exposed manikins in the room can be ignored. The Figure 41 illustration of the expiratory jet flow in a thermally satisfied environment (F. Liu et al., 2021)Figure 41 shows an upward flow, this means that the exhaled air is warmer than the surrounding air, which suggesting the possible impact of thermal plume.

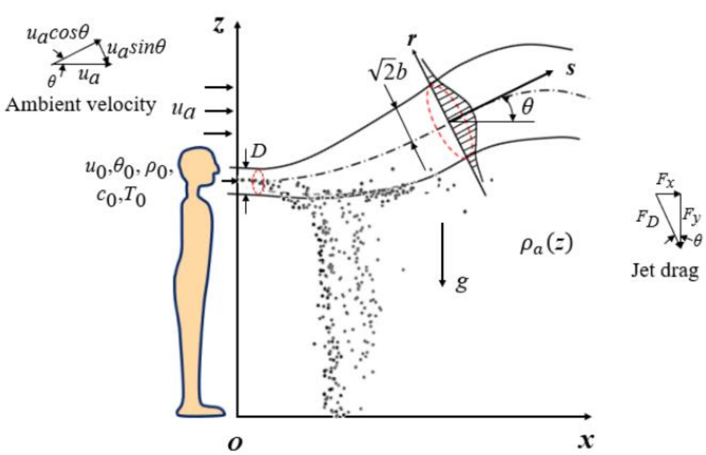


Figure 41 illustration of the expiratory jet flow in a thermally satisfied environment (F. Liu et al., 2021)

The application of Wells-Riley Model

The unavoidable and unremovable difficulties in biomedical science and human-orientated environmental engineering make the commercial ventilation design hard to achieve corona-proof level:

- Biomedical science
  There are two objects in epidemic infectious diseases: receptors and ligands.

For **receptors**, there is *tolerance dose*, a deterministic indicator, for every exposed individual. When an individual receives an intake dose exceeding his/her tolerance dose, that individual will be infected. For different individual, the tolerance dose is different, some can be easily infected even under a low dose, while others may be able to tolerate a high dose.
For **ligands**, in this case, which is COVID-19 virus, there is threshold dose, a minimum amount of pathogens required to initiate infection, based on the pathological characteristics. When a population intakes a dose lower than the threshold dose, none of the individuals would acquire the infection, which means the risk is zero even there is already virus under certain amount existing in the space.

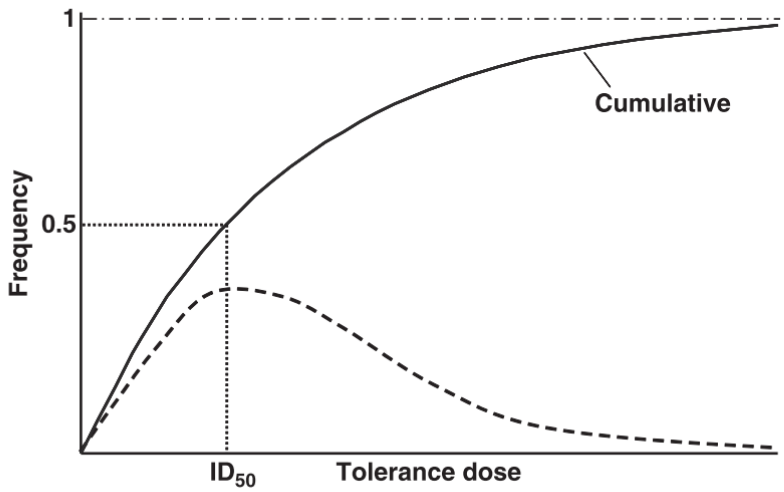


Figure 42 An illustration of the frequency distribution of the tolerance dose (from (Sze To & Chao, 2010)*)*

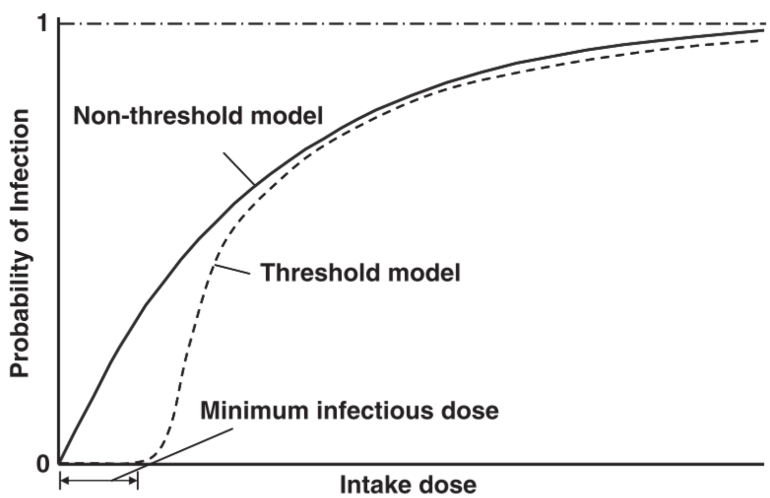


Fig. 2 An illustration of the difference between a non-threshold model and a threshold model

Figure 43 An illustration of the difference between a non-threshold model and a threshold model (from (Sze To & Chao, 2010)*)*

- Environmental engineering

There are two natures of engineering cannot be ignored: design precision and mechanical limitation.

For design precision, different environments requires for different design precision. Construction, a part of social production behaviours, based on the user needs, puts the capital return rate as the priority. Cleanrooms are of the highest ventilation standard, commercial buildings for healthy public, like offices and supermarkets, are of the lowest ventilation standard. The general engineering design can be optimized to pay more attention on the hygiene quality after the corona crisis, but can hardly shift to another level according to the building's attributes about the commercial productivity and indoor comfort. The optimization of the partial design is usually effective and of high capital return for those low ventilation standard building till a certain precision. Over that design precision, further partial alternative will be inefficient in ventilation performance and expensive in capital costs. The extreme cases for high ventilation standard design would be cleanrooms, operation rooms and toilets.

For mechanical limitation, as previously discussed in virus removal engineering methods (see Table 2), though there is different efficiency in different engineering methods, none of them can promise a 100% virus removal rate.

Wells-Riley model is applied is the important analysis method to connect the biomedical science and environmental engineering. Wells (1955) proposed a hypothetical infectious dose unit: the quantum of infection. A quantum is defined as the number of infectious airborne particles required to infect the person and may consist of one or more airborne particles. These particles are assumed to be randomly distributed throughout the air of confined spaces. Riley et al. (1978) considered the intake dose of airborne pathogens in terms of the number of quanta to evaluate the probability of escaping the infection as a modification of the Reed-Frost equation (Abbey, 1952). Together with the Poisson probability distribution describing the randomly distributed discrete infectious particles in the air, the Wells–Riley equation was derived as follows:

$$P_I = \frac{C}{S} = 1 - \exp\left(-\frac{Iqpt}{Q}\right)$$

Equation 1 Wells Riley calculation formula

where PI is the probability of infection, C is the number of infection cases, S is the number of susceptible, I is the number of infectors, p is the pulmonary ventilation rate of a person, q is the quanta generation rate, t is the exposure time interval, and Q is the room ventilation rate with clean air. The quanta generation rate, q, cannot be directly obtained, but estimated epidemiologically from an outbreak case where the attack rate of the disease during the outbreak is substituted into PI. If the exposure time and ventilation rate are known, the quanta generation rate of the disease can be calculated from Equation

Constant value in Wells-Riley model

In the calculation of the infection risk of COVID-19, the q and the p are the two constants that need to be settled as a base for the whole research. According to the methodology of a number of existing researches, the **q** is chosen as **25 quanta/h** and the **p** is **0.5 m3/h** for this research:

- Quanta generation rate, "q"
  So far, there have been no available literatures reported the quantum generation rate (q) of COVID-19. To obtain a reasonable quantum generation rate of COVID-19 for applying the Wells–Riley equation, we collected the known quantum generation rate (q) and basic reproductive number (R0) for other airborne transmitted infectious diseases in previous studies, and fitted the association between q and R0. Then we estimated q with R0 of the COVID-19 based on the fitted equation. The basic reproductive number is the key epidemiological determinant that characterizes the transmission potential of a certain infectious disease, which is defined as the average number of infectious individuals created by a single infectious person in a completely susceptible population. As basic reproductive number essentially determines the rate of spread of an epidemic, thus we think it may be logical and reasonable to obtain quantum generation rate based on its association with basic reproductive number. Table 7 lists the values of q and R0 for several typical infectious diseases collected from references. With the values listed in this table as inputs, we fitted the association between q and R0 with a least square method implemented in Origin 2019.

	***q*(/h)**	***R_0***
Tuberculosis	1-50 [10]	2.22-5.46 [11]
MERS	6-140 [10]	<1(1.0-5.7) [12]
SARS	10-300 [10]	2-5 [13]
Influenza	15-500 [10]	1.6-3.0 [14]
Measles	570-5600 [10]	11-18 [15]

Table 7 q and R0 of airborne transmitted infectious diseases (from (Dai & Zhao, 2020)*)*

The fitted curve representing the association between q and R0 is shown in Figure 44, and the fitted equation is

$$q = A + B_1 * R_0 + B_2 * R_0^2$$

where A= -26.06428±68.60109, B1= -0.61896±29.44301, B2=17.40102±1.46132. With the widely used range of R0 of 2-2.5, we obtained the corresponding range of q for COVID-19, which is 14 - 48/h. In the model, q is chosen as 25/h.

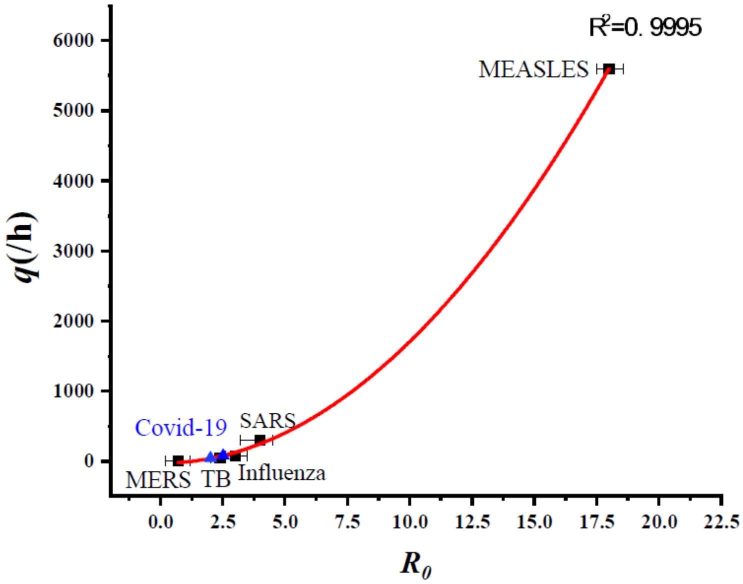


Figure 44 The fitted curve between q and R0 (from (Dai & Zhao, 2020)*)*

- Pulmonary ventilation rate of a person, "p"

The breathing volume is 0.5m3/h, which is the minimum volume of respiratory modes. This value is for an oral breathing when resting.

Description of the exposure scenarios tested in the prospective assessment.

	Scenario A	Scenario B	Scenario C	Scenario D
Type of indoor environment	Hospital room	Gym	Public indoor environments (e.g. restaurant, bank)	Conference room or auditorium
Emitting subject	Patient (Resting, oral breathing; IR = 0.49 $m^3 h^{-1}$)	Exercising person (heavy exercise, oral breathing; IR = 3.30 $m^3 h^{-1}$)	Speaking person (light exercise, voiced counting; IR = 1.38 $m^3 h^{-1}$)	Singer or conference loud speaker (light exercise, unmodulated vocalization; IR = 1.38 $m^3 h^{-1}$)
Exposed subject	A-1. Medical staff (light exercise; IR = 1.38 $m^3 h^{-1}$) A-2. Patient (resting; IR = 0.49 $m^3 h^{-1}$)	Exercising person (heavy exercise; IR = 3.30 $m^3 h^{-1}$)	Speaking person (light exercise; IR = 1.38 $m^3 h^{-1}$)	Spectator (sedentary activity; IR = 0.54 $m^3 h^{-1}$)
Volume (m^3)	100	300	300	800
Ventilation, AER (h^{-1})	• Natural ventilation 0.5 h^{-1}, • Mechanical ventilation 3 h^{-1}, • Mechanical ventilation 10 h^{-1}			
Deposition rate, k (h^{-1})	0.24			
Inactivation rate, λ (h^{-1})	0.63			

Table 8 Description of the exposure scenarios tested in the prospective assessment (from (Buonanno et al., 2020)*)*

"Acceptable" infection risk for engineering design

The practical ventilation strategy to control the airborne transmission of corona virus will be based on an acceptable risk level. Recent researches that discussed a possible design value of individual infection risk referred to different resources.

- Existing guidelines of infection risk control for other diseases
  The US Environmental Protection Agency (EPA) typically uses a target reference risk range of 10−4 to 10−6 for carcinogens in drinking water (Cotruvo, 1988), which is in line with World Health Organization (WHO) guidelines for drinking water quality, which base guideline values

for genotoxic carcinogens on the upper bound estimate of an excess lifetime cancer risk of 10−5 (World Health Organization, 2011). If the estimated lifetime cancer risk (whose death rate is 8% - 90% in UK, https://www.nuffieldtrust.org.uk/resource/cancer-survival-rates#background) is lower than 10−6, the risk is considered acceptable, while risks above 10−4 are considered unacceptable (Toner, 2008).

Based on the mortality rate of COVID-19 (1.4% in NL, Coronavirus Death Rate (COVID-19)) the research chooses two lower orders of magnitude than that of carcinogenic diseases, which is 1%.

- Extensive research database on situation of US schools

  (Y. Xu et al., 2021) takes the value of 1% as the acceptable risk reference for SARS-CoV-2 after the evaluation on one-year corona pandemic scenario in 111,485 U.S. schools (Kissler et al., 2020). Under the current epidemiological scenario, more than 90% of counties exhibit an infection risk of greater than 1%, indicating the significance of implementing intervention strategies to decrease the infection risk.

  The further feasibility research of (Y. Xu et al., 2021) proves that the infection risk lower than 1% can be achieved by increasing the ventilation rate by 100%, having half of students learn online and replacing with MERV 13 filters (not applicable for all schools).

- Mathematical logics of quantitative evaluation

  According to the mathematical logic conjecture from (Buonanno et al., 2020), the acceptable infection risk is based on the design capacity. The assumed design capacity is 1000 people from (Buonanno et al., 2020), and the acceptable risk is calculated as 0.1%. The further feasibility research of (Buonanno et al., 2020) proves that there is no possibility to achieve such low infection risk in any practical ventilation strategy even in large public space of a standard occupation condition.

  For the purpose of managing an epidemic and keeping the infection under control, it is also important to estimate the basic reproduction number of the infection, R0, which is calculated as the ratio between the number of susceptible people infected (C) and the infected subject (I). Thus, R0 can be easily evaluated by multiplying the individual infection risk, R, by the number of exposed susceptible individuals (S). To control an epidemic, the R0 value must be <1. Therefore, in addition to estimating an acceptable individual infection risk, it is necessary to specifically verify that, with the crowding expected within the environment, the corresponding value of R0 is <1. In view of this, adopting an acceptable contagion risk (Rmax) 50%, would results in a R0≤1 when up to 2 persons gather in the same closed environment. But, 50% is a high risk in any condition, so this infection risk is not an acceptable risk under all situations.

- Building survey in the Netherlands

  Based on the building survey and the duration measurement, the probability of contamination for the various rooms has been estimated. The results are shown in Table 3. The individual aerosol contamination probability (assuming I=1, or the scenario where one of the persons present happens to be infectious) is characterised as 'low' (coloured 'Green') when the probability does not exceed 5%. This is a standard percentage that is used by various engineering agencies as a limit value; a formal limit value for this (e.g. described in a standard) does not yet exist. In the case of a risk group (older target group), a stricter limit value of 1%

may be used. If the individual contamination rate is between 5 and 20%, an 'increased contamination rate' (colour coding: 'Yellow') is assigned. If the calculated individual contamination rate is higher than 20%, there is a clearly increased risk (colour coding: 'Red'). In a corona risk analysis of a Dutch church, the individual theoretical probability of contamination in the large church hall for a gathering of 1.5 hours where one third of the time is spent singing is around 5%. When singing for a shorter period of time (one sixth of the time) or without singing, this theoretical contamination probability drops to 2% and <1% respectively. In the sample room, the users are communicating in most cases. Thus, the acceptable infection risk is 5% for the communication cases, and 1% for non-communication cases.

In conclusion, the bottom line for the acceptable infection value would be 1%. For a higher ventilation design goal, the optimized ventilation strategy with a lower infection risk lower than 1%, can be regarded as an feasible ventilation strategy that achieve the optimization goal.

2.5 Practical advanced ventilation design study

The ventilation design for public building with special purposes, like hospitals and cleanrooms, emphasize the ventilation efficiency and local pollutant concentration control. There is no specific ventilation design looking into the “corona-proof” ventilation yet. The study of the practical advanced ventilation design would be as the reference for the commercial hygiene ventilation design.

2.5.1 Literature study of cleanroom design principle

The principle to interrupt the airborne transmission of respiratory infectious diseases:

- Isolating the particle sources
- Cutting off the transmission paths
- Protecting the target subjects, in this case, healthy people

In cleanrooms, the principles for ventilation design are:

- *identify the source of the target particle and extract it in time*
- *avoid working areas in the shadow of the wind (see* Figure 44*)*
- *rejection of direct indoor return air*
- *local high air velocity flushing to improve local cleanliness*
- *visual air cleanliness monitoring*
- *creation of air curtain walls to block particle sources*
- *control of uncontrollable variables - people: fixed movement flow lines, prescribed high coverage clothing, same entry and exit times (reducing the possibility of contamination of clean spaces by non-clean areas)*
- *application of clean technology in HVAC air circulation systems*

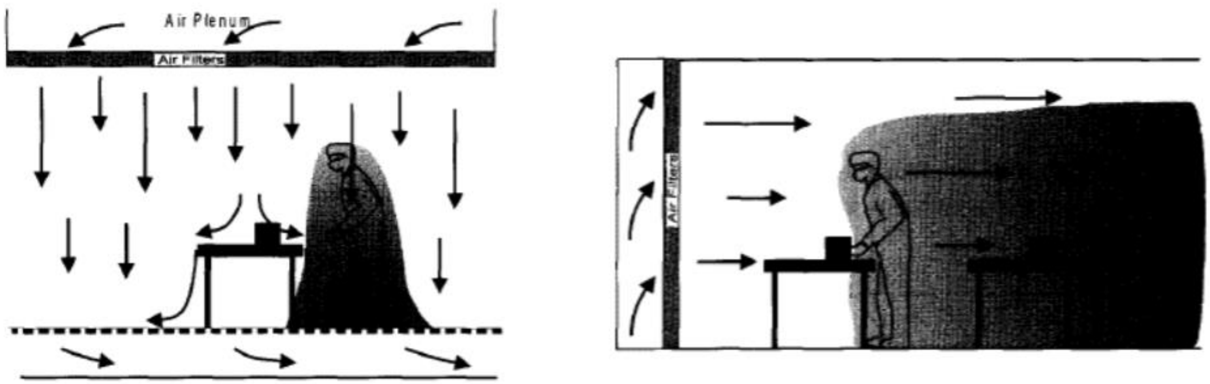


Figure 45 ventilation shadow (from (Z. Xu, 2013)*)*

Based on the one-direction ventilation airflow, setting low-height exhaust opening to effectively avoid the wind shadow.

In cleanroom design, the techniques are system self-cleaning, creating partial clean zone, single ventilation air flow direction for the whole space to create highly efficient irrigation and dilution and strict graded filtration systems.

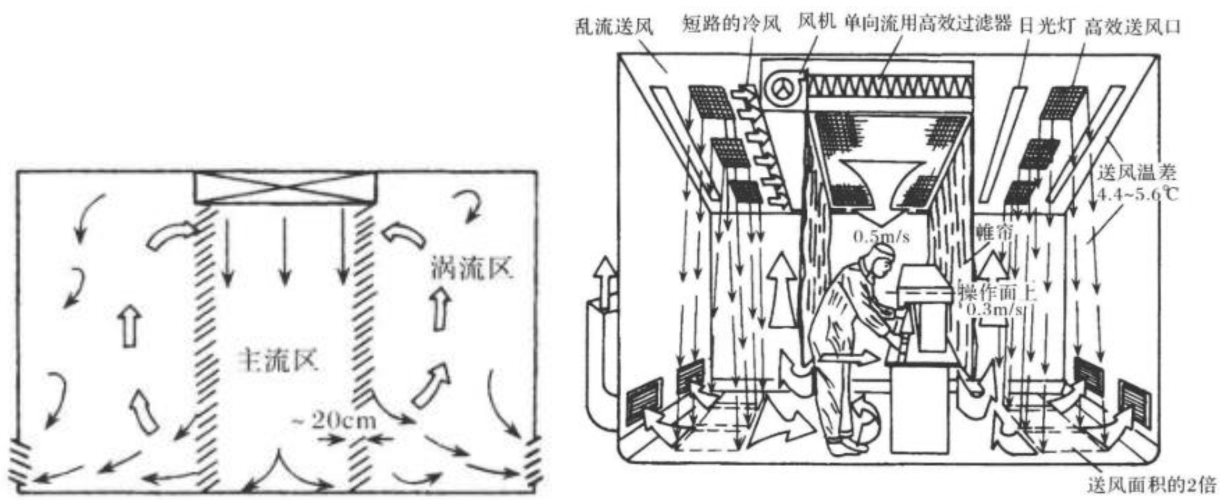


Figure 46 cleanroom ventilation design principle (from (Z. Xu, 2013)*)*

Thus, the supply opening should always locate at the most closed area (normally in the centre of the room) to the working area and can provide the direct airflow to the breathing openings of users.

2.5.2 On-site excursion of cleanroom assemble

During the internship in the cleanroom ventilation system design and installation of Kuijpers, the ventilation, especially partial system, including the indoor end units, end control panel and openings, are prefabricated and fast installed on site. The cleanroom ventilation construction elements are based on the standard dimension design with extra consideration of trails and cavity. The prefabricated components can be installed on the construction site by dry processing. The building information management of the construction process can be precisely controlled by the high-integration workflow.

Figure 47 The construction site of cleanroom ventilation system installation from Kuijpers (photo by the author)

Based on the ventilation system construction modular element design and installation process, the partial ventilation system control for the practical applications only need to pay special attention to the opening locations, indoor end unit location and their integration with the internal construction element prefabrications. Inspired by the installation of the ventilation system in cleanrooms, efficient ventilation openings in the vertical direction using **assembled cavity walls** to adjust the distance between opening with high design flexibility for the hygiene ventilation strategy.

3. Experiments

As one of the three research methods in this project, experiments, including pre-phase experiment and exploring-phase experiment.

The first experiment (chapter 3.1) is to analyse the current ventilation condition and the mechanical principles in the sample office and explore a possible solution for future epidemic prevention product design. There are two initial elements in the experiment: building system and users. The possible interaction among these two elements and their impacts for the whole space is also worthy looking into for the variant control in the further experiments and reasonable parameter setting in CFD modelling.

The second experiment (chapter 3.2) is to analyse the current ventilation condition and the mechanical principles in the office sample, to explore the effect of the air recirculation mode in the multi-split indoor unit on airborne particle in the sample space.

The third experiment (chapter 3.3) is to check the realities of design in practical application scenarios.

The forth experiment (chapter 3.4) is an additional test for the third experiment to quantify the experiment objects, the respiratory airflow and rough filter cloth, in particle number per minute, for the further check of deviation from computational design case and realistic installation.

The fifth experiment (chapter 3.5) is to further explore the possible renovation ventilation product integrated with ESP purifier. The possible problems about the pressure drop during installation is discussed. And further notification for achieving the conceptual ventilation strategy in the realistic built environment has been clarified also.

	phase	**times**	duration per time	**content**	**results**	**additional**
1	current situation evaluation	1	7 days	current indoor air quality due to the building system & ventilation system	working hours of building system, existing air recirculation, temperatured sensor based	
2	secondary pollution analysis	4	5 hour	ON / OFF air return openings for air recirculation	when off air recirculation, longer responding time, higher peak point, longer peak monments. NO SECONDARY POLLUTION RISK. Positive role in hygiene ventilation design.	1. longer responding time --> intenser responding (higher ACH) 2. limitation of the application of CO2, high expandability.
3	design testing	2	6 hour	before / after the instullation of design	the design works as expexted	1. the high applicability of CO2 as the tracer gas, the initial starting value. 2.ventilation enlarges local air recirculation and decreases the ACH

						for heating purpose in winter
4	filter qualification	3	1 hour	before / after the filter & instant short-distance	filter performance of 37%, the pressure drop: breathing airfklow velocity drops to almost still level	

There are two parameters for the experiments: CO2 and particle. CO2 is widely applied for the indoor air quality sensors. Particle is for precise ventilation quality control (detail see Table 16, Table 22 and Table 24). The 0.3 um particle is the minimal particle size that the particle meter can count. Since the virus nuclei laid airborne particle size is a domain from 0.1 – 0.5 um (see chapter 2.1.2), 0.3 um particle is regarded as the average-size airborne particle for this research.

3.1 Experiment about the current situation

The experiment is a part of the graduate research process at the start point to understand the performance of the whole building system and detect the possible problems for current ventilation situations in the office meeting room under the topic about the indoor airborne transmission of infectious diseases, like COVID -19. This experiment is to explore the building engineering control on the general level and the common variants when doing the commercial building engineering control for indoor air quality.

3.1.1 Background

During the COVID-19 crisis, the indoor public spaces usually show a high infection rates. And the shared places are the first places to be locked down or being subject to strict access restrictions. Ventilation, as the most effective method for the indoor air quality control on the general level. And the ACH (air change rate) has been proved as an obvious controllable method to directly decrease the indoor infectious rate.

Therefore the research question for this experiment is:

How the ventilation system working in the standard Dutch offices as for epidemic prevention measures?

To answer the above main question, the following sub-questions were defined to proceed with the research:

1. What is the working logics of the current ventilation system in the sample building, Haagse Schouwweg 6, Leiden?
2. What is the current ventilation condition in the sample meeting room of Kuipers Leiden?
3. What is the interaction between general ventilation control and local ventilation efficiency?
4. What is the potential in the existing ventilation for the epidemic prevention methods?

3.1.2 Methodology

a. Equipment

The experiment is based on quantitative analysis. A series of measurement were done on the two levels separately – breathing zone at 1.1 m to the floor and exhaust grills at ceiling level. The indoor air quality and other indoor comfort are evaluated by CO2 concentration, temperature, humidity, local air speed and volume level.

For different parameters, the equipment applied for the experiment are CO2 sensors and sound level meter:

	parameter	type	Measurement Range	Accuracy	reference
Indoor air quality	CO2 concentration	HOBO CO2 logger	from 0 to 5000 ppm	±50 ppm or ±5 % at 25°C	https://www.onsetcomp.com/
Indoor comfort	temperature		from 0° to 50°C	± 0.35°C	https://www.onsetcomp.com/
	humidity		from 10% to 90 % RH	± 2.5 %	https://www.onsetcomp.com/
	Draught risk	Air flow speed sensor TSI model 9535	From 0 to 6000 ft/s	±3% of reading or ±3 ft/min (0.05 m/s) (whichever is greater)	https://tsi.com/getmedia/55fef147-7c6f-4057-9ff6-d6ec02d03486/9535A-VelociCalc-1980563-web?ext=.pdf
	Acoustic	Integrating-averaging Sound Level Meter and Spectrum Analyser	30 to 140 dB peak	0.5 dB	https://download.cesva.com/datasheets/sc160_en.pdf

		CESVA SC160			

Table 9 equipment information for experiment about current situation (by author)

Figure 48 the photo of HOBO CO2 logger (from https://www.onsetcomp.com/)

b. Execution plan

Based on the observation from pre-phase experiments, there are a lot of variants to be controlled for a relatively same utilization scene and building system performance.

The possible variants are:

variant		**setting**
human related	occupant number	0, 1, 2
	occupant position	position 1 & 3, 1, 3 (when there is only one occupant)
	activity	sitting & communicating
building system related	working mode	auto
	working performance	fully conducting, half conducting, rest
	working hours	24 hours including weekdays and weekends

Table 10 possible variants in the current situation (by author)

Because of the unsure possible variants to control, the execution will be held in more than one week:

no.	parameter					experiment time			equipement & measuring point				occupant number	sitting position		is it in full working mode?	remarks
	CO_2	T	humidity	airflow velocity	volumn level	start time	end time	duration [h]	HOBO CO2 logger		airflow velocity sensor	dB(A) meter		1	3		
1	√	√	√			23/04/2021 18:30	23/04/2021 21:00	2.5	front	back			2	√	√	no	
2	√	√	√			23/04/2021 21:00	26/04/2021 09:00	60	supply	exhaust			0			no	the primary purpose is to check the impacts caused by human.
3	√	√	√			26/04/2021 09:20	26/04/2021 17:20	8	supply	exhaust			1	√		yes	
4	√	√	√			26/04/2021 17:30	27/04/2021 11:00	17.5	supply	exhaust			0			no	
5	√	√	√			27/04/2021 11:30	27/04/2021 17:30	6	front	back			1	√		yes	
6	√	√	√			27/04/2021 17:30	28/04/2021 09:30	16	front	back			0			no	
7	√	√	√			07/05/2021 19:30	07/05/2021 21:30	2	front	back			1		√	yes	
8					√	23/04/2021 18:30	23/04/2021 19:30	1				front	2	√	√	no	peak values when the unit was on working peak is recorded
9					√	23/04/2021 20:00	23/04/2021 21:00	1				back	2	√	√	no	
10				√		30/04/2021 20:50	30/04/2021 22:50	2			supply opening		0			no	these two experiments are for a comparison of ACH calculated by supply airflow velocity under different working performances
11				√		03/05/2021 08:40	03/05/2021 10:30	1.83			supply opening		0			yes	
12				√		03/05/2021 11:55	03/05/2021 12:05	0.17			position 1, z		0			yes	this series of experiments is to evaluate the possible draught, so the measurements are located at the sitting positions
13				√		03/05/2021 12:05	03/05/2021 12:15	0.17			position 1, x		0			yes	
14				√		03/05/2021 12:55	03/05/2021 13:05	0.17			position 1, y		0			yes	
15				√		03/05/2021 13:05	03/05/2021 13:15	0.17			position 2, y		0			yes	
16				√		03/05/2021 13:15	03/05/2021 13:25	0.17			position 2, z		0			yes	
17				√		03/05/2021 13:25	03/05/2021 13:35	0.17			position 2, x		0			yes	
18				√		03/05/2021 13:45	03/05/2021 13:55	0.17			position 3, x		0			yes	
19				√		03/05/2021 13:55	03/05/2021 14:05	0.17			position 3, z		0			yes	
20				√		03/05/2021 14:10	03/05/2021 14:20	0.17			position 3, y		0			yes	
21				√		03/05/2021 14:20	03/05/2021 14:30	0.17			position 4, y		0			yes	
22				√		03/05/2021 14:35	03/05/2021 14:45	0.17			position 4, x		0			yes	
23				√		03/05/2021 14:45	03/05/2021 14:55	0.17			position 4, z		0			yes	

Table 11 the excursion plan of the experiment about the current situation (by author)

There are 2 measuring levels and 6 measuring points in this series of experiments (see Figure 49 and Table 12). Where to measure:

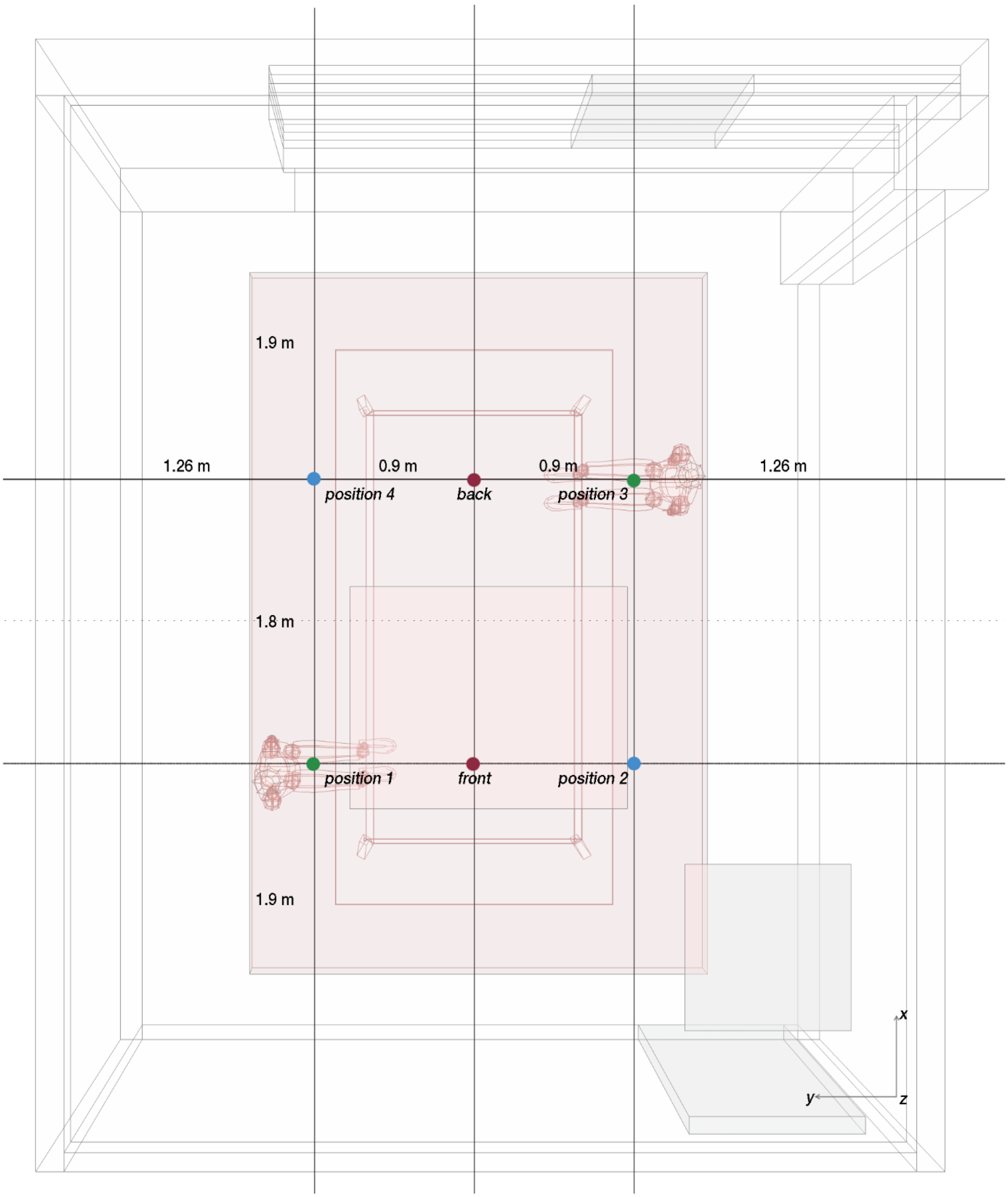


Figure 49 user positions and equipment locations (by author)

	Observation level	height(z)	location(x,y)
Sample point - front	breathing zone	1.1m from floor	(2.2, 2.26)

Sample point - back	breathing zone	1.1m from floor	(3.4, 2.26)
One of the supply opening (all the supply air for the room will go through this opening)	Exactly at the ceiling level	2.8m from floor	(1.9 , 1.76)
exhaust opening (all the exhaust air from the room will go through this opening)	Above ceiling level	Nearly half a meter above the ceiling (the modelling level)	(1.2 , 0)
Sitting position 1	breathing zone	1.1m from floor	(1.9 , 3.06)
Sitting position 2	breathing zone	1.1m from floor	(1.9 , 1.26)
Sitting position 3	breathing zone	1.1m from floor	(3.7 , 1.26)
Sitting position 4	breathing zone	1.1m from floor	(3.7 , 3.06)

Table 12 details of measurement points (by author)

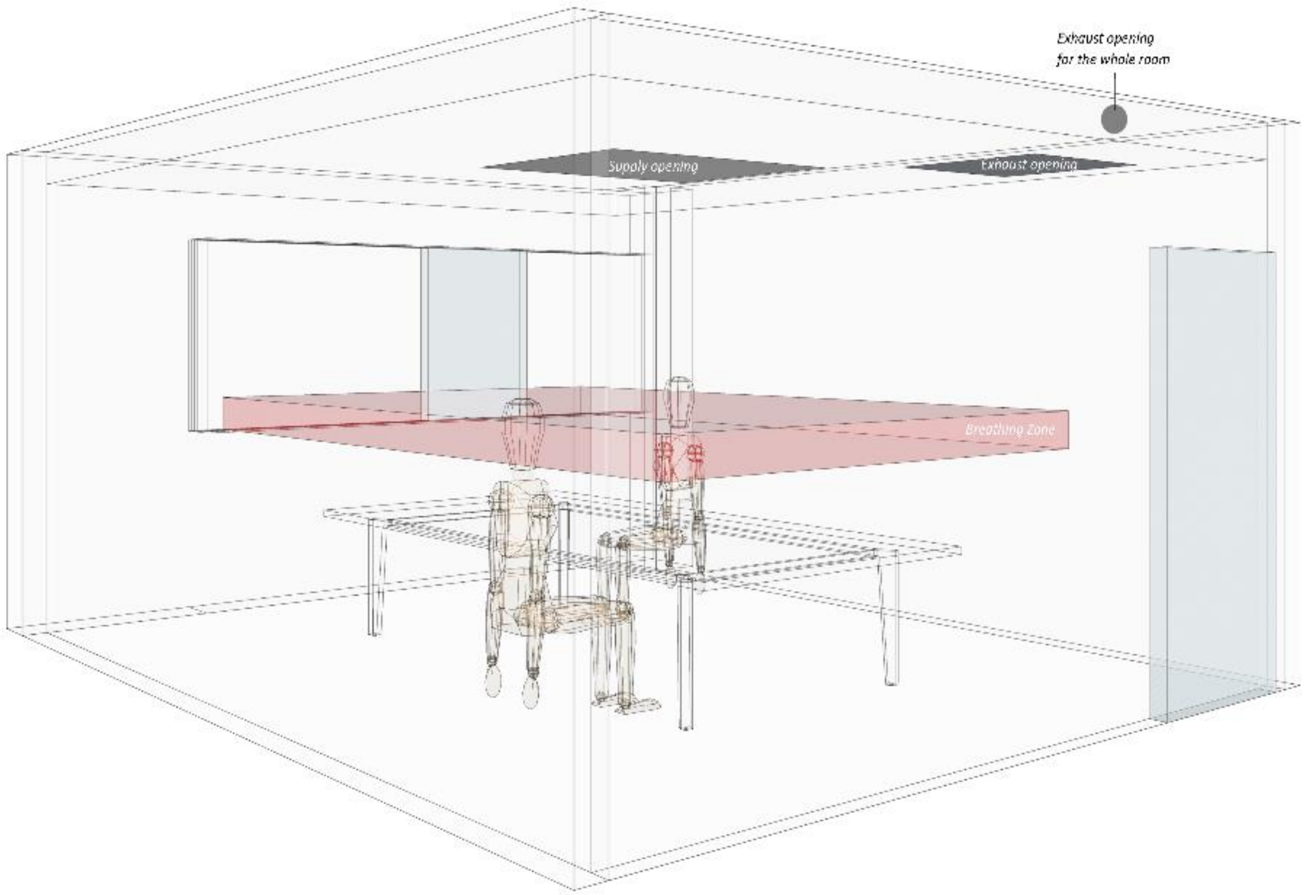


Figure 50 the perspective of the experiment site (by author)

3.1.3 Results and analysis

a. CO2 concentration

- Two occupants:

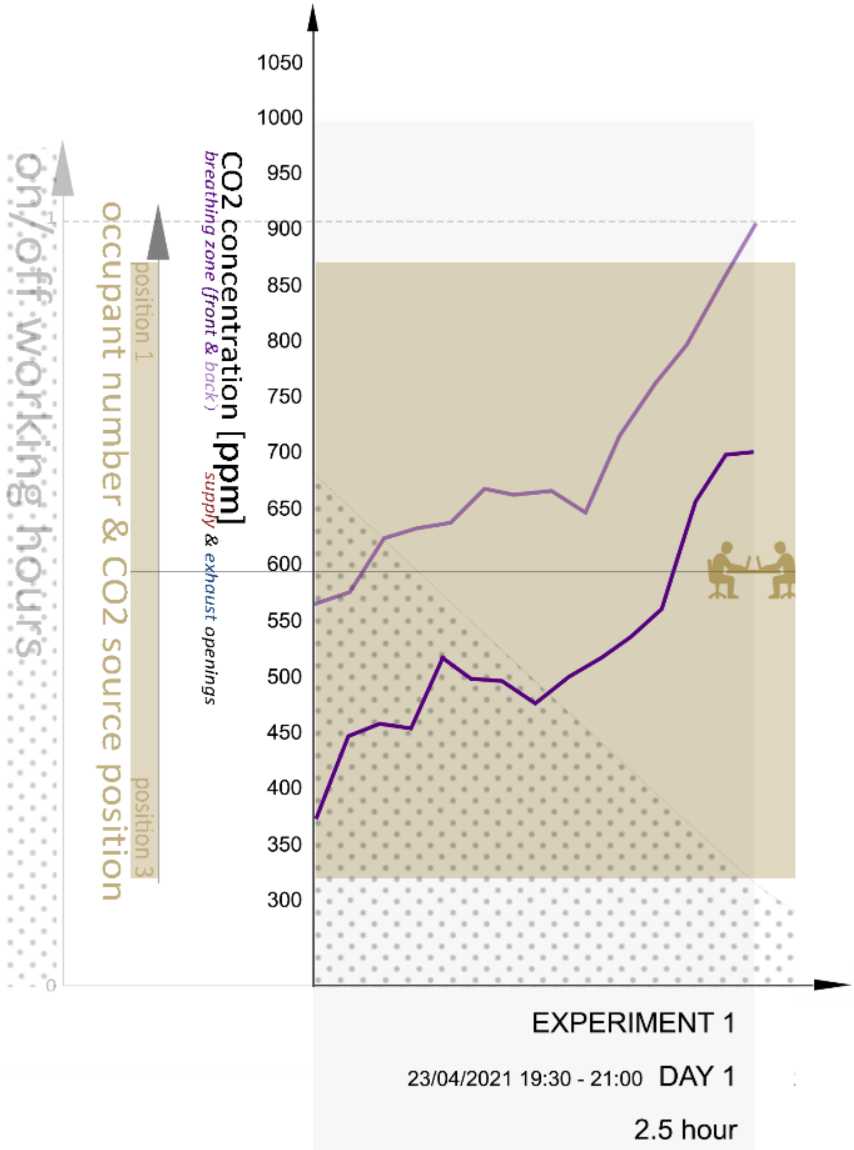


Figure 51 scenario 1 of experiment about current situation (by author)

The whole experiment is set up in a small confined shared space. The two occupants in this space would be the minimum requirement and totally meet the safe social distance requirement during COVID-19 time. There was already a quite obvious difference between the two measurement points. As shown in the fig, the deep purple is the sample "front" point directly under the supply opening, whose value is always lower than that of the one further to the supply opening, the "back" sample point. The CO2 concentration difference is nearly 200 ppm all the time, which predict the different local ventilation efficiencies from place to place.

- Different sitting positions of one occupant:

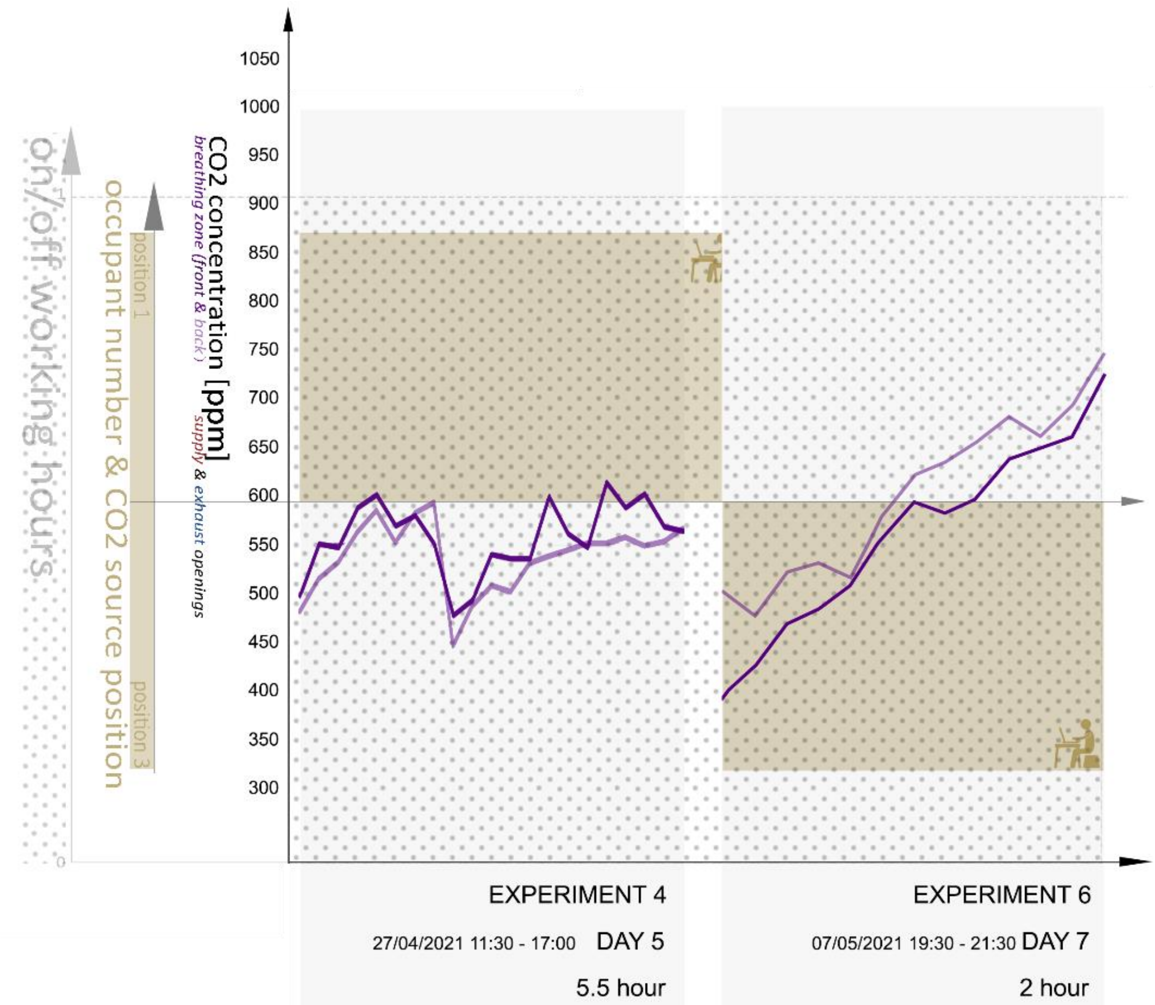


Figure 52 scenario 2 for one user in two positions in fully working mode of experiment about current situation metered in breathing zone (by author)

There are two seats provided to the only one occupant in this experiment under the full working performance of the HVAC system. When the occupant sitting in the front of the room which is directly under the supply opening, there is a delay between the two interlaced data lines because of impacts from mixing ventilation. When the occupant sitting in the back of the room which is a location with relatively worse ventilation efficiency, the delay is still there and the data line of “back” sample point is always with higher CO2 concentration value than that of the “front” sample point. Compared to when the occupant sitting in a better-ventilated location, when the occupant was sitting in the back of the room, the CO2 concentration at the both of sample points can achieve a higher value.

- On or off full working performance of the HVAC system

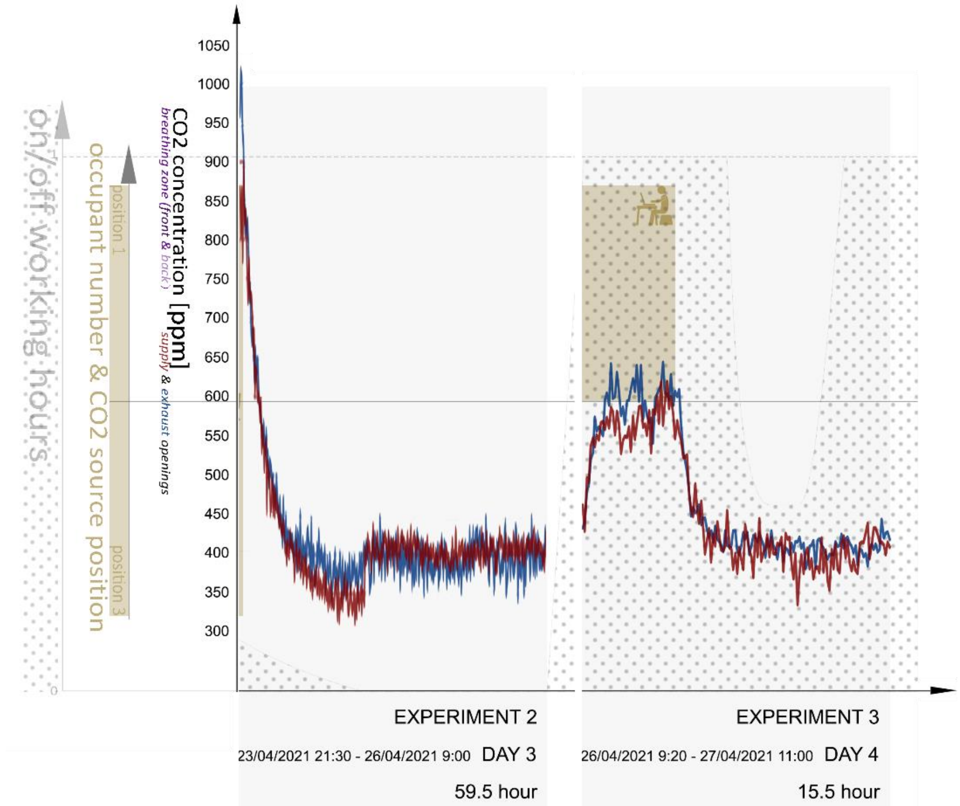


Figure 53 scenario 2 for one user in two positions in fully working mode of experiment about current situation metered in breathing zone (by author)

There are almost the same peak values and trends in both the CO2 concentration of exhaust and supply openings, though there is an obvious delay of the CO2 concentration in the supply opening behind the exhaust opening.

After the room having been occupied for 3 hours, the CO2 concentration fell back to the non-occupation value after nearly 24 hours under the resting working performance (during weekends). While under the full working performance, though there is only one person in the room for 8 hours, the room can achieve a steady state at the end of that experiment and the falling speed of the CO2 concentration is much higher than that under the resting working mode, which means the mechanical ventilation takes a decisive role in indoor air quality control. The Figure 54 below also tells the same story that the mechanical ventilation conquer the indoor CO2 concentration changes.

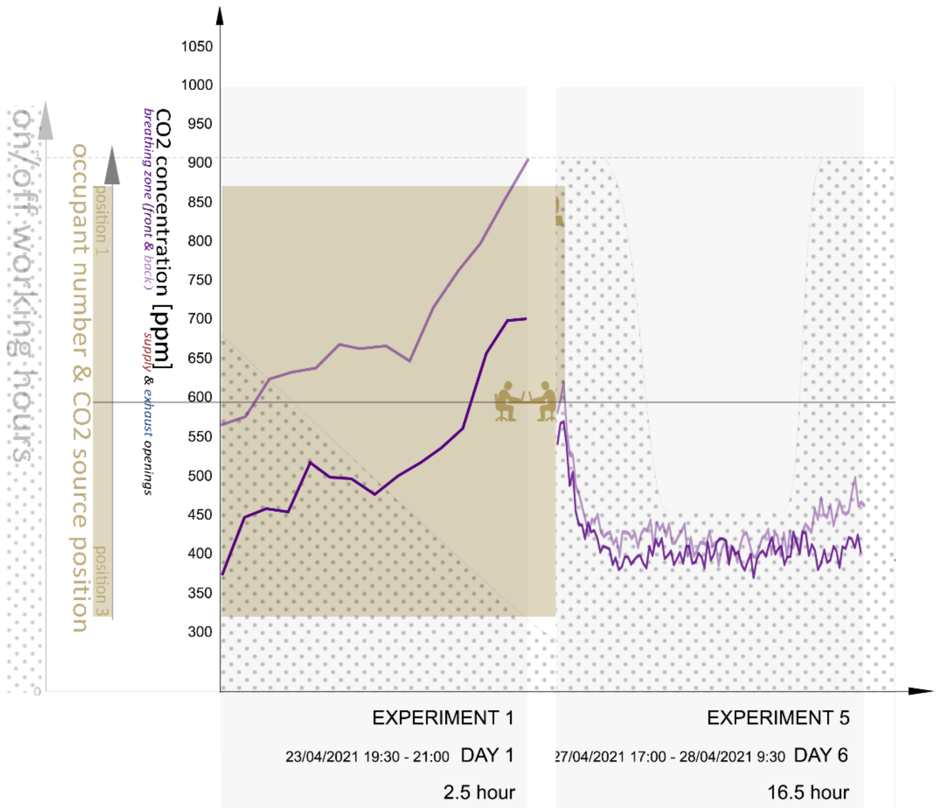


Figure 54 scenario 2 for one user in two positions in fully working mode of experiment about current situation metered in breathing zone (by author)

b. Air flow velocity under the full working mode and no occupant indoors

position	measured average value during full working hours of HVAC system [m/s]			calculated result [m/s]
	x	y	z	all directions
1	0.08	0.03	0.05	0.10
2	0.05	0.08	0.04	0.10
3	0.01	0.01	0.03	0.03
4	0.03	0.01	0.02	0.04

Table 13 airflow velocity at different sample points in different directions

The front seats which are directly under the supply opening may be faced a high risk of draught experience, but the HVAC system is under an AUTO control mode, the high airflow velocities from 3 dimensions don't happen at the same time. Thus , the draught feeling is of a low risk level for general speaking.

c. *Sound level*

The experiment was done in the Friday evening after workers leaving the building. The building is located in a science park nearby the highway. In this regular silent indoor environment without any further artificial acoustic control, the   During two-hour observation after working hours:

When the HVAC system is off, the minimal sound level is 31.2 dB(A). When the HVAC system is on, the maximal sound level is 37.5 dB(A). By the sound level calculation, the maximum noise that may be caused by the HVAC system is 36.3 dB(A), which exceeds the value mentioned in the product information, 27 dB(A). But it seems that all the users aren't disturbed by the HVAC system at all. And the background noise sound level is below the maximum value allowed in offices, 45 dB(A). Thus, though the noise produced by the HVAC does not meet the standard that promised in the product information, it still meet a good acoustic office environment.

d. *Temperature during the whole measurements*

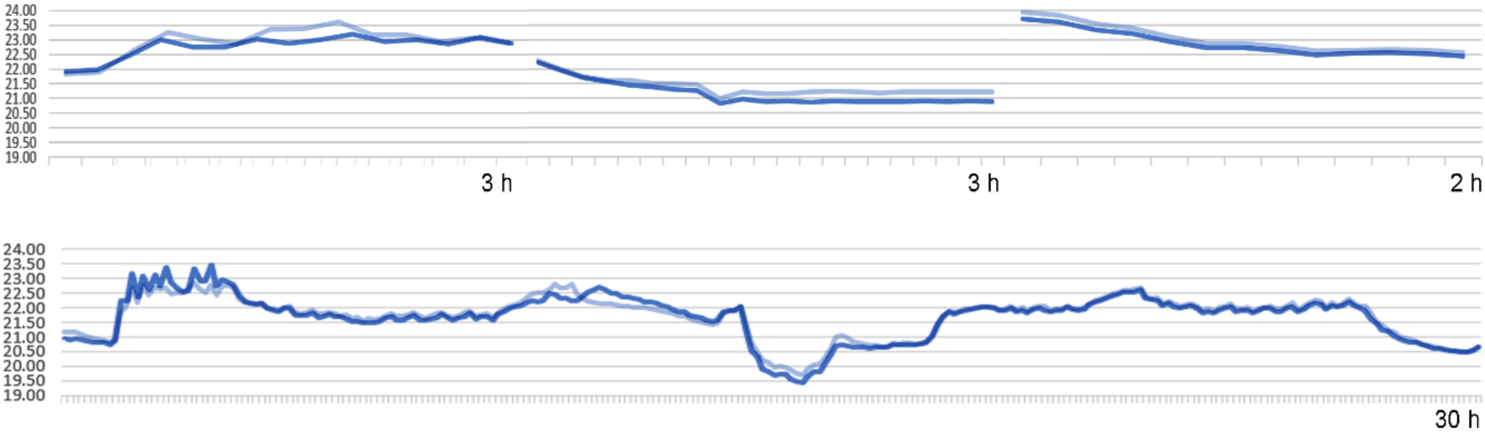


Table 14 the temperature changes during the whole week observation

The thermal comfort is also an important part that need to pay special attention to. The temperature at the human activity zone (in sitting areas at breathing zone level) was being recorded during the whole measurements. The first three graphs are recorded when there is at least one person indoors. And the below one was recorded for the automatic commissioning process of one indoor unit during one working day without any human interference. As you can see, the temperature is well controlled in a domain of 19.5 – 24 °Ç which proves the information provided by the product information booklet, that this city smart VRF ventilation system show strength in thermal comfort control. The temperature under auto mode is perfect for most Dutch workers and totally meet the thermal suggestions from Dutch construction guidelines. Though there is an obvious mechanical control delay from building engineering level to human feeling level in the daytime for about two hours. The thermal comfort still qualified for the office requirements in a relatively steady state.

e. Humidity during the whole measurements

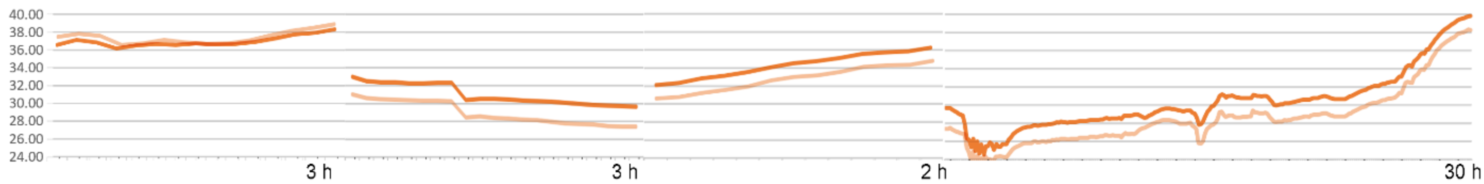


Table 15 the humidity changes during the whole week observation

The humidity control is another aspect for indoor comfort. The humidity should not be lower than 30% as suggested in the Dutch construction code. When there is any occupant in the meeting room, the humidity can meet the code. But when there is nobody, the building system tend to control the humidity at a low level, since human is the main source of humid and the wet Dutch weather can humidity at any time. In conclusion, the humidity is strictly controlled in this office and on a low level.

3.1.4 Discussion

After the one-week observation of the multi-interactive elements impacting a small meeting room. The manoeuvre logics of the building system become clear. The changes in different parameters tell the integrated outcomes of the likely actual experience by the modern advanced building engineering techniques. As covid-19, the unanticipated social event, spreading all over the world, a review of the existing space, including the technical engineering methods, parameter system and the social regulations for human behaviours, is a must for the control of indoor epidemic spreads.

a. Mixing ventilation

Mixing ventilation is popular among those offices with low clear floor height, below **2.8 m**, for its equal temperature distribution, in this way, to promise a relatively high-quality indoor thermal comfort. The space is of **2.8m** height and applying this mixing ventilation method. The supply air is well mixed with the existing indoor air at the supply opening of the indoor unit. According to the measurement results, the temperature in the human mobility space is equally distributed without an obvious intolerable temperature differences. The mixing ventilation did achieve its oriental goal. The indoor air has been well mixed already since the primary air entered the enclosed space.

The VRF based mixing ventilation implements the goal of remaining good indoor thermal comfort by a smart control panel. This smart control panel can be automatically controlled by a sensor in that panel or manually controlled by setting different user-readable parameters, like the target temperature and fan speed. But all these controls are temperature based, mainly by the temperature sensor in the control panel in that space, none of the parameters directly promise a high air exchange rate or a good ventilation efficiency. In this case, there is a lack for the commercial building engineering to evaluate the indoor air quality from a disease prevention & control perspective.

b. Air recirculation in the indoor end unit

The calculation based on the CO2 concentration changing rate shows that the air exchange rate of the meeting room is 1.1 per hour, but the calculation based on the air flow velocity supplied at the supply opening, the air exchange rate can achieve 14.5 per hour which is impossible. The huge difference between real air exchange rate (based on CO_2 concentration) the supply air provided by the indoor unit indicates that there is a large amount of recirculated indoor air combined with the primary fresh air and supplied to the room again. The air recirculation in the indoor end unit is an engineering method to well mix the low temperature and air temperature air and remain a good thermal comfortable condition. Based on the calculation, the recirculation rate can achieve 8.

3.1.5 Conclusion

From the building engineering aspect, the smart building system is a temperature based ventilation system. There are two attributes of the ventilation playing the conquering role in the airborne transmission control by ventilation:

1. From the general strategic level, one is the mixing ventilation indoor air distribution mode. This general control method mainly impact the existing indoor air quality by air exchange rate.
2. On the secondary level, the other one is the air recirculation mode in the indoor unit that gives a second chance to process the air. This kind of method mainly impact the indoor air quality by the mechanical detail design of the end unit that may process the air.

From the user aspect, the variant control for later research should include:

1. Occupant number
   The number of the occupant decides the cooling load of that room. Because human is the mean source of the heat source and also pollutant source in that space. The same heat source tend to promise the same cooling load for the building system, and thus, the same air change rate. And for later computational modelling, because the whole building system is temperature based, the same cooling load allows the same indoor temperature and a relatively steady indoor modellable environment.
2. Occupying hours
   Because the working hours of the building is scheduled based on the normal working hours of most Dutch offices, the working performance is also based on the worker's schedule. To avoid the possible working performance difference caused by the time schedule, every measurement should start at the specific same time and end at the same time during the peak working hours (9:00AM – 17:00PM) when the building system is in fully working mode.

Despite of the extra requirements asked by epidemic prevention, the current building system is smart and is doing a good job for thermal comfort.

3.2 Experiment about ON/OFF air recirculation

The experiment is a part of the graduate research process on a further level to explore the possible impacts of secondary pollution from indoor units. The possible impacts may include two parts, fan coil and air-recirculated mode of the indoor unit.

3.2.1 Background

VRF HVAC system is a popular choice for public commercial buildings, like offices, hotels, city complex. This kind of HVAC system allows a flexible layout for different temperature control zones and high controllability for individuals. In this case, the indoor units also play a role in processing the supply air rather than simply supplying the primary air from central air handling unit. During the processing or re-processing of the primary air and re-circulated indoor air in the indoor units, the mechanical impacts on indoor particle movement is still unclear. Under the corona times, the indoor hygiene quality control has been brought to a new high level. The virus-nuclei-laid particle is the main object in all research on prevention and control of all respiratory infectious diseases during transmission. The indoor units, as the end part of HVAC system, directly impact the indoor air quality and protection against epidemic.

Therefore the research question for this experiment is:

What is the impact of fan-coil indoor units during standard air recirculation working mode on particle movement?

To answer the above main question, the following sub-questions were defined to proceed with the research:

1. What would be the parameters to show the particle movements?
2. Which parts of the indoor unit have the high possibility to directly impact the particle movements?
3. How the mechanical elements in the indoor end unit interact with each other and impact the particle indoor movements?
4. What is the potential in the existing indoor end unit for the epidemic prevention methods?

3.2.2 Methodology

a. Method

The experiment is based on quantitative analysis. A series of measurement were done on the two levels – breathing zone at 1.1 m to the floor and exhaust grills at ceiling level. The particle movement, produced by human and dispersing in the whole space, is determined by CO2 concentration and particle concentration. Human are the main source to produce both CO2 and particle indoors. But there are still pros and cons between the two parameters:

Parameter	***CO2***	***Particle***
pros	convenient for instant reading	precise and direct to know the number of indoor particle
	meter is economic to apply in the market	meter is expensive for wide application

	already used as the parameter for indoor air quality in some codes	already used as the parameter for clean level in high-standard large spaces, like food factories, medicine labs and electronic product workshops
cons	cannot tell the effects from filters	applied in regular maintenance and delivery, but no application in smart building control
	shows different movement mechanism from airborne particles	not convenient for instant reading or carrying
	variants of human, like activities, positions, body temperature, have less impacts on the CO_2 values.	it would inefficient for measurements if there is a huge number of particle or particle sources

Table 16 differences between CO_2 and particle as the parameter in experiments

For different parameters, the equipment applied for the experiment are CO_2 sensors and particle counter:

HOBO CO_2 logger

parameter	type	Measurement Range	Accuracy	reference
CO_2	HOBO CO_2 logger	from 0 to 5000 ppm	±50 ppm ±5 % of reading at 25°C	https://www.onsetcomp.com/
particle	Met One 3400 Series Particle Counter	Particle Size Ranges: 0.3, 0.5, 1.0, 3.0, 5.0, 10.0 [um] The maximum limit for any particle size is 9,999,999	5% at 14,126,000 particles/m3 (400,000 particles/ft3)	https://manualzz.com/doc/39825449/met-one-3400-series-particle-counter

Table 17 product information of the equipment in the measurement

Figure 55 The photo of Met One 3400 Series Particle Counter (from https://manualzz.com/doc/39825449/met-one-3400-series-particle-counter)

b. Execution plan

Based on the observation from pre-phase experiments, there are a lot of variants to be controlled for a relatively same utilization scene and building system performance.

The controlled variants include:

variant		**setting**
human related	occupant number	2
	occupant position	position 1 & 3
	activity	sitting & communicating
building system related	working mode	auto - maintaining the same temperature at about 21℃
	working performance	fully conducting
	working hours	10:50 - 15:50

Table 18 the controlled variants for the experiment about ON/OFF air recirculation

Because of the limitation of the equipment, the execution will be held in four days:

no.	date				CO_2 meter	particle counter		

		start time	end time	duration [h]	exhaust opening	breathing zone	exhaust opening	breathing zone	occupant number	air recirculation
1	17/08/2021	10:30	11:50	1	TU Delft 2	TU Delft 1	√		0	on
		11:50	13:50	2					2	
		13:50	15:50	2					0	
2	18/08/2021	10:30	11:50	1	TU Delft 2	TU Delft 1	√		0	off
		11:50	13:50	2					2	
		13:50	15:50	2					0	
3	19/08/2021	10:30	11:50	1	TU Delft 2	TU Delft 1		√	0	off
		11:50	13:50	2					2	
		13:50	15:50	2					0	
4	20/08/2021	10:30	11:50	1	TU Delft 2	TU Delft 1		√	0	on
		11:50	13:50	2					2	
		13:50	15:50	2					0	

Table 19 the excursion plan for the experiment about ON/OFF air recirculation

To evaluate the local ventilation efficiency, both of the two levels, breathing zone level and exhaust opening, should be where to measure:

	height(z)	location(x,y)
breathing zone	1.1m from floor	Back point as Figure 49 and Figure 50 show
exhaust opening	0.2m from ceiling	central point of opening geometry

Table 20 the location of sample points for the experiment about ON/OFF air recirculation

3.2.3 Results and analysis

There are two parameter being observed in this research. Different parameters evaluate different characters of the ventilation system.

a. *Particle*

- Particle of all sizes

  Because metering results are on different orders of magnitude when measuring different particle sizes, the graphs without the quantity axis can only tell the tendency of the different particles during different times. The grey shadow area is the duration when two occupants sitting and talking in the room. There are obvious peaks in large and mid-size particles, 1.0 um, 3.0 um, 5.0 um and 10.0 um, when the occupants entered and left the room. While, the small particles, 0.3 um and 0.5 um, mainly impacted by the indoor air flow, thus they may have deep relationship with the ventilation performance of the indoor unit, rather than temporary human movements. Large particles are also easier to settle, while the small particles, which are the main media in airborne transmission as well, tend to suspend in the air.

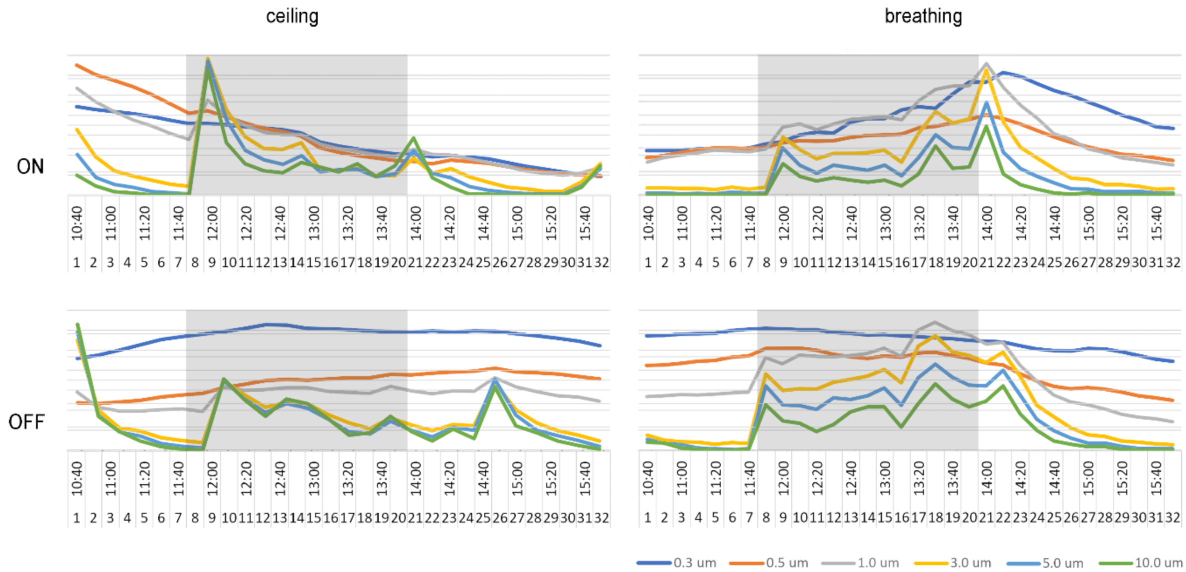


Figure 56 the tendency of particle concentration of different sizes (by author)

- Large particles (3 um – 10 um)
  There is no obvious difference between on and off air recirculation in the indoor unit for large particles. Most large particles directly and only impacted by human behaviours, and they can be totally removed by current ventilation system already. The small particle concentration is lower with ventilation on. These particles can also stick to the walls.

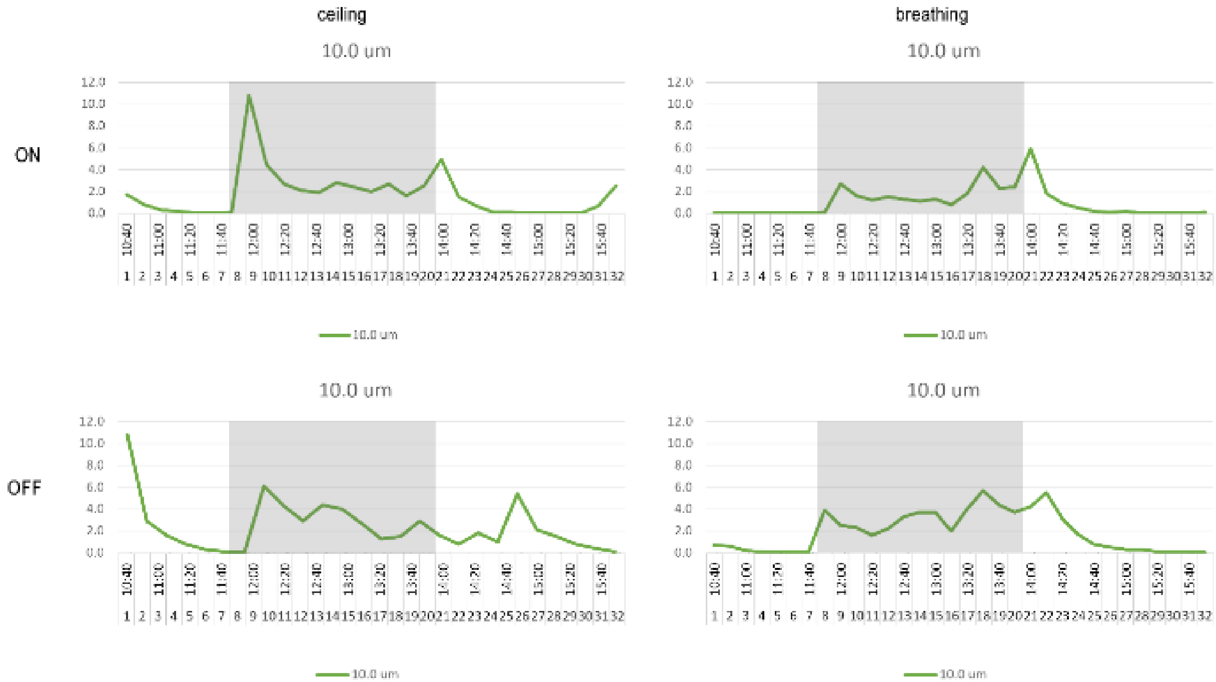


Figure 57 Particle of 10um

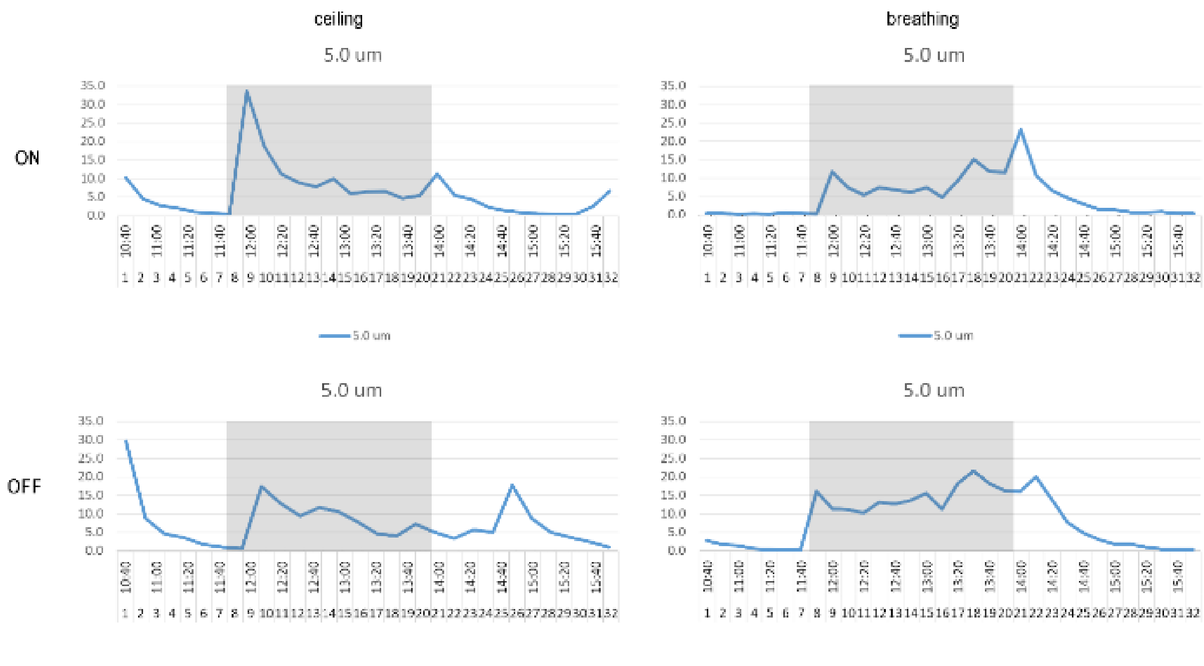


Figure 58 Particle of 5um

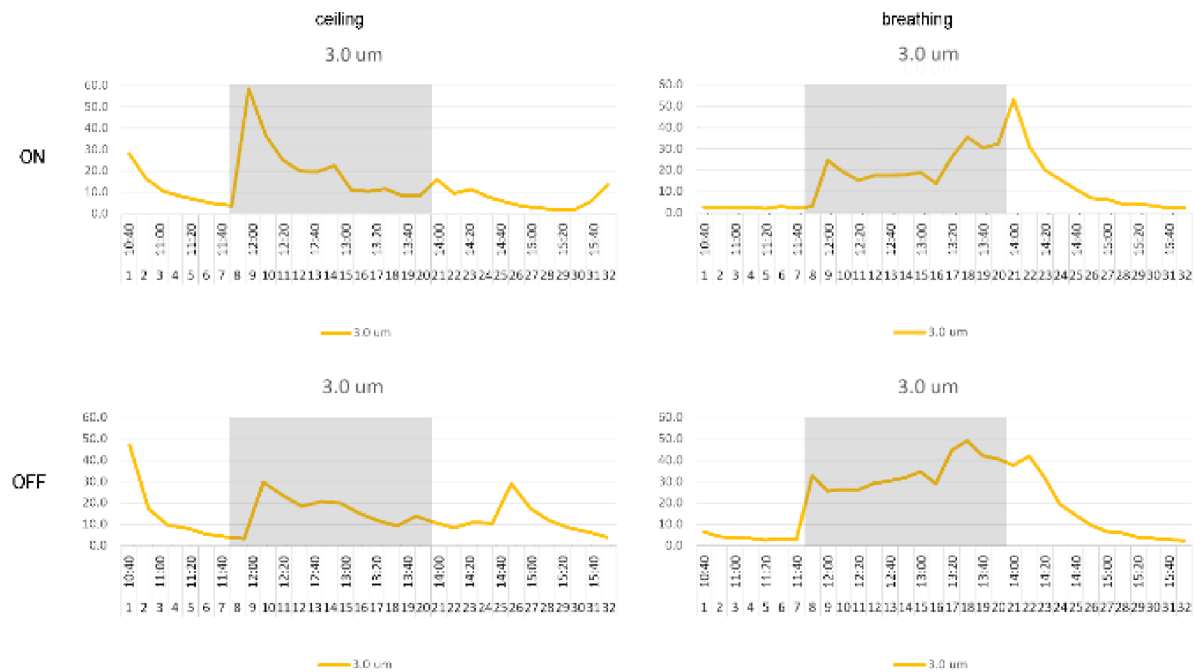


Figure 59 Particle of 3um

- Middle-size particle (1.0 um)

  While 1.0 um particle is a middle size particle which shows some mechanical characters from both large particles and small particles. In breathing zone, it is obvious that the 1.0 um particle number is higher than that at the exhaust opening. The high concentration in the breathing zone may prove that two facts from previous literature study:

  1. Human is the main source of indoor particle pollutant source;
  2. 1.0 um particle is the major particle size that produced by respiratory air and body air.

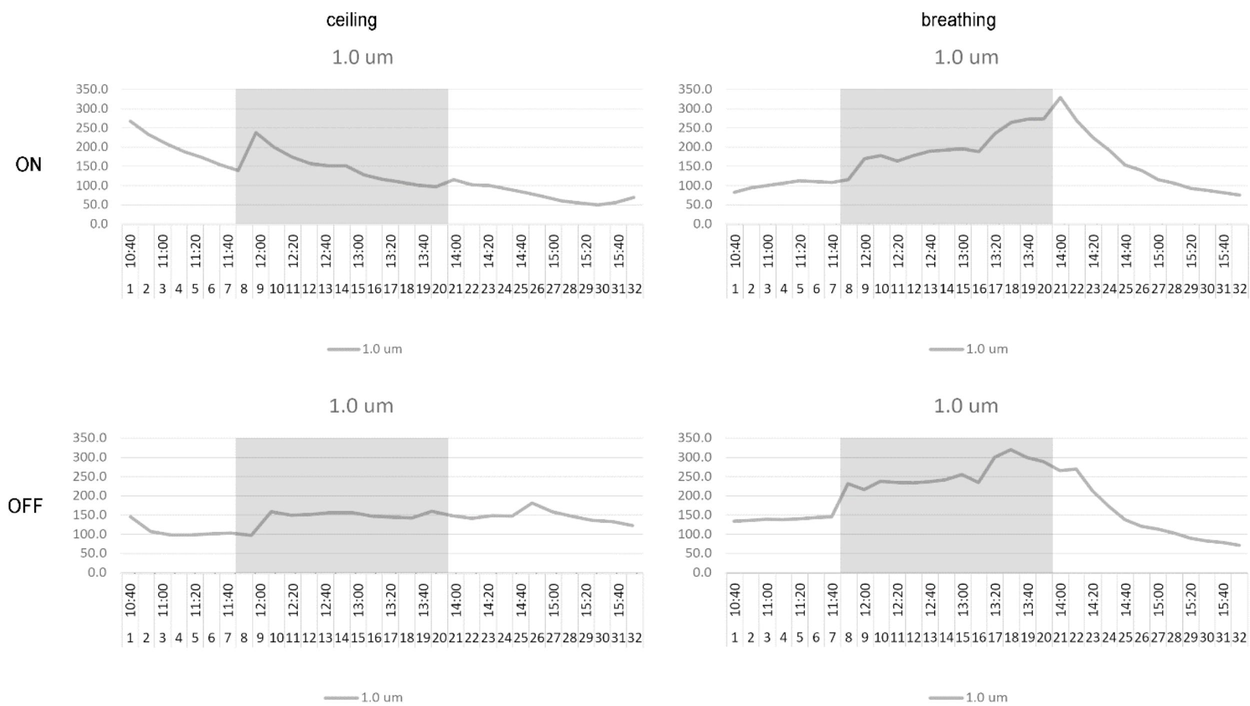


Figure 60 Particle of 1um

The movement of 1 um particle is impacted by both human activities and indoor air flows. 1 um is a threshold value to distinguish between large and small particles.

- Small particles (0.3 um & 0.5 um)

  The small particles are the main virus nuclei carriers in airborne transmission. And 0.5 um is a typical airborne particle size recognized by a large number of existing studies as the research scalar, although there are also a lot of research talking about 1um particle in the airborne transmission of infectious disease for its major quality in human produced pollutant and the complexity in mechanical movement. The 0.5um particles typically characterize the mechanical movement of airborne particles and represent the majority of the airborne particles in the particle spectrum.

  According to the measurement result on 0.5 um particle:

  1. The fluctuates of 0.5um particle concentration are at a much **faster rate** when the air-recirculation is on than when it is off.
  2. The peak value can achieve a relative **low level** in the breathing zone when the air recirculation is on. It may also be of a lower level at the exhaust opening when the air recirculation is on than when it is off, which can be told by the recording values after 13:00pm, the system achieved a relatively steady state. The value first experiment is at a high start point, because the measurement equipment was assembled on different height levels in that early morning which causing the dust and particle raising in the whole room.

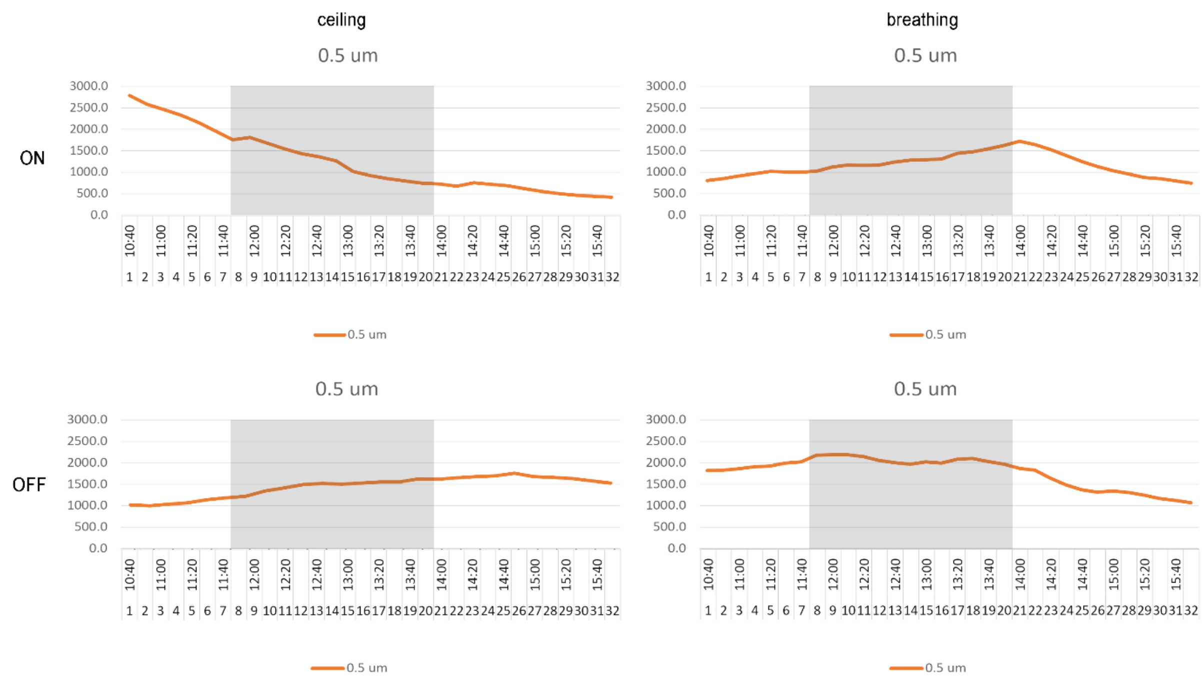


Figure 61 Particle of 0.5um

The measurement result on 0.3 um particle also shows a higher fluctuating rate when the air recirculation is on than when it is off. But the particle concentration can achieve a high level under both situations.

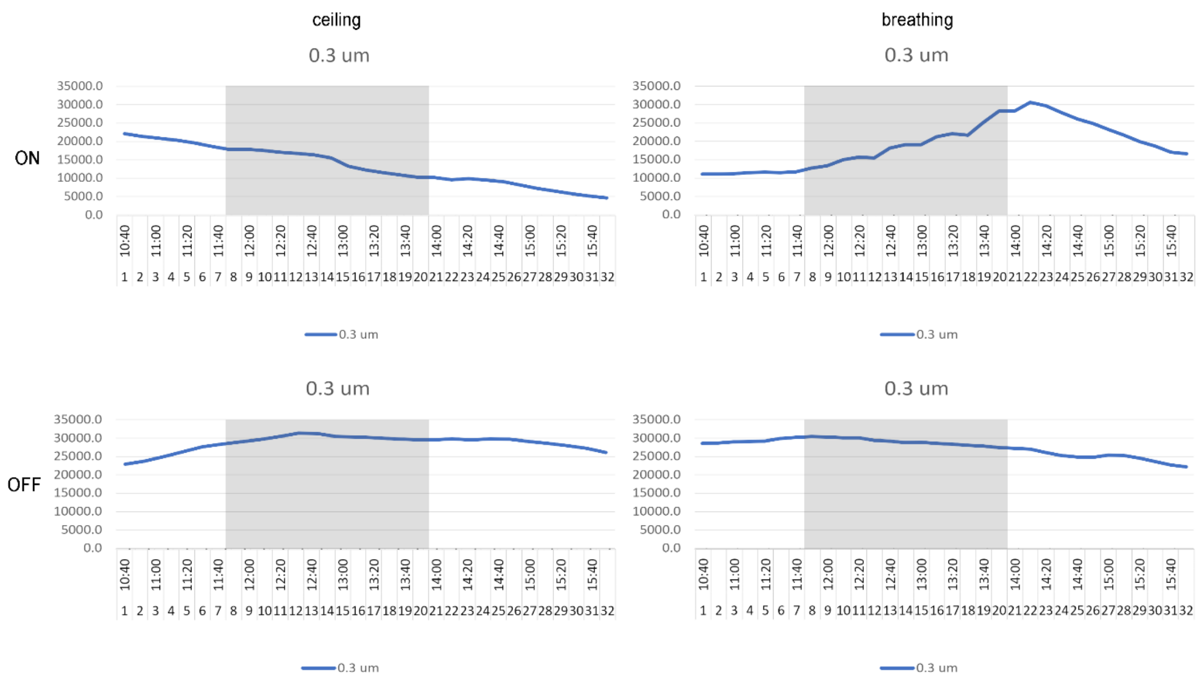


Figure 62 Particle of 0.3um

b. CO2

The measurement of CO2 concentration results in a different conclusion to that of the particle concentration:

1. In most time, the CO2 concentration is higher at the exhaust opening than that in the breathing zone;
2. The fluctuates of CO2 on both height levels are at a much **faster rate** when the air-recirculation is on than when it is off;
3. The peak value can achieve a relative **low level** on both height levels when the air recirculation is off.

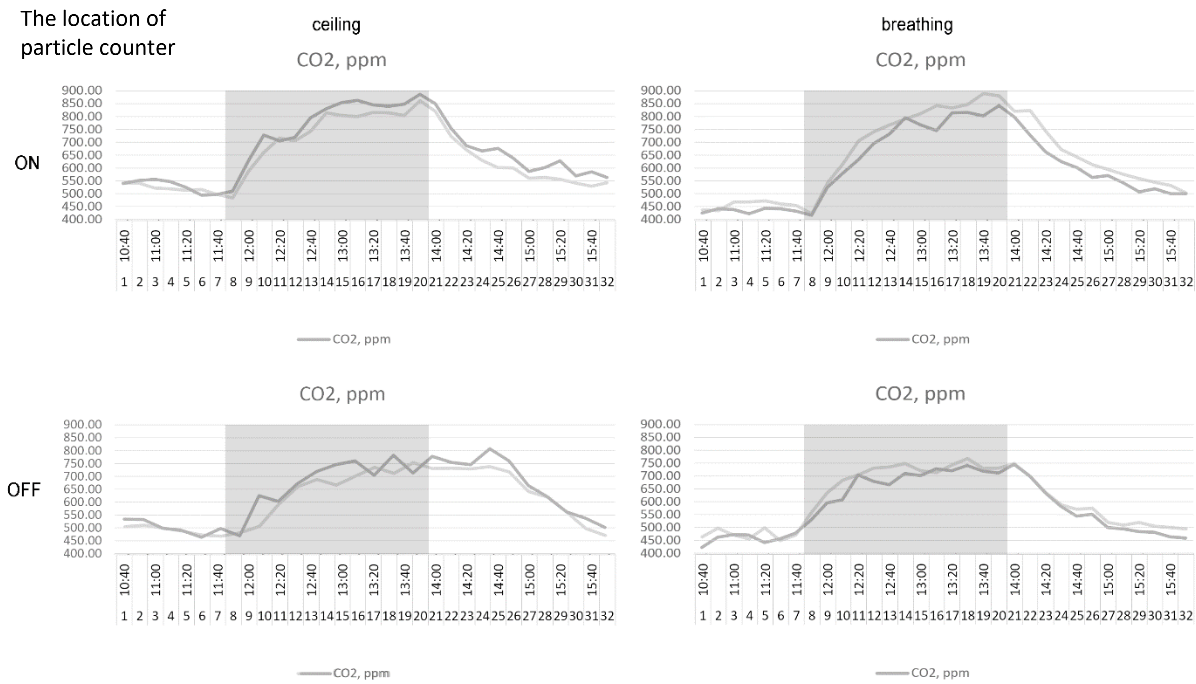


Figure 63 CO2 concentration, light: different position as where the particle counter is, dark: same position as where the particle counter is (by author)

c. Temperature

To discuss the different outcomes of different parameters, understanding the engineering mechanism of the space is important for some clues.

The measurement results of temperature are:

1. the temperature is always higher in the breathing zone than that at the exhaust opening;
2. The falling rate of temperature on both height levels are **faster** when the air-recirculation is off than when it is on,
3. The temperature changes are of higher frequency but smaller fluctuations when the air recirculation is on than those when it is off. The temperature control from the ventilation is more active when the air recirculation is than when it is off.

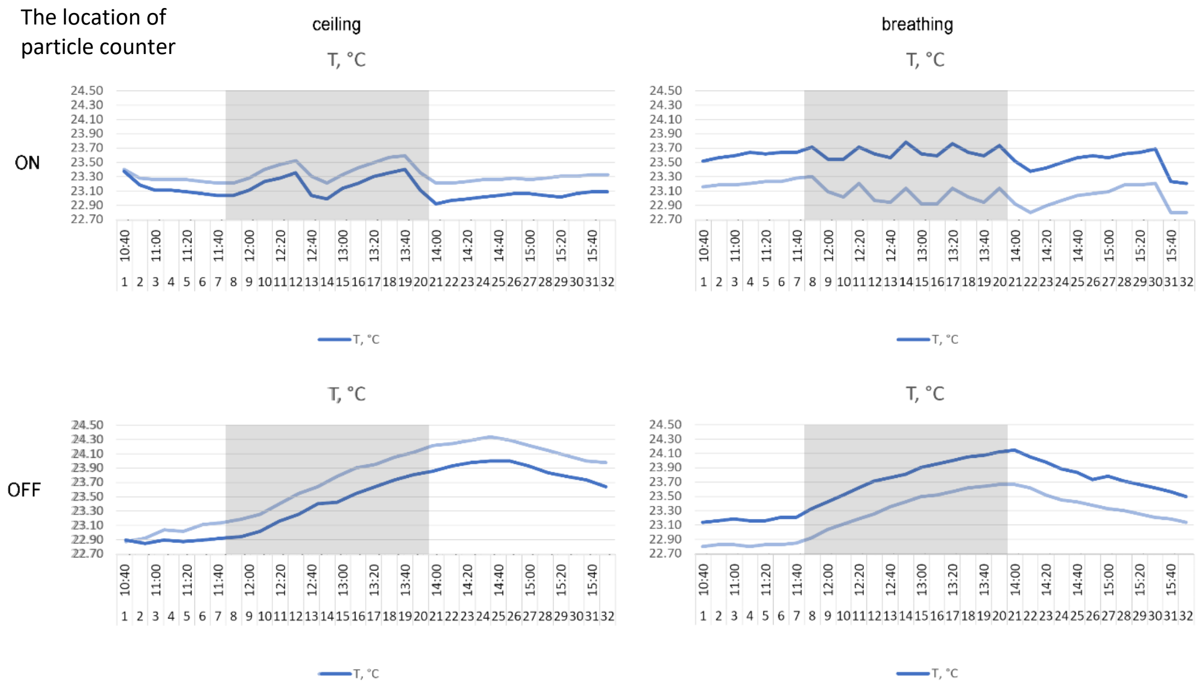


Figure 64 temperature, light: different position as where the particle counter is, dark: same position as where the particle counter is (by author)

The temperature is the direct control reference for the ventilation system to perform. The temperature sensor is attached on the control panel of 1.5 m height on the wall. The sensitivity of the ventilation system is higher when the air recirculation is on, which means the indoor air is well mixed and the temperature differences are little from location to location or else the reacting time will be longer as shown in the data when the air recirculation is off.

Based on the observation of the temperature, the ventilation system was in continuous steady air supply mode when the air recirculation mode is on, which is under low air exchange rate based on the primary economic design purpose of the smart system. While, when the air recirculation is off, the ventilation assume that there is a need of huge cooling load, because the temperate sensed by the system remain on a high level for a relatively long time. Thus, the ventilation is on fully performance for a longer time, and in this way, the space is under a high air exchange rate.

The higher air exchange rate when the air recirculation is off is the reason that why the peak value of CO2 concentration can achieve a relative **low level** on both height levels when the air recirculation is off, while the particle concentration's tend to achieve a **high level** on both height levels. In this way, though the air exchange rate has been improved to a high level, the concentration rate of small particle is still high when the mixing level is low in the mixing ventilation pattern. The **mixing level**, thus, is a key elements in the ventilation efficiency of mixing ventilation strategy.

3.2.4 Discussion

There are two levels for building engineering control on the target indoor space. one is from the general level, like directly increasing the input of primary air and enhancing the air exchange rate in this case, which is strong-armed and of simple logics. The other one is from the partial level, including a lot details, like the mixing level of supply air and the performance of filter in the indoor unit in this case, which is based on a complex integration of mechanical elements. Different parameters, focusing on different aspects of the indoor environment quality, cannot directly evaluate the risk level of being infected by airborne transmission. An overview of all these parameters are needy to evaluate engineering performance on the theoretical foundations of biomass.

3.2.5 Conclusion

When the air recirculation is on, the particle decreased faster than when it is off. When the air recirculation is off, the CO2 concentration drops faster than it is on. Thus, CO2 concentration focus more on the air exchange efficiency for the whole space. While particle concentration shows that the indoor end unit can help decrease the airborne particle to protect people from indoor infectious disease transmission.

3.3 Experiment about WITH/WITHOUT ventilation design installed

The experiment is a part of the graduate research process at the last step to roughly test the "corona-proof" performance of the ventilation design in the real scenario. Though the installed design model on site faced with unavoidable limitation of the equipment and the unqualified model materials in 0.3 um particle concentration. The design is functional as the experiment results predicted.

The draft model for fast economic indoor renovation is installed on site, following the mixed-method ventilation strategy promoted in design phase (chapter 5):

- Extra installation of cleansers, purifiers or filter: filter rol NF 290 without qualified standard for ePM 1 particles.
- Remote air return openings: the 4 ducts (diameter of 200mm) stemmed from the box directly glued below the indoor end unit, which covered the previous return openings and didn't impact the supply air flow, to the ceiling corners in the room.
- Remote air exhaust openings: the ceiling in this scenario is a cavity, and the central exhaust opening of the room locates above the ceiling in the cavity zone, thus, the ceiling panels are removed to create direct exhaust openings for air exhaust.

Figure 65 *the draft ventilation renovation product model (photo from author)*

			surface centre		*z [m]*	*shape*	*size*
			x [m]	***y [m]***			
Design installed	**return opening**	1	1.1	0.8	2.6	circle	diameter 200mm
		2	1.1	3.72			
		3	4.5	0.8			
		4	4.5	3.72			
	exhaust opening	1	0.9	0.75	2.8	rectangular	600mm*300mm
		2	0.9	3.77			
		3	4.7	0.75			
		4	4.7	3.77			
design uninstalled	**return opening**	1	2.23	2.26	2.8	rectangular	50mm*800mm
		2	2.58	2.26			
	exhaust opening		0.9	0.9	2.8	rectangular	600mm*600mm

Table 21 Openings locations

3.3.1 Background

The design is CFD based, the realistic "corona-proof" performance of the ventilation design is still unclear. A rough on-site ventilation model is necessary to prove the fast ventilation renovation product at the end of the HVAC can significantly improve the performance of indoor ventilation against epidemics.

Therefore the research question for this experiment is:

What is the "corona-proof" performance of the mixed-method ventilation strategy for fast economic indoor renovation in the realistic scenario?

To answer the above main question, the following sub-questions were defined to proceed with the research:

1. What would be the ventilation impacts from the design product on current ventilation system?
2. How much optimization of the indoor hygiene ventilation quality can the draft ventilation design model can achieve in current building system?

3.3.2 Methodology

a. Object

The experiment is based on quantitative analysis. CO_2, with the strong expansibility, can't be filtered by the filter cloth but can directly indicate the instant ventilation working mode, thus, is to observe the possible disturbances in the ventilation system in the smart building system. The particle is the direct object to evaluate the airborne particle local concentration condition, thus, will be measured to evaluate the "corona-proof" performance of the ventilation renovation design.

Parameter	*CO2*	*Particle*
purpose	Observation of the ventilation working mode	To measure the local 0.3 um particle concentration condition

Table 22 illustration of the application purposes of two parameters in experiment about WITH/WITHOUT ventilation design installed

For different parameters, the equipment applied for the experiment are CO_2 sensors and particle counter same as the experiment about ON/OFF air recirculation (chapter 3.2.2 a). 1.1

b. Execution plan

Based on the observation from pre-phase experiments, there are a lot of variants to be controlled for a relatively same utilization scene and building system performance.

The controlled variants include:

Variant		**setting**
human related	occupant number	2
	occupant position	position 1 & 3
	Activity	sitting & communicating
	working mode	auto - maintaining the same temperature at about 21℃

building system related		fan – stay at the maximum speed mode
	working performance	fully conducting in working days
	working hours	10:50 - 15:50

Table 23 controlled variants for experiment about WITH/WITHOUT ventilation design installed

Because of the limitation of the equipment, the execution will be held in two days:

	time	***occupation condition***	***product installation***	***particle counter***	***CO2 meters***
28/12/2021	**10:40 - 18:40**	**13:00 - 15:00 2 persons**	**yes**	breathing zone center	breathing zone center & ceiling level center
31/12/2021	**10:40 - 18:40**	**13:00 - 15:00 2 persons**	**no**	breathing zone center	breathing zone center & ceiling level center

To evaluate the ventilation system working mode, both of the two levels, breathing zone level and exhaust opening, have been placed with CO2 meters. But the only one particle counter is located at the room centre at breathing zone height. The sample point locations follows the same geometry layout axis as the experiment about ON/OFF air recirculation (chapter 3.2.2 b):

	x [m]	***y [m]***	***z [m]***
breathing zone center	2.8	2.26	1.1
ceiling level center	2.8	2.26	2.5

3.3.3 Results and analysis

There are two parameter being observed in this research. Different parameters evaluate different characters of the ventilation system.

a. 0.3 um Particle

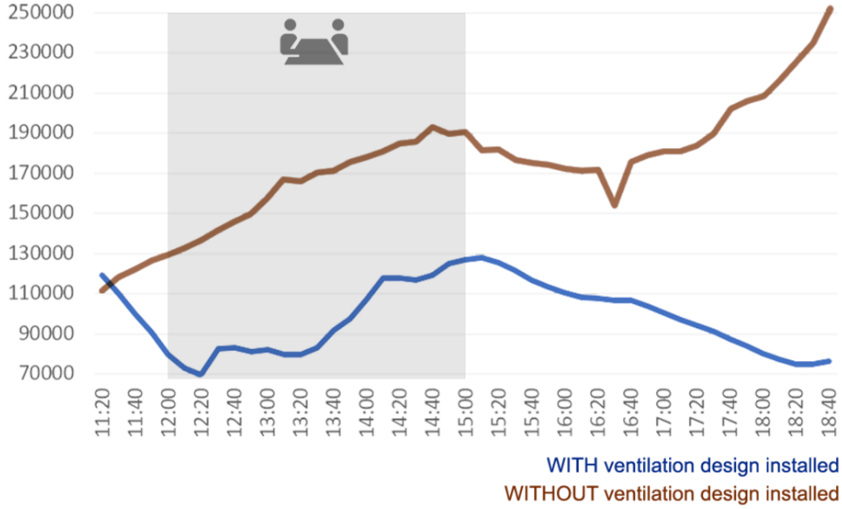


Figure 66 0.3 um particle number changes WITH/WITHOUT ventilation design installed, shadow duration is when two users were indoor (by author)

When the filter is applied, for airborne particles (0.3 um):

- Why the small particle numbers keep dropping once the building system started working, even when nobody in the room, from the same start point?

The smart building system starts working when the indoor facility are working, the system starts working on first day morning and until 11:20am they are at the same start value for both day and both of CO2 and particle measuring. As long as the system working, the indoor particle will drop until around 75000.

The local particle concentration in the design installed case is always lower than that in the non-design-installed case. The peak value difference can achieve 1/3 of the particle concentration in non-design-installed case when users left the room. The airborne particle number kept dropping once the ventilation awaked in the design installed case. While the airborne particle number kept rising once the ventilation awaked in the design installed case. The different starting condition may be because the different outdoor air conditions in two days, because the window of the room were open before and after the experiments.

b. CO2

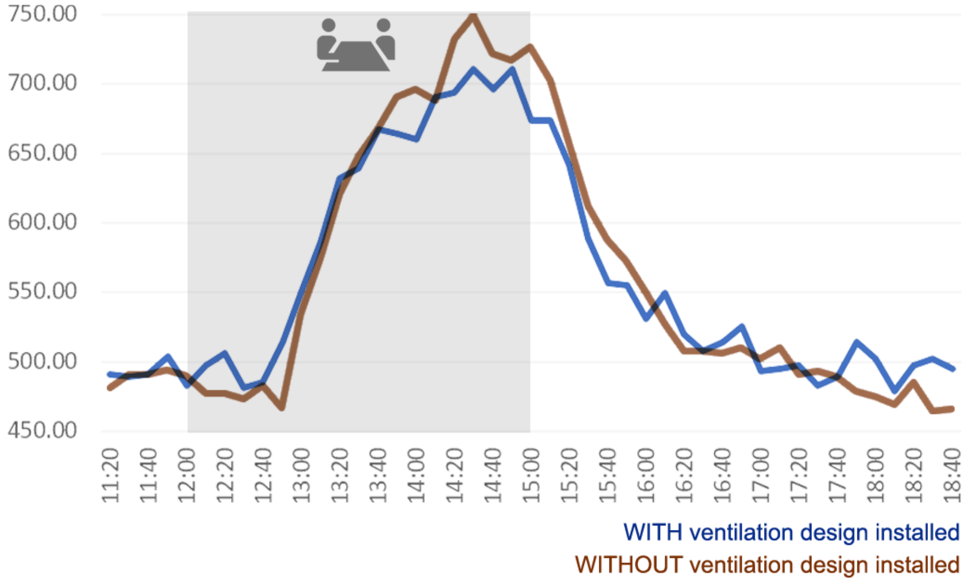


Figure 67 the CO2 concentration changes in the breathing zone WITH/WITHOUT ventilation design installed, shadow duration is when two users were indoor (by author)

The ACH of the room during both measurements is almost the same. Thus, the experiments are based on the same ventilation working mode from the automatic system controls. After the users entered in the room, the CO2 concentration in the design-installed case is always lower that in the non-design-installed case. The CO2 concentration differences between two experiments were within 50 ppm difference, which can be ignored. Thus, the ventilation system in two days have the same working mode. Since filter CONNOT remove CO2, the CO2 measurements showed: 11:20 am is a same start point for both days; CO2 measurements shows the building system performs almost the same in both days.

c. Temperature

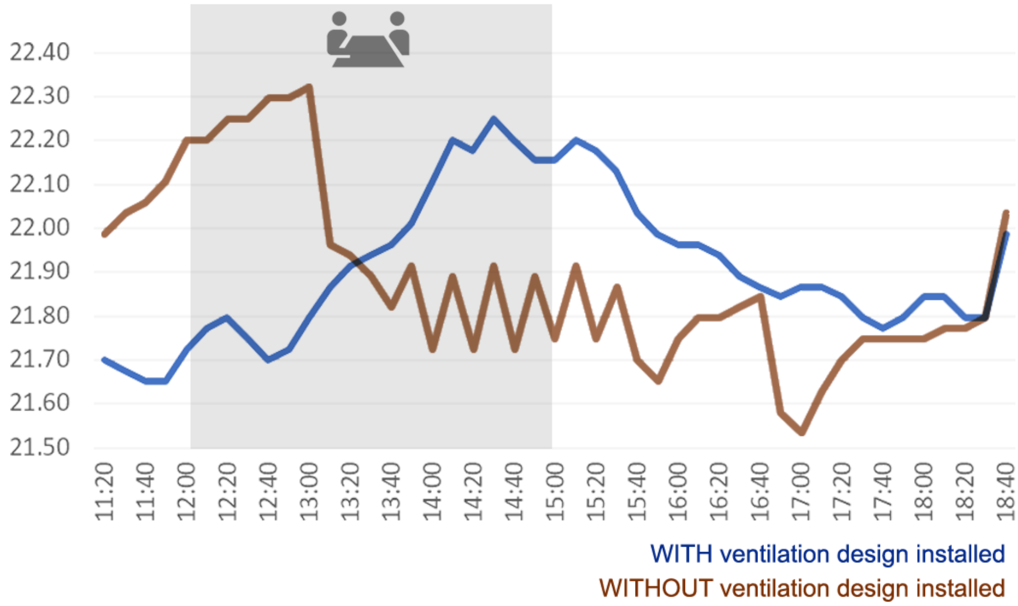


Figure 68 temperature changes in breathing zone WITH/WITHOUT ventilation design installed, shadow duration is when two users were indoor (by author)

After 18:20 pm every work day, the building system will not maintain the room temperature at around 22.8 degree in winter, and the temperature rises until the next day when the system sensed an obvious temperature changes will the system respond and starts to ventilate the room again. The temperature differences between two experiments were within 0.5 degree difference, which can be ignored. Thus, the ventilation system in two days have the same working mode.

3.3.4 Discussion

Impacts from the design on existing ventilation system

The installation of the design has nearly no impacts on the ventilation system and the smart building system control. Because the CO2 and temperature differed little during the experiments on the two days, the almost same temperature and CO2 levels during the two experiment indicated a same performance of the two experiment (see Figure 67 and Figure 68).

The "corona-proof" of the renovated ventilation system

The local airborne particle concentration decreasing rate can achieve 33.43%. The filter started to function once the ventilation system works, it even works when the ventilation system works in a "resting" mode, when there is no users indoors. The pressure-drop effect is still hard to predict based on the limited quantification method. There may be an impact on the ventilation efficiency, but the smart building system control may cover the differences and make the impact hard to distinguish. Further precise exploration of the pressure drop effects for the ventilation performance is needy for the practical wide application of the ventilation product.

3.3.5 Conclusion

There is no negative impacts from the design on the current ventilation performance. And the contaminant concentration decreasing rate of 33.43% may predict a **5%** indoor infection risk rate referring to the contaminant concentration decreasing rate in CFD analysis (Chapter 4.4).

3.4 Experiment about model material qualification

The experiment is a additional part of the graduate research process at the last step to roughly test the "corona-proof" performance of the ventilation design in the real scenario. There is no quantification about 0.3 um particle produced by human quiet respiratory mode. And there is no quantification about the filter efficiency on 0.3 um particle on filter rol NF 290, which is applied in the draft ventilation model. The qualification experiment is to simulate the design-installed scenario in CFD. The CFD is for a relative higher precision in infection risk prediction of the realistic design-installed case. Because of the limitation of the measurement equipment, there are unavoidable errors in the quantification results. If there is an opportunity to refine this study in depth in the future, with better experiment facilities, the precise prediction is needy of the wide application of this ventilation product in the construction market.

Therefore the research question for this experiment is:

How many 0.3 um particles are produce by human still respiratory mode?

How many 0.3 um particles can be filtered by filter rol NF 290?

3.4.1 Methodology

a. Object

Parameter	***CO2***	***Particle***
purpose	Observation of accuracy of measurement, based on the widely quantified CO2 concentration rate from existing researches	To measure the local 0.3 um particle concentration

Table 24 illustration of the application purposes of two parameters in experiment about model material qualification

For different parameters, the equipment applied for the experiment are CO2 sensors and particle counter same as the experiment about ON/OFF air recirculation (chapter 3.2.2 a).

b. Execution plan

- Instant measuring respiratory air, with the mouth directly closely towards the sensor for 0.3 um particle produced by human quiet respiratory mode

- Continuous particle number counting via a duct with/without filter interrupted in: Every 5 minutes for one hour, 1 minute of air is inhaled and the number of 0.3um particles in the volume of air inhaled is calculated.

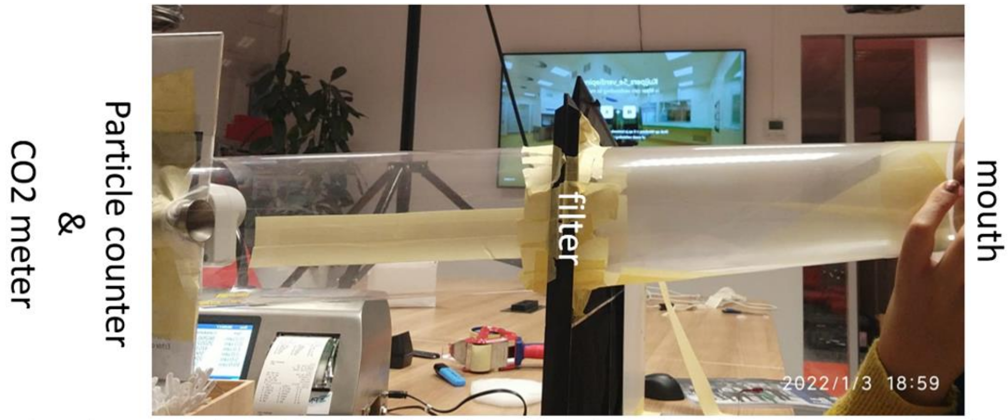


Figure 69 Experiment process for qualification of the model materials (by author)

3.4.2 Results and analysis

Qualification about 0.3 um particle produced by human quiet respiratory mode

	DATE TIME	T, °C	HR, %	CO2, ppm	DT, °C		
1	2022-01-03 18:41:12	22.49	45.47	591.00	10.14		
2	2022-01-03 18:47:12	23.16	45.99	1024.00	10.92		
3	2022-01-03 18:53:12	23.54	45.04	954.00	10.95		
4	2022-01-03 18:59:12	23.59	44.74	898.00	10.90		
5	2022-01-03 19:05:12	23.38	45.25	1370.00	10.87		
6	2022-01-03 19:11:12	23.79	44.31	1288.00	10.93		
7	2022-01-03 19:17:12	23.76	44.83	1323.00	11.08		
8	2022-01-03 19:23:12	23.79	43.49	938.00	10.65		
9	2022-01-03 19:29:12	24.05	43.35	1292.00	10.84		
10	2022-01-03 19:35:12	23.95	45.21	1995.00	11.38		assumption
11	2022-01-03 19:41:12	23.91	43.46	938.00	10.74		dispersal rate
				1202.00		without filter in duct	51%
12	2022-01-03 19:47:12	24.00	43.23	608.00	10.75		
13	2022-01-03 19:53:12	24.07	43.01	558.00	10.74		
14	2022-01-03 19:59:12	23.98	42.93	523.00	10.62		
15	2022-01-03 20:05:12	23.98	44.17	1009.00	11.05		
16	2022-01-03 20:11:12	24.07	44.12	1901.00	11.12		
17	2022-01-03 20:17:12	24.10	45.13	2845.00	11.49		
18	2022-01-03 20:23:12	24.07	46.07	2574.00	11.78		
19	2022-01-03 20:29:12	24.05	44.63	1844.00	11.27		
20	2022-01-03 20:35:12	24.19	43.36	1227.00	10.97		
21	2022-01-03 20:41:12	24.12	44.15	1918.00	11.18		
22	2022-01-03 20:47:12	24.05	43.28	820.00	10.81		
23	2022-01-03 20:53:12	24.12	43.91	1671.00	11.09		
24	2022-01-03 20:59:12	24.12	43.89	1695.00	11.09		
				1853.78		with filter in duct	24%
25	2022-01-03 21:05:12	24.07	49.07	4366.00	12.74	instant respiratory air	
26	2022-01-03 21:11:12	23.93	44.75	1110.00	11.20		
27	2022-01-03 21:17:12	23.88	43.42	590.00	10.71		
28	2022-01-03 21:23:12	24.53	48.83	1841.00	13.08		
				2439.00			

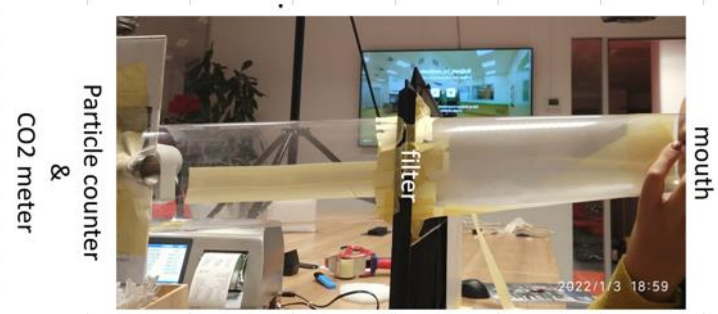


Table 25 data collected from the measurement with different processes (by author)

The dispersal rate, due to the open opening at the end of the duct where the sensor is, can achieve 51%. Thus, the instant measurement of respiratory air, with the mouth directly closely towards the sensor is used as the rough qualified value of 0.3 um particle amount produced by human quiet respiratory mode.

Qualification of the filter efficiency on 0.3 um particle on filter rol NF 290

no.	time	0.3	0.5	1	3	5	10
1	20:00	90289.8	25400.9	3056.2	272.2	103.1	16
2	20:06	106597	35265.9	6568.6	351.2	78.1	13
3	20:12	114278	38747.4	7766.5	322.2	67	8
4	20:18	139432	52121.8	12433.8	478.3	84.1	2
5	20:24	142989	54761.7	13566.6	506.4	69	4
6	20:30	158124	61721.8	15697.5	531.2	84	7
7	20:36	165413	65375.2	16533.7	560.4	85.1	16
8	20:42	191117	78044.1	20948.8	787.6	117.1	8
9	20:48	167651	65996.6	16375.6	561.4	65	2
10	20:54	181267	72535.2	18929.4	683.5	76.1	6
11	21:00	184996	73820.1`	19049.7	633.2	80	5
		149287	54997.1	13720.6	517.055	82.6	7.90909
instant respiratory airflow					duration	1	min
				paricle size			
		0.3	0.5	1	3	5	10
03/01/202	21:05	235942	97133.6	31738.4	1779.3	352.2	55
	filter effe	37%	43%	57%	71%	77%	86%

Table 26 comparison between the particle numbers in filtered breathing air and instant respiratory air (by author)

As the 0.3 um particle amount produced by human quiet respiratory mode has been settled, the filter efficiency on 0.3 um particle on filter rol NF 290 is about 37%

3.4.3 Conclusion

the filter efficiency on 0.3 um particle on filter rol NF 290 is about 37%.

The quantified value for modelling:

(num.)/mol	6.02E+23	/mol
particle mass	44.0128	g/mol
air mass	1.29	g/L
dispersal rate for open openings	3	
sample volume of the measurement machine	0.0283	L/min
	from human mouth	**constant indoors**

particle[(num.)/min]	88178.47273	115582.05
particle[ppm]	5.29773E-12	2.31471E-12

3.5 Experiment about pressure resistance of the design

The experiment is an additional part of the graduate research process with the perspective for the commercial renovation product integrated with ESP purifier at the indoor end unit. To make the product accessible to the construction market, especially for commercial renovation cases, the pressure resistance is necessary to be tested, in case for the additional installation, like an extra fan coil unit. The pressure resistance experiment is based on instant data collecting at different locations in the room while the ventilation system is fully working and the maximum performance of the fan coil unit, under the two scenarios, with / without the draft design installed.

Therefore the research question for this experiment is:

What is the pressure resistance impact from the draft design model?

3.5.1 Methodology

a. Object

Parameter	***Airflow velocity***	***Pressure difference***
purpose	To measure the resistance mainly caused by ducts	To measure the pressure drops caused by filter and ducts

Table 27 illustration of the application purposes of two parameters in experiment about pressure resistance of the design (by author)

For different parameters, the equipment applied for the experiment are CO2 sensors and particle counter same as the experiment about ON/OFF air recirculation (chapter 3.2.2 a).

parameter	type	Measurement Range	Accuracy	reference
Airflow velocity	TSI model 9535	From 0 to 6000 ft/s	±3% of reading or ±3 ft/min (0.05 m/s) (whichever is greater)	https://tsi.com/getmedia/55fef147-7c6f-4057-9ff6-d6ec02d03486/9535A-VelociCalc-1980563-web?ext=.pdf
Pressure difference	TSI model 5825	-15 to +15 in. H2O (-28.0 to +28.0 mm Hg, -3735 to +3735 Pa)	±1% of reading ±0.005 in. H2O (±0.01 mm Hg, ±1 Pa)	https://tsi.com/getmedia/fe5ea956-809c-4369-8bd0-385d1de02c5f/5825-DP-Calc-1980568-web?ext=.pdf

Table 28 product information of the equipment in the measurement

(a) TSI model 9535 (b) TSI model 5825

Figure 70 product photos of the equipment in the measurement (by author)

b. Execution plan

- Instant measuring the pressure difference between supply opening and air return box when the draft design model is installed, with TSI model 5825 (see Figure 71). And Instant measuring the pressure difference between supply opening and air return opening when the design is not installed, with TSI model 5825 (see Figure 72).

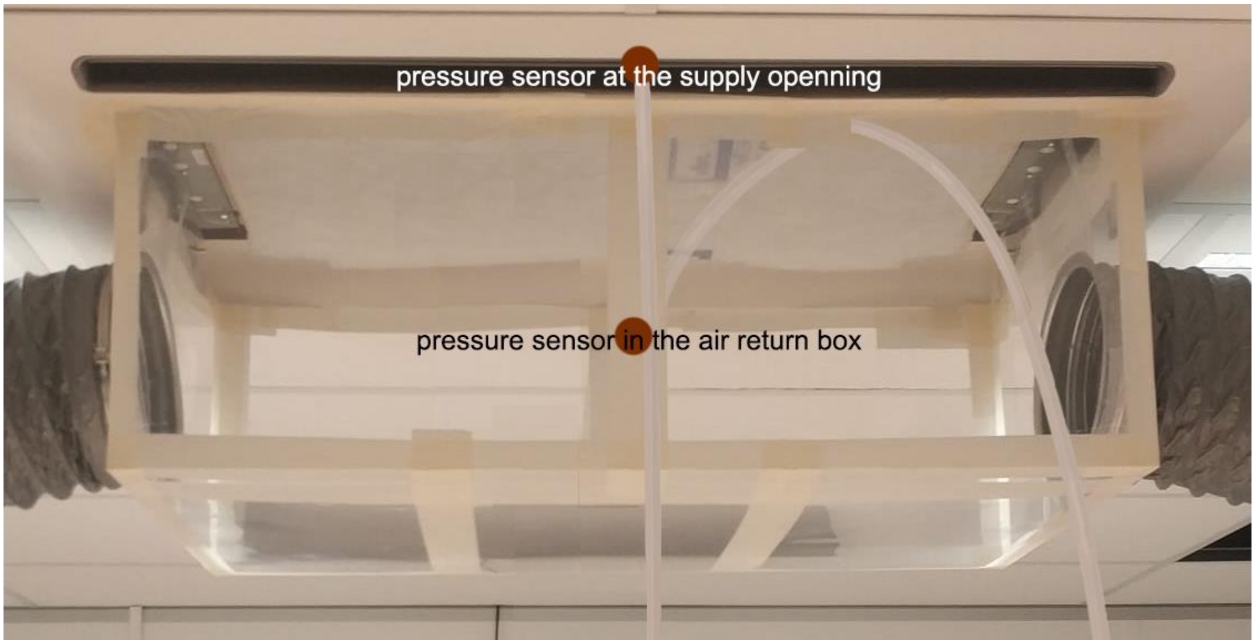


Figure 71 pressure sensor locations (by author)

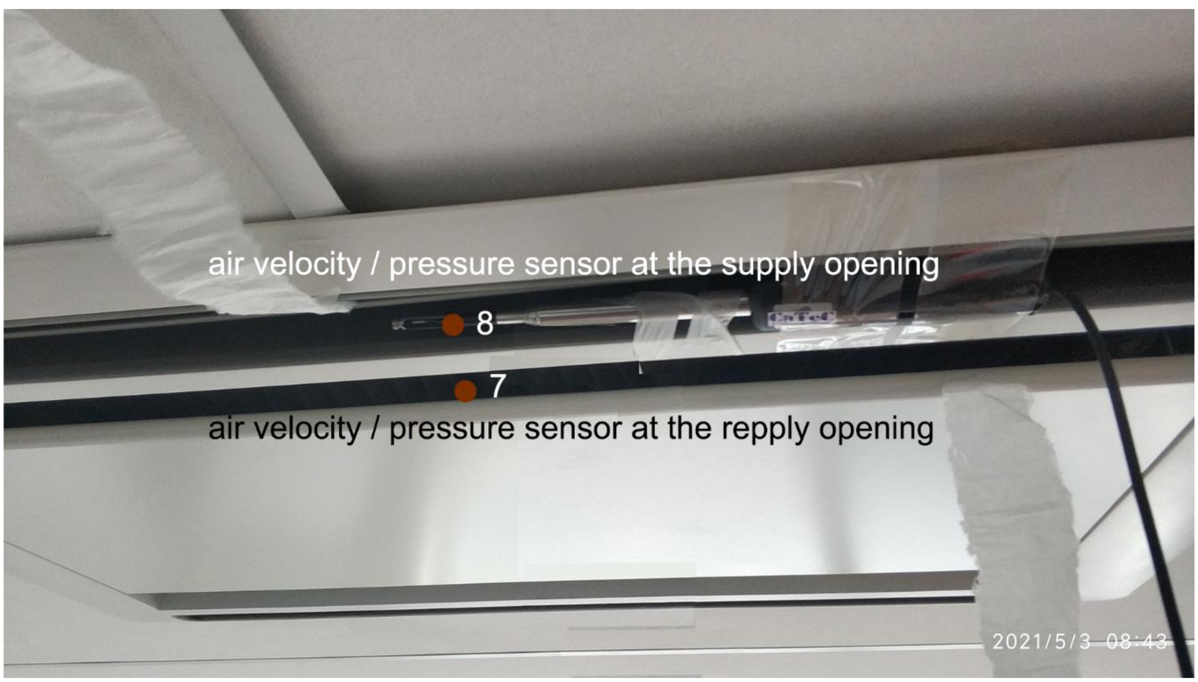


Figure 72 the sensor position directly at the openings of the indoor end unit

- Instant measuring the airflow velocities at different locations in the draft model system, in the ducts or at the openings (see Figure 73), with TSI model 9535. The sensor probe was placed squarely in the direction of the airflow on the section of the delivery pipe. After the reading stabilized, the real-time airflow rates of independent three times were recorded. And the

average value of the three real-time airflow rates is regarded as the airflow rate at that position.
*For the scenario where the draft design is installed:
The airflow at the air return openings (see positions 1, 2, 3, 4, 1', 2', 3', 4' in Figure 73), near the air return center box (see positions 5 and 6 in Figure 73) and supply opening (see positions 8 in Figure 73) are measured. Because of the obvious impacts from the turbulence closed to the duct openings (see positions 1, 2, 3, 4 in Figure 73). Another turn of metering is done at the distance from opening at twice of the duct diameter (see positions 1', 2', 3', 4' in Figure 73) to avoid the turbulence impacts.
*For the scenario where the draft design is not installed:
The airflow at the air return openings (see positions 7 in Figure 73 and supply opening (see positions 8 in Figure 73) are measured.
All these measurements were done in 16:00 pm to 18:00 pm 24th Feb 2022 in the meeting room of Kuijpers, Leiden, while the pressure meter also sensed a static pressure differences for each scenario.

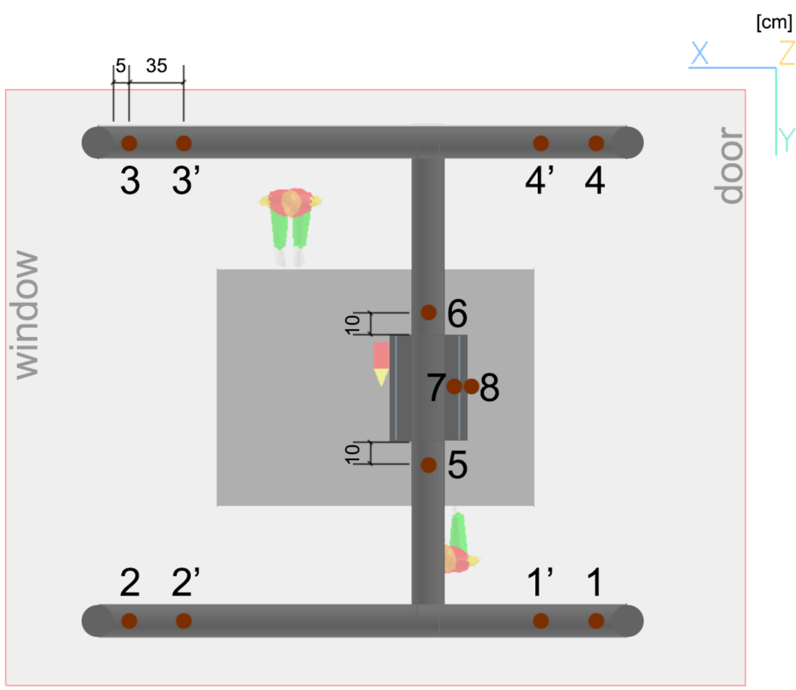


Figure 73 the airflow velocity sensor locations

3.5.2 Results and analysis

The pressure differences between air return end and supply end

with design installed	14.1	Pa
without design installed	15.2	Pa

Table 29 pressure difference between return opening and supply opening

The pressure is 1.1 Pa in the air return box and supply opening in the draft design model.

The airflow velocity at different positions in the draft design

sensor point	**with** design installed [m/s]	**without** design installed [m/s]	function
1	0.495		return
1'	0.500		
2	0.704		
2'	0.283		
3	0.538		
3'	0.337		
4	0.877		
4'	0.428		
5	1.547		
6	1.668		
7		1.955	
8	5.160	6.168	supply

Table 30 air velocity in air return ducts and supply opening

	air recirculated amount [m3/s]	air supply amount [m3/s]
with design installed	0.10	0.41
without design installed	0.16	0.49

Table 31 the supply and return air amounts before / after the draft design installed

The draft ventilation design model caused about 1/3 air recirculation rate decreasing and 1m/s decreasing for air supply velocity. Referring to the duct length difference caused by the opening location (see Table 21 Openings locations, the air velocity dropping in the duct is 0.07 m/s per meter of the length of ducts, the fraction force is 0.0028 N/m, the pressure resistance caused by ducts is 0.089 Pa per meter of the length of ducts.

3.5.3 Conclusion

The draft design model may cause a relatively high resistance for the recirculated air. In the future design, the open cavity ceiling is preferred to decrease the resistance caused by ducts.

4. Computational modelling

CFD modelling is a part of the graduate research process through the whole research and design to help visualize the air fluid in the sample meeting room based on current condition and the design outcome after optimization. The main goal of the CFD modelling is to narrow down the design and practice in the ventilation engineering, and provide a reasonable ventilation solution for prevention and control of respiratory infectious diseases by integrating general and partial methods.

The parameter in modelling settings

Particle size

The particle size is airborne particle size, 0.1 um – 0.5 um, which is the airborne particle has the same mechanical properties as tracer gas (see 2.1.2). There is no specific size to define particle size, since it is a In the cut-off value between airborne and droplet particle sizes and also the median value of respiratory particle size for infection analysis.

Tracer air

There are two types of popular tracer gas, CO_2 and N_2O, applied in airborne transmission experiments in labs to simulate the droplet nuclei from the source patient. These two tracer gases have the same density, but CO_2 is widely applied in most cases, for its convenient accessibility. N_2O is usually widely applied in the lab experiment to visualise the respiratory airflow track from manikins, as a substitute to distinguish from CO_2. The CO_2 concentration in nature is 407 ppm (the value differs from year to year, the outdoor CO_2 concentration is 420 ppm in 2022). In the case of this research, the tracer gas is CO_2 for the CFD model calibration.

According to the mass and concentration condition of CO_2 in the environment, the relaxation control of CO_2 is 50 on "Factor" and 1 on "Max increment" (see Figure 75).

The "Limits on Variables Settings" is different when the filter effect on CO_2 is considered:

- With outdoor CO_2 concentration, 407 ppm
  These cases are mostly for accuracy check. The setting are: setting Inlet value of 4.07E-4 in the attribute of "ANGLED-IN" objects for air supply (see Figure 76); setting CO_2 variant domain as min. 4.00E-4 and max. 1 in "Limits on Variables Settings" in domain setting (see Figure 77); setting 0 kg/s under the CO_2 setting scaler, with the domain of min. 4.00E-4 and max. 1 for Outlet in "ANGLED-IN" objects for air re-supply (see Figure 78).
- Without outdoor CO_2 concentration, 407 ppm
  These cases are mostly to evaluate the filter effect. The setting are: setting Inlet value of 0 in the attribute of "ANGLED-IN" objects for air supply (compared with Figure 76); setting CO_2 variant domain as min. 0 and max. 1 in "Limits on Variables Settings" in domain setting (compared with Figure 77); setting 0 kg/s under the CO_2 setting scaler, with the domain of min. 0 and max. 1 for Outlet in "ANGLED-IN" objects for air re-supply (compared Figure 78 and other detail see Modelling logics).

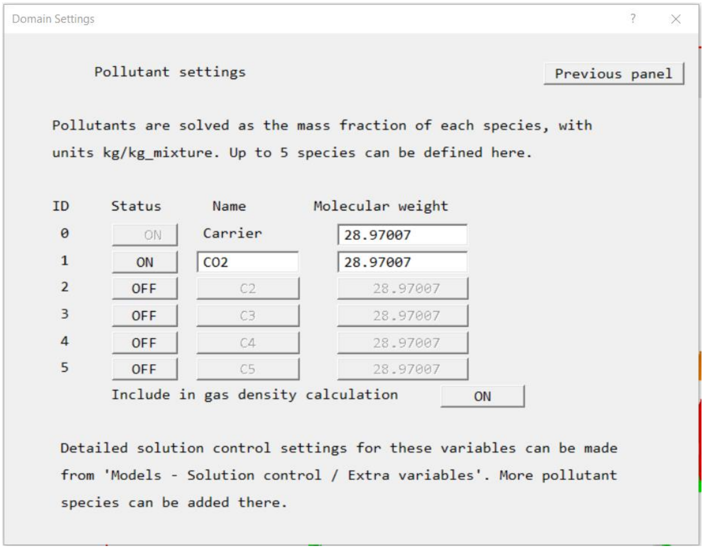


Figure 74 CO2 as the only pollutant in CFD modelling

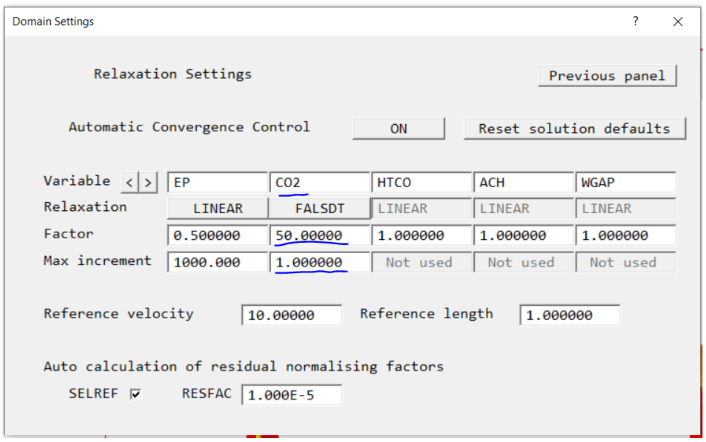


Figure 75 convergence control of CO2 in the domain setting

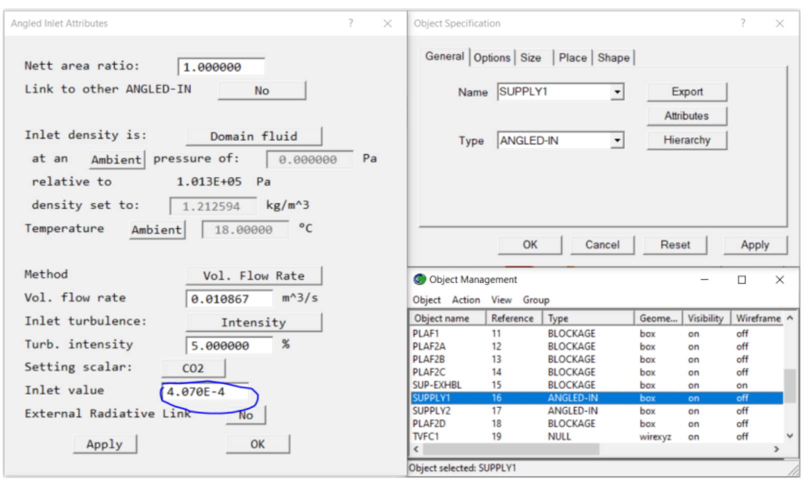


Figure 76 for those cases with outdoor CO2 concentration (407 ppm in this case), the setting in the supply objects

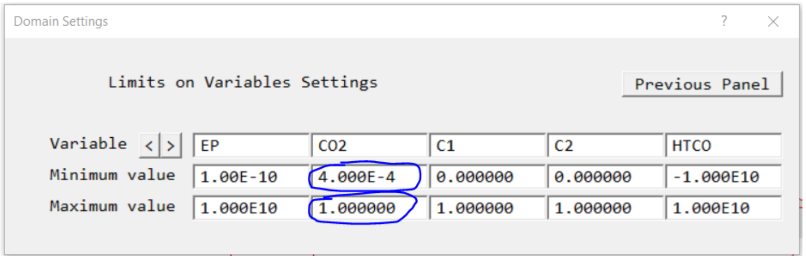


Figure 77 Limits on Variables Settings for the scenario where there is outdoor CO_2 concentration

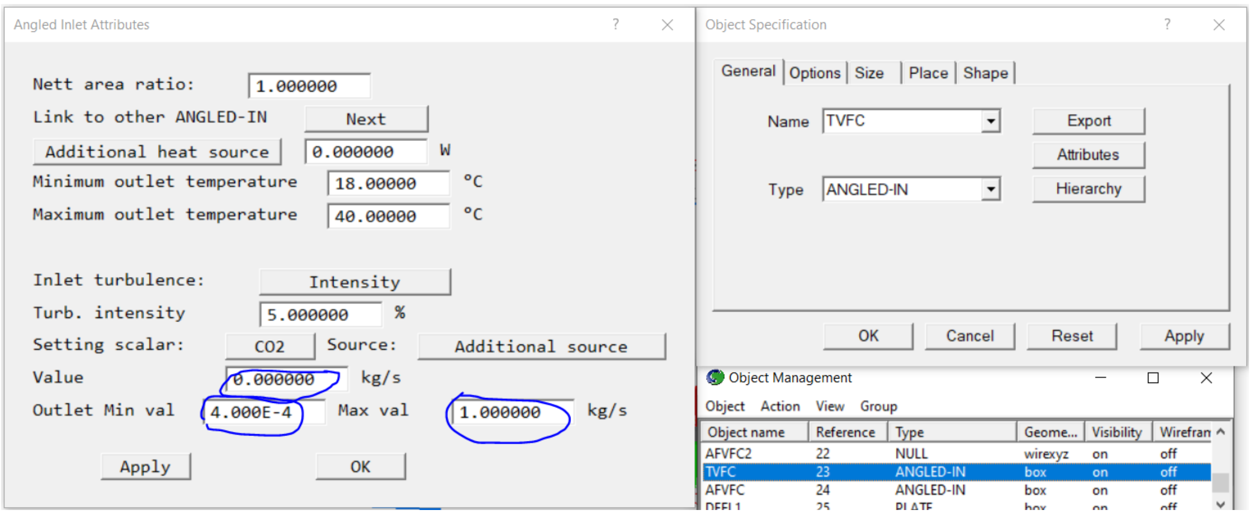


Figure 78 Object TVFC setting for the scenario where there is outdoor CO_2 concentration and no filter effect.

Manikin

The temperature of manikins' skin is 34 degree in sitting position. The clothing insulation (Clo) is 1 which simulating the indoor workers in trousers, long-sleeved shirt, long-sleeved sweater, T-shirt. The pulmonary ventilation for each manikin was chosen as 0.000183 m3/s, corresponding to an adult at rest. The heat power of each manikin was set to 80 W, also corresponding to an adult at rest. The area of oral and nasal opening is 0.011*0.011 m2. Respiratory flow (air ventilated by the lungs for one minute in rest status) is: 500 ml (1 breathing volume) x ca. 14 breaths (1 insp.+1 expir.)/min ~ 7 l /min or ca. 420 l/h. Under physical effort the respiratory flow increases up to 80-100 l/min, that means 4800-6000 l/hr. This should be divided by 2 to get the expiration air flow, that is from 210 to max. 3000 l/h. Knowing that inspired air contains 0.03% CO_2 but expired air contains 4% CO_2, it means that CO_2 generation (l/h) is got from expired CO_2 minus inspired CO_2: 210x4/100 - 210x0.03/100 ~ 8.37 l/h expired CO_2 in rest status; 3000x4/100 - 3000x0.03/100 ~ 119.1 l/h expired CO_2 in maximum physical effort (Mateescu, 2018). The CO_2 concentration for each manikin was chosen as 0.030303, corresponding to an adult at rest. The sitting height is set as 1.3 m, corresponding to an adult at rest. Thus, the breathing zone for analysis is set at 1.1 m height.

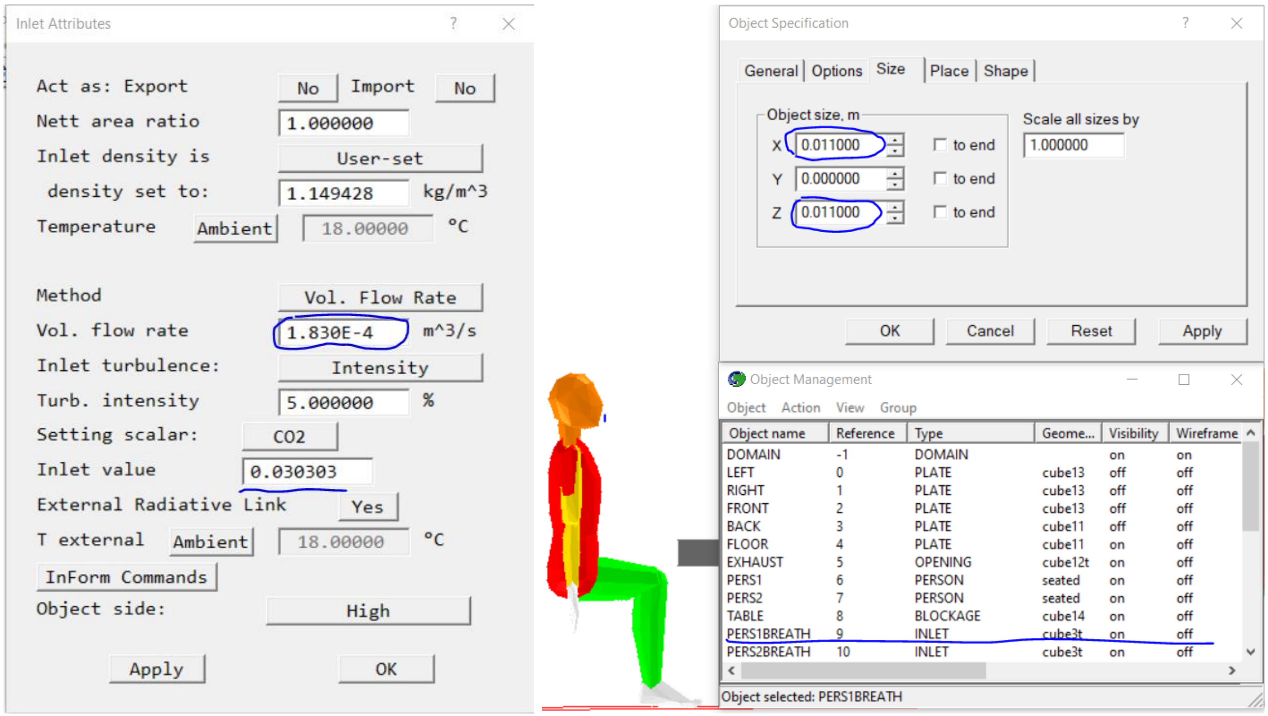


Figure 79 the setting of the respiratory mode in CFD (by author).

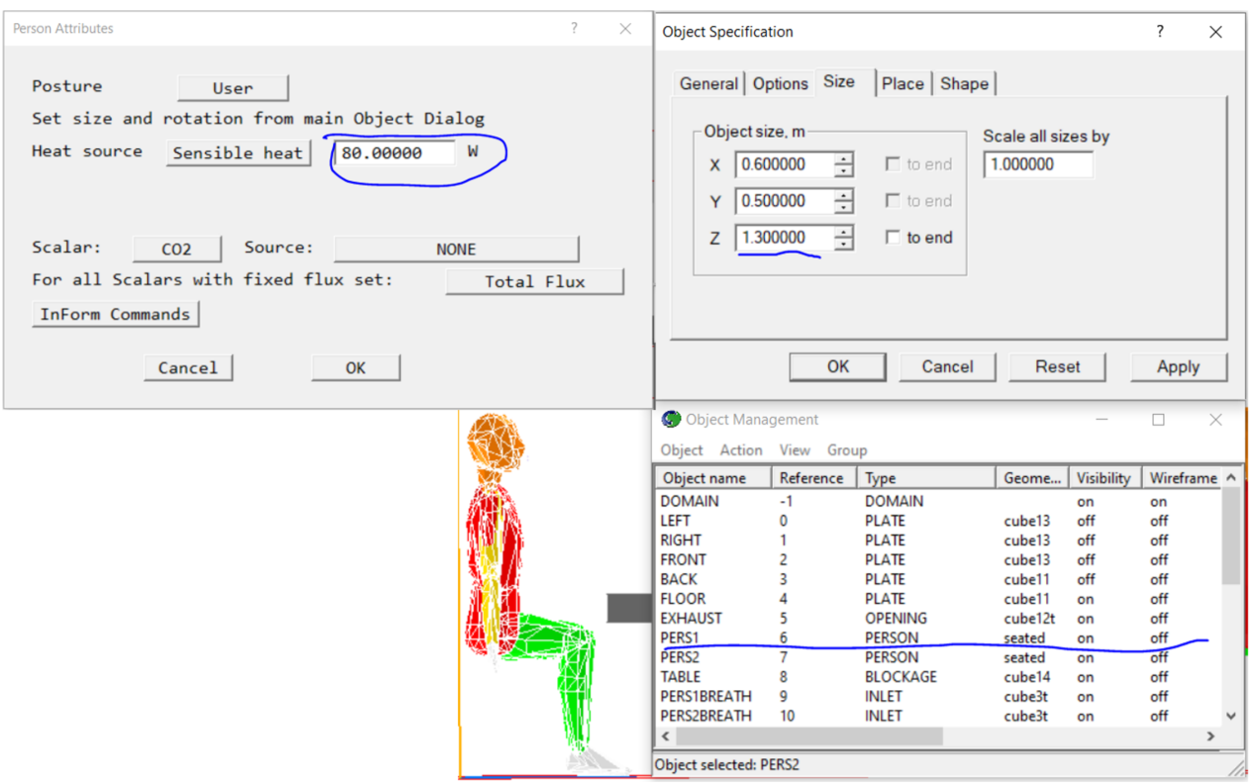


Figure 80 the setting of the manikin in CFD (by author).

There is a flaw in the manikin setting for “Temperature” in Figure 79, the “Ambient” should be turned off and the temperature should be set as 34℃. The impact of this flaw is the contaminant concentration is relatively higher because there is no thermal effect from respiratory airflow and the thermal plume is only impacted by the body temperature. The contaminant concentration of the breathing zone tends to be higher in this research. In the further research, the correction is needy for the precise analysis of the effect of thermal uplift in respiratory gases.

Geometry and grid

The simulated space is 4.52m*5.6m*2.8m(height). The computational geometry replicates in detail the experiments carried out in the full-scale chamber (see Figure 81). Most of the chamber geometry is created with a hexahedron. Only near the manikins and the diffuser has a tetrahedral mesh been used. A conformal mesh joins both blocks of cells. Due to their geometry complexity and the expected high velocity and temperature gradients, mesh refinement was performed around the two manikins, the radiator, the two exhausts, and the diffuser. The mesh is significantly refined at the manikins’ faces and in the breathing zone in order to accurately simulate the interaction between the two breathing flows.

The grid mesh follows default setting. The domain size is 5.6m*4.52m*3.1m(including the height of ceiling). The tolerance of the model is 10^-3m,

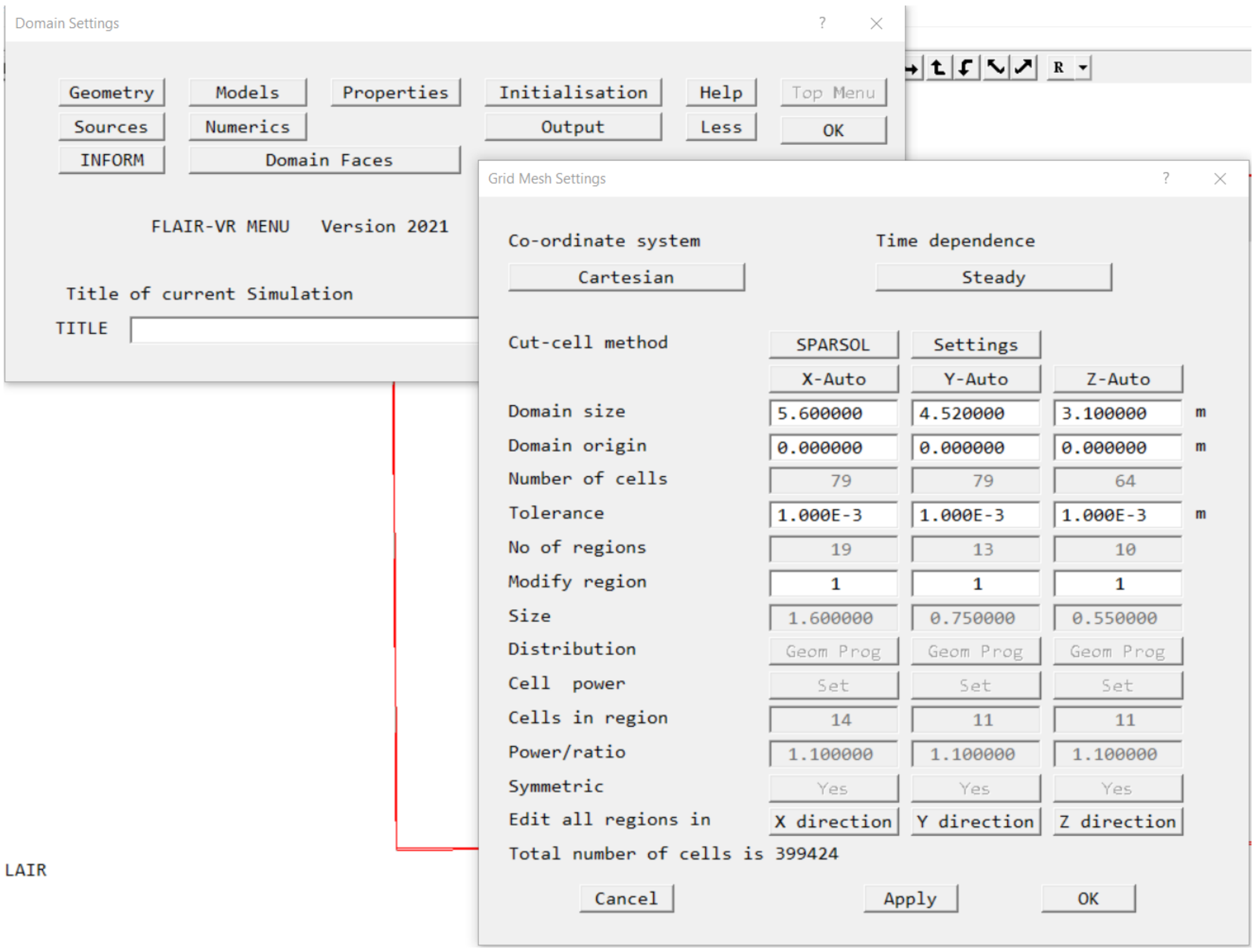


Figure 81 the grid mesh settings of the modelling

Convergence control

Good convergence curves are the solid basis for any conclusions about room ventilation parameters. The following research try to integrate the ventilation efficiency evaluation with the “corona-proof” ventilation performance. To avoid the non-convergence, the thermal setting should be after the domain setting well finished. In this research, there are further attempts needing for precise collaboration between CFD modelling and room ventilation parameters. The limitation of CFD modelling in the realistic ventilation system design is the evaluation of the ventilation efficiency is indirectly provided by the modelling output. The consensus of ventilation performance in practical design is not widely reached yet. Thus, the exploration of the software in this aspect is still on its way. In this research, the controls in “Domain setting”” are:

- Switch off the Immersol radiation model. It is a feature of considerable additional complexity for the model. Best to omit it during the basic stage of trying to get full convergence.
- Reduce the number of objects "affecting the grid", to reduce the number of region boundaries, making it easier to have a nice smooth mesh with less cells.

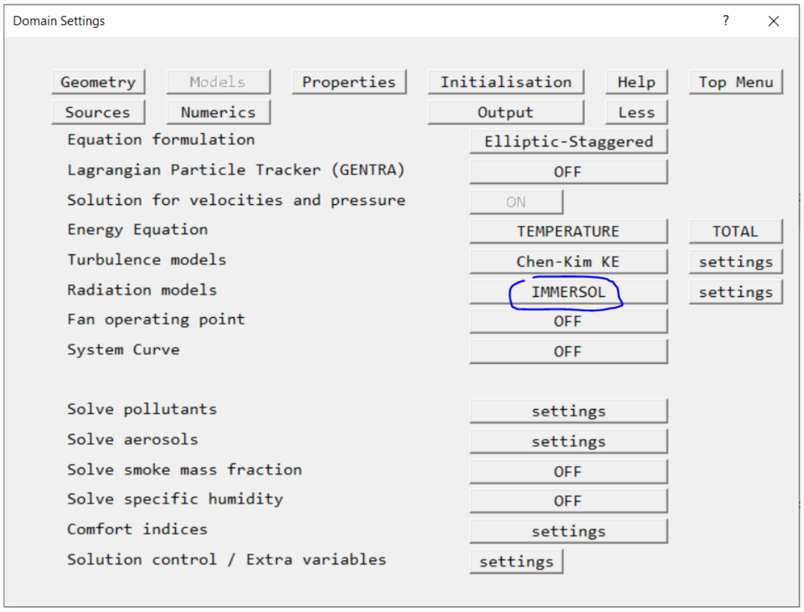


Figure 82 the setting to switch off IMMERSOL

- Optimize the number of cells in in-let "objects", to avoid models requiring too much local detail and high precision.
- Relaxation - switch off CONWIZ, and set FALSDT on the velocity components (in this case, 0.2s), AGE (in this case, 10s), based on assumed values that the model can well converge faster.
- Set iteration numbers (LITER) for the linear solver as follows ("Numerics" / "Iteration control"): 300 for P1, 50 for KE, EP, AGE and concentration variables. It is important for the linear solvers for the scalar variables to be fully converged.

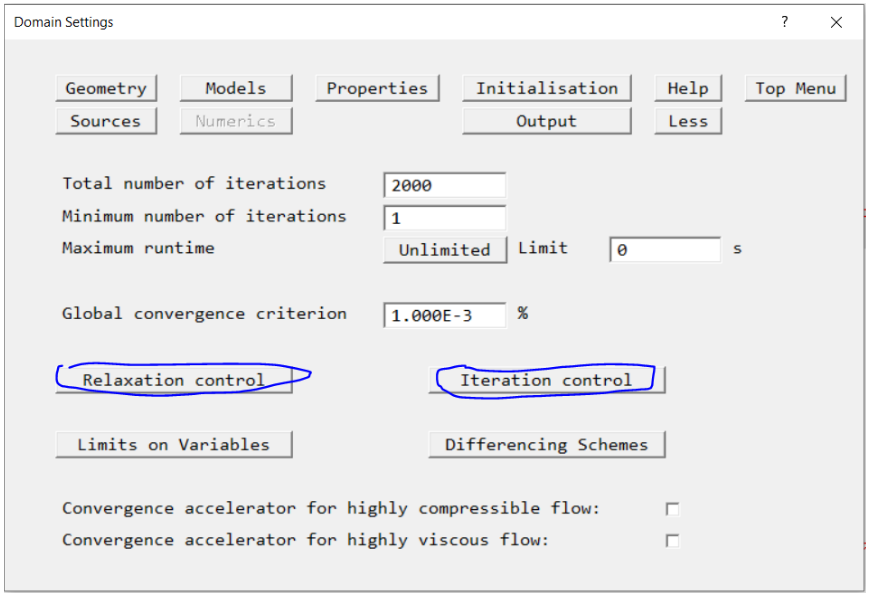


Figure 83 the main panel for convergence control in domain setting

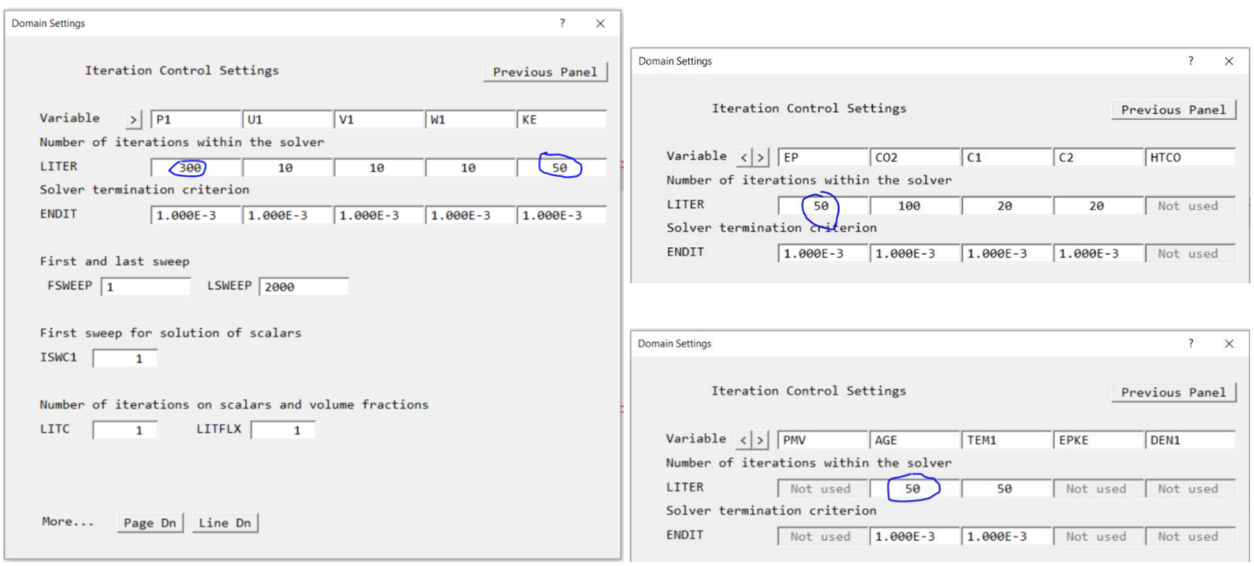


Figure 84 The setting in iteration numbers (LITER) for the linear solver

Some further simplifications in "object" controls, which can be reset for personal design after the convergence impacts have been clarified:

- Remove the two people and their breathing sources;
- Remove solution for temperature (and by implication, buoyancy);
- Increase the width of the air supply ducts - so that the grid did not need to be quite so fine round there.

Modelling logics

To carry on the CFD modelling, there are still some important practical modelling details to be illustrated.

Simulation of Fan coil based air recirculation

The simulation of the air recirculation pattern in the indoor end unit applied the logics of creating two pairs of suction in the model. Firstly, the model separately links the pair of angled-in objects and merges geometry to create the suction opening, AFCFV in the model. And then, the model makes the two angled-ins to act as outflow as the resupply opening of the air-recirculation mode, TVFC in the model. Since the AFCFA and TVFC are a pair, the changes, like duplication, need to be done in pairs.

Simulation of filter effect following air recirculation simulation

The simulation of filter effect ignored the pressure drop caused by the purifier facility in practice, and simply focused on the contaminant removal performance and its synergetic impacts in the ventilation design. With the ANGLED-IN objects for re-supply automatically created following the fan coil modelling, the removal mode can be set in its attribute. To simulate the contaminant produced by indoor users only, the outdoor CO2 concentration is omitted, the pre-setting for this scenario can be referred to The parameter in modelling settings. The filter effect can be set by the removal value, in this research, it has been set as 50%, 70%, 90%, to discuss the different ePM 1 standards that widely applied in the filter market. The Outlet scale should range from Min val 0.

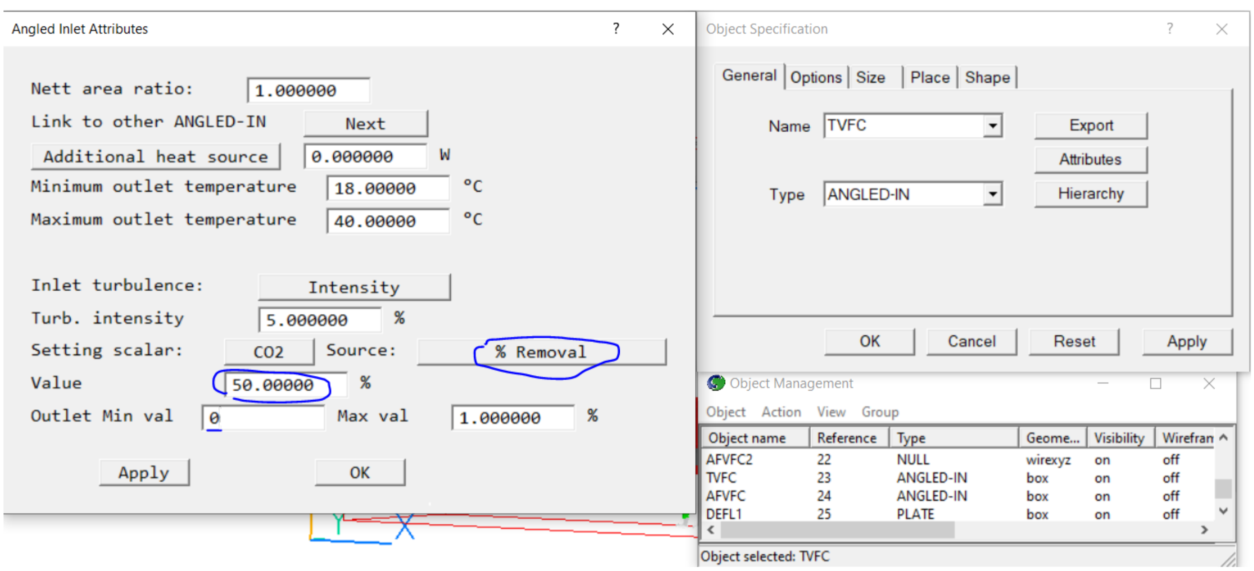


Figure 85 the filter effect setting via angled inlet attributes of TVFC

Simulation of airborne particle by applying CO2 as the tracer gas

CO2 is regarded as the tracer gas in the model, because of the amount of this contaminant concentration rate is relatively and widely known. To increase the sensibility of the CO2 concentration by human beings, the existing CO2 concentration in nature outdoor supply air is only ignored in the matrix modelling.

Simulation of the occupation condition of the small enclosed space

There are two manikins in the model. Both of them are of default parameters for their indoor thermal impacts. The detail simulation of their breathing mode is by creating an inlet object at each mouths, perpendicular to y-axis, and setting respiratory volume and CO2 concentration rate respectively.

CFD research process

In this phase, all the CFD modelling research is based on the comprehension of interdisciplinary knowledge base, **theoretical ventilation design, infectious disease pathology** and **practical systematic control.** Though each modelling has its own emphasis: the *accuracy test* focusing on the practicability of theoretical ventilation design (see 4.1 and 4.2.2), the *synergy exploration* focusing on the "corona-proof" efficiency of the theoretical ventilation design (see 4.3), the *draft position analysis* focusing on the "corona-proof" efficiency in the practical ventilation systematic control (see 4.4.1), the *draft filter effect analysis* focusing on the feasibility of theoretical ventilation design in the practical ventilation market (see 4.4.1), and the *design result test* comprehending the "corona-proof" performance of the ventilation design in practice.

	phase	**model number**		**content**	**purpose**
1	accuracy test	2 in total	1	current situation	accuracy of Phoenics software
			1	standard case	accuracy of infection-risk research method
2	synergy exploration	a matrix of 36 in total	18	ventilation patterns	the applicability engineering evaluation for infection risk analysis
			18	application of filter	the sufficiency and necessarily of filter in decreasing the infection risk
			18	application of air recirculation	the possibility of secondary pollution of indoor end unit
3	draft position analysis	vertical	1	foot height	the technical recommendation from cleanroom design methods
		horizontal	1	4 openings at ceiling level	the multiple openings with the same efficient opening area will provide higher flexibility for the usages of the room (to avoid the cross air flow from unpredictably-located users in reality)
		return opening	1	the overlapping of return opening and exhaust opening	to figure out if overlapping the exhaust opening and return air opening will impact the hygiene performance
4	draft filter effect analysis	filters	3	50%, 70%, 90% commercial filter efficiency	to figure out an optimal commercial choice for the application of filter
5	design result test	2 in total	1	the simulation accuracy	accuracy of Phoenics software and on-site draft insulation

			1	the infection risk result	getting rid of the initial starting value, 407ppm for CO_2 as the tracer gas

Table 32 CFD modelling content

4.1 CFD modelling of current situation

To model the current situation of the ventilation performance is to check the accuracy of the CFD research method, and prove the prospective significance and practical value of the experimental results for practical engineering..

4.1.1 Background

The CFD modelling of the current situation is the start point for the CFD modelling phase. Since the research is interdisciplinary, using CFD modelling to understand the current ventilation situation also include the three aspects, **theoretical ventilation design, infectious disease pathology** and **practical systematic control.**

Therefore the research question for this experiment is:

1. How accurate is the CFD modelling research method for the practical realistic ventilation design case?
2. What is current infection risk in the space based on the current ventilation pattern?

4.1.2 Current ventilation performance

The CFD modelling simulated the real ventilation situation by using CO_2 as the tracer gas. As the fig. shows, the CO_2 concentration in the breathing zone under this type of ventilation situation is 914.8 ppm, which is consistent with previous on-site measurement results. It promise a high accuracy between computational modelling and possible real situation.

CFD modelling setting:

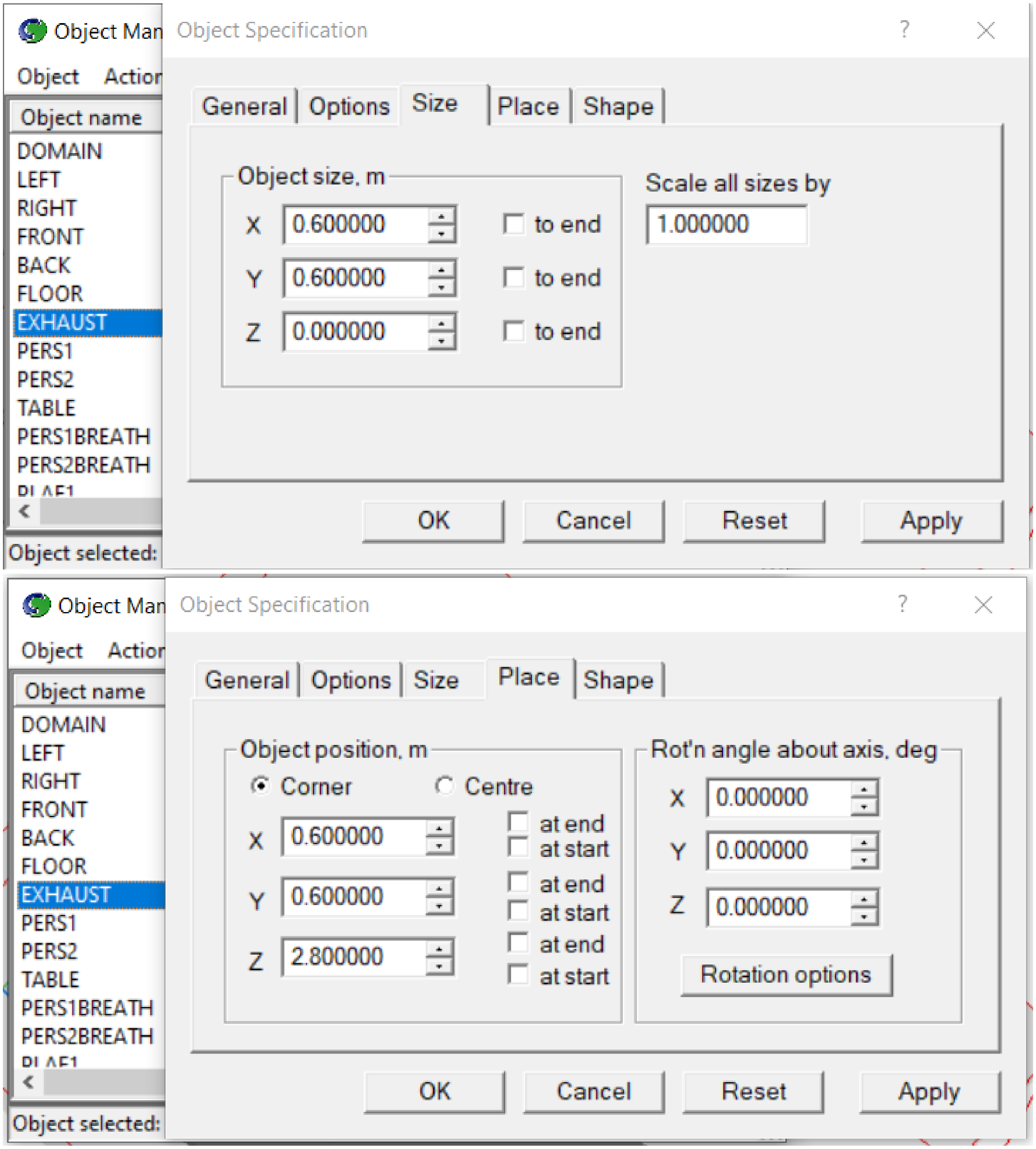


Figure 86 Size and place setting of the Exhaust in the simulation of the current situation (case 00)

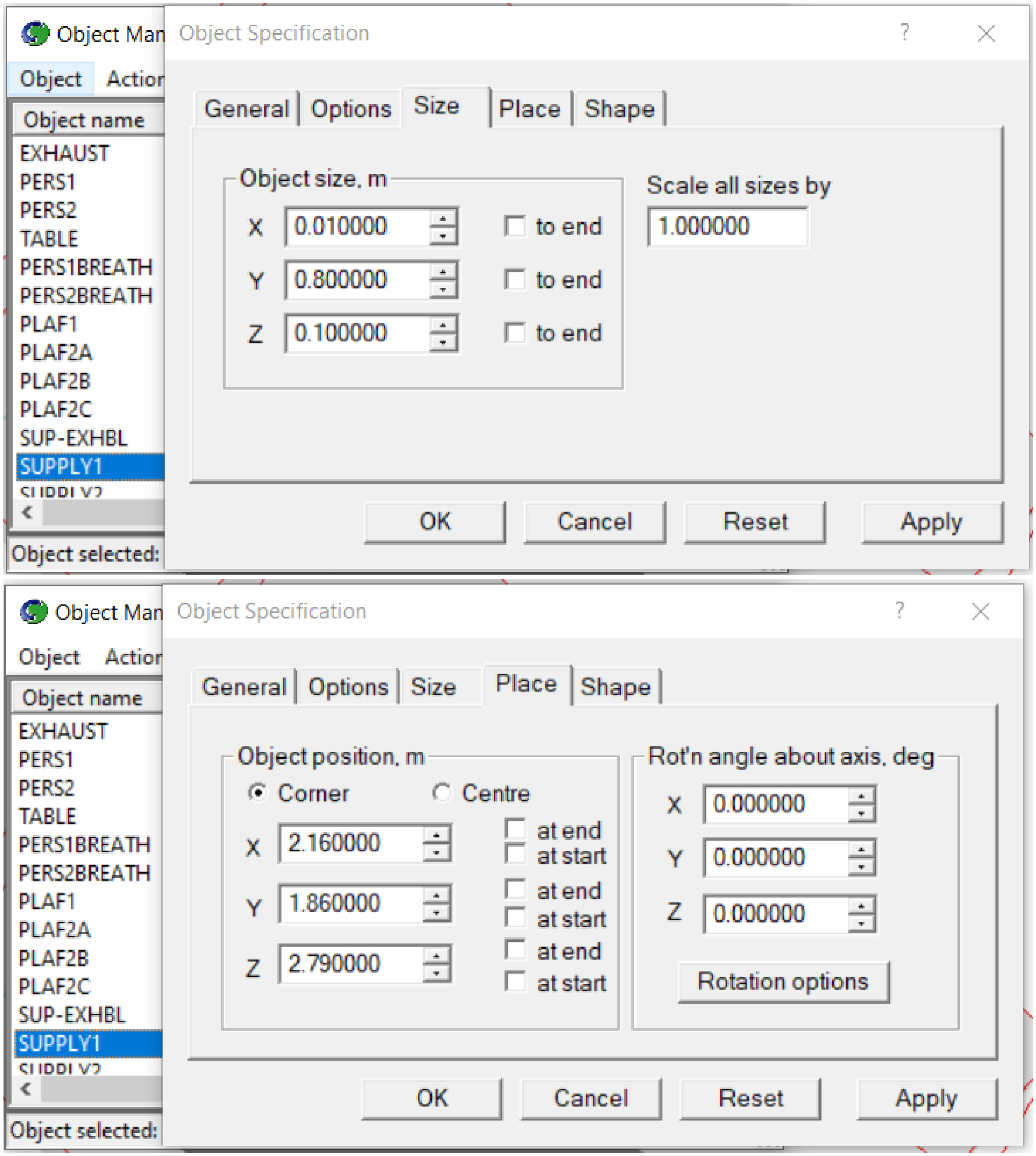


Figure 87 Size and place setting of the Supply 1 in the simulation of the current situation (case 00)

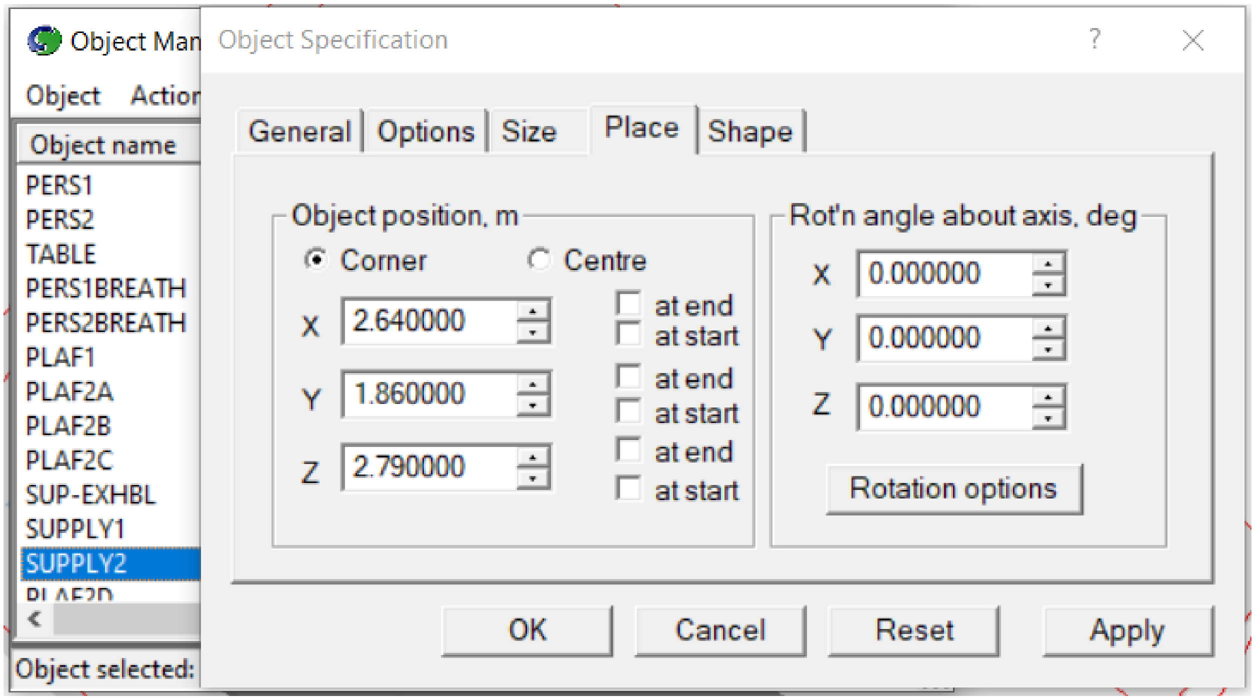


Figure 88 place setting of the Supply 2 in the simulation of the current situation (case 00)

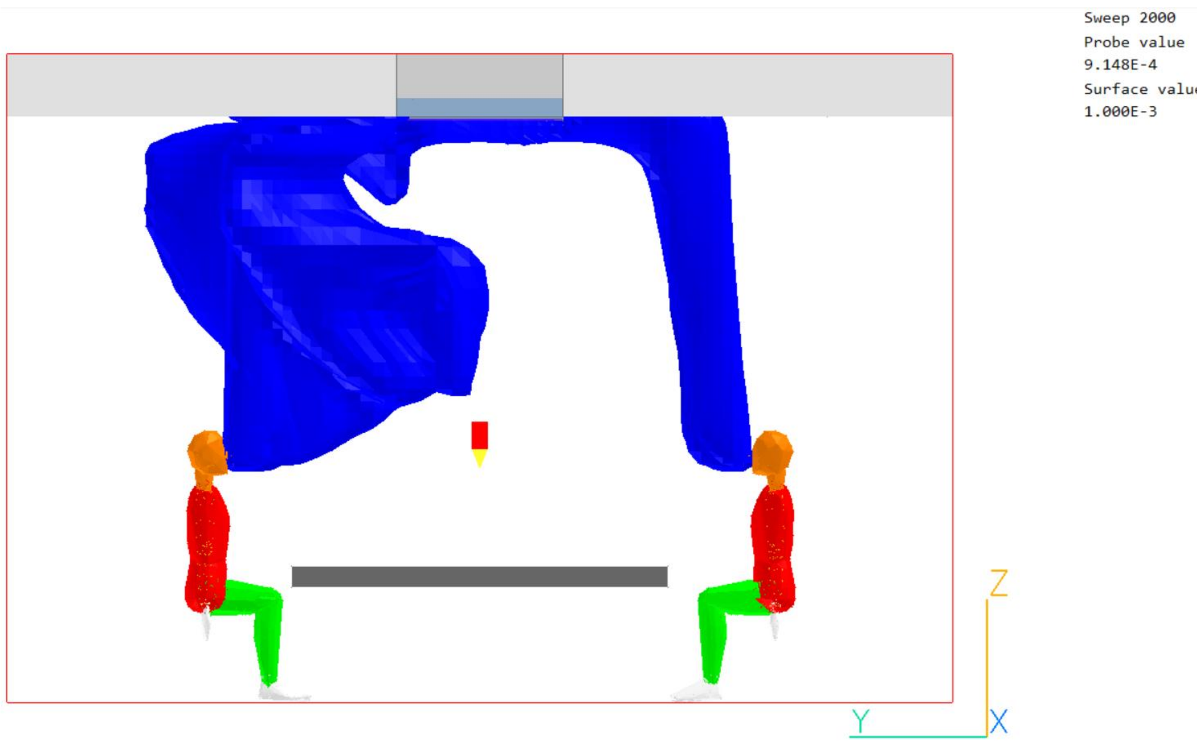


Figure 89 the outcome of the simulation of the current ventilation environment

The ventilation efficiency is evaluated by air change rate and pollutant removal efficiency based on Rehva Ventilation Effectiveness Guidebook (M. Mundt, H. M. Mathisen, M. Moser, 2004):

For general air change rate calculation:

$$\varepsilon^a = \frac{\tau_n}{\bar{\tau}_r} \cdot 100 = \frac{\tau_n}{2\langle \bar{\tau} \rangle} \cdot 100 \quad [\%]$$

Equation 2 general air change rate calculation

For local air exchange rate calculation:

$$\varepsilon_P^a = \frac{\tau_n}{\bar{\tau}_P} \cdot 100 \quad [\%]$$

Equation 3 local air exchange rate calculation

The evaluation reference for air change rate:

Flow pattern	Air change efficiency, ε^a
Ideal piston flow	100 %
Displacement flow	$50\ \% \le \varepsilon^a \le 100\%$
Fully mixed flow	50 %
Short-circuit flow	≤ 50 %

Table 33 the evaluation parameters for the ventilation efficiency and its flow pattern

For general pollutant removal efficiency:

$$\varepsilon^c = \frac{c_e}{\langle c \rangle}$$

Equation 4 general pollutant removal efficiency

For local pollutant removal efficiency (also local air quality):

$$\varepsilon_P^c = \frac{c_e}{c_P}$$

Equation 5 local pollutant removal efficiency (also local air quality)

		general	*local*	
			seat 1	*seat 2*
Ventilation efficiency	**air change rate**	51%	> 100%	> 100%
	pollutant removal efficiency	82%	102%	102%

Table 34 the modelling results of the ventilation calculation of current ventilation situation

From the calculation based on the CFD results of current situation simulation, the room is under the well mixing ventilation condition and the ventilation efficiency is of a good level. The general air change rate is 51%, very closed to 50%, which means the room is a well mixing ventilation pattern. And all the local air change rate in the breathing zone is > 100%, which means the air change in breathing is above the average efficiency of the whole space. Though the general pollutant removal efficiency is 82% for the whole space, the local pollutant removal efficiency is 102% in the breathing zone which means the air quality in the breathing zone is of a good level and above the general air quality in the room.

4.1.3 Infectious risk

Based on the performance of the current meeting-room the infection risk is 12 %,based on a fresh air supply of 79 m3/h. This is 0,011 m3/s per person = 0,022 m3/s when there are two persons in the room. In order to create a better situation other climate-measures should be considered. In the following case (figure 1) one infected person is 1 hour in the meeting room. When this person is for 2 hours in the meeting room the infection risk will rise to 19 % already.

Berekening Wells-Riley benadering			
P_{inf}	**besmettingskans via aerosolroute**	-	12%
P	ademvolume	m3/h	0,5
t	blootstellingsduur	h	2
C_{gem}	gemiddelde virusconcentratie	quanta/m3	0,13
q	virusemissie 1 persoon	quanta/h	25
I	aantal geinfecteerde personen (waar?)	-	1
Q	totale verse luchttoevoer in ruimte	m3/h	79
V	volume van de ruimte	m3	70
T	aanwezigheidsduur geinfecteerden	h	1
C_{gem}	gemiddelde virusconcentratie	quanta/m3	0,13

De Wells Riley formule:

$$P(inf) = 1 - e^{-P*t*C_{gem}}$$

P(inf) =	besmettingskans (via aerosolroute)	[-]
I =	aanname aantal geïnfecteerde personen	[-]
P =	ademvolume	[m³/uur]
t =	blootstellingsduur	[uur]
C_{gem} =	de gemiddelde virusconcentratie	[q/m³]

$$C_{gem} = \frac{1}{T}\int_0^T C(t)dt = \frac{q}{Q}\left[1 - \frac{1}{Q/V * T}\left(1 - e^{-Q/V*T}\right)\right]$$

C_{gem} is afhankelijk van:

q =	aanname virusemissie één geïnfecteerd persoon	[quanta/uur]
Q =	totale verse luchttoevoer in de ruimte	[m³/uur]
V =	volume van de ruimte	[m³]
T =	aanwezigheidsduur geïnfecteerde personen	[uur]

Table 35 Calculation result of the current ventilation condition via Wells-Riley calculation method in Excel

4.1.4 Conclusion

The ventilation pattern in the sample meeting room is the well-mixing ventilation pattern. The current ventilation condition cannot allow any kind of indoor gathering activities because of the high infection risk, though the general air change rate and the pollutant removal efficiency is of a generally good standard.

4.2 Evaluation system

The priority of the evaluation standard under this topic focuses on the design indicators that indicate infection risk. Consistency of formula application scenarios, an acceptable infection risk level as the reference for design, modelling and evaluation effectiveness of the ventilation strategy is the key in this research. The evaluation standard study is to discuss the design reference, including the acceptable infection risk and constants for Wells-Riley formula under the COVID-19 virus situation.

How to evaluate the local infection risk based on the Wells-Riley formula?

1. How to relevant the current “corona-proof” ventilation performance with the series of optimization ventilation cases analysis?
2. How to evaluate the local infection risk based on the Wells-Riley calculation in CFD modelling?

4.2.1 Methodology

As the dynamic parameter system introduced in the Chapter 2.4.2, the local infection risk directly mapped to the local contaminant concentration. And the applicability of Wells-Riley calculation method matched with the **medium-scale environment** attributes (see chapter 2.4.3). The mapping logics is the basis of the evaluation system for the “corona-proof” performance of CFD modelling cases with different variants. After extracting the variants that worthy to research from the current situation, the variants have been controlled or changed and developed a series of modelling cases (see Figure 90). The infection risk directly relates to the local contaminant concentration rate (see Figure 92). Thus, the CO2 concentration rate in the breathing zone is regarded as the main object value discussing in the evaluation system. A standard case is developed to equalise the differences caused by the manikins’ positions and indoor end unit position in the geometry layout of the room under the same ventilation pattern with the same ACH, but with the maximum fan coil performance. The CO2 concentration rate in the breathing zone of standard case functioned as the initial reference value to illustrate the changes and fluctuations of the “corona-proof” performance of cases with different ventilation strategies.

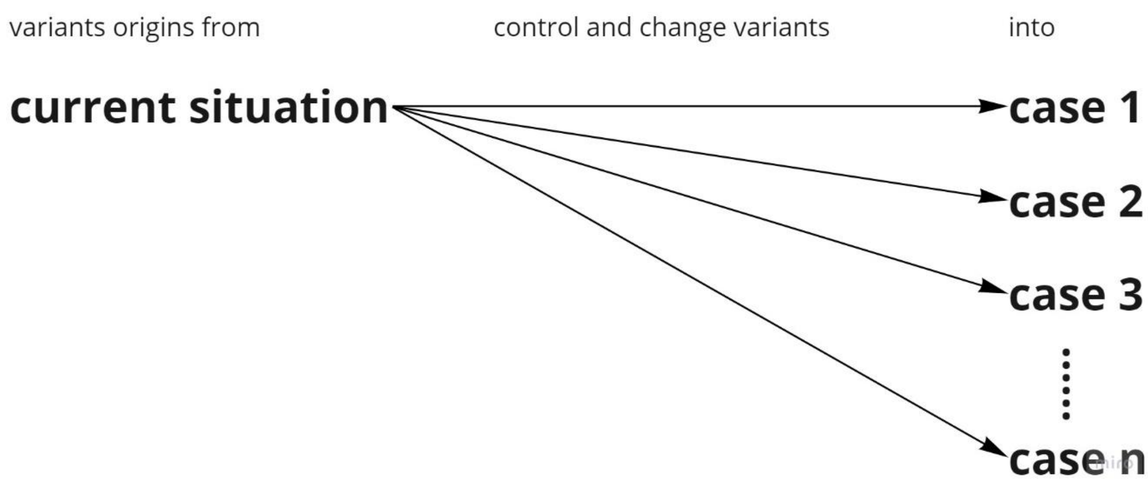


Figure 90 cases developing mapping

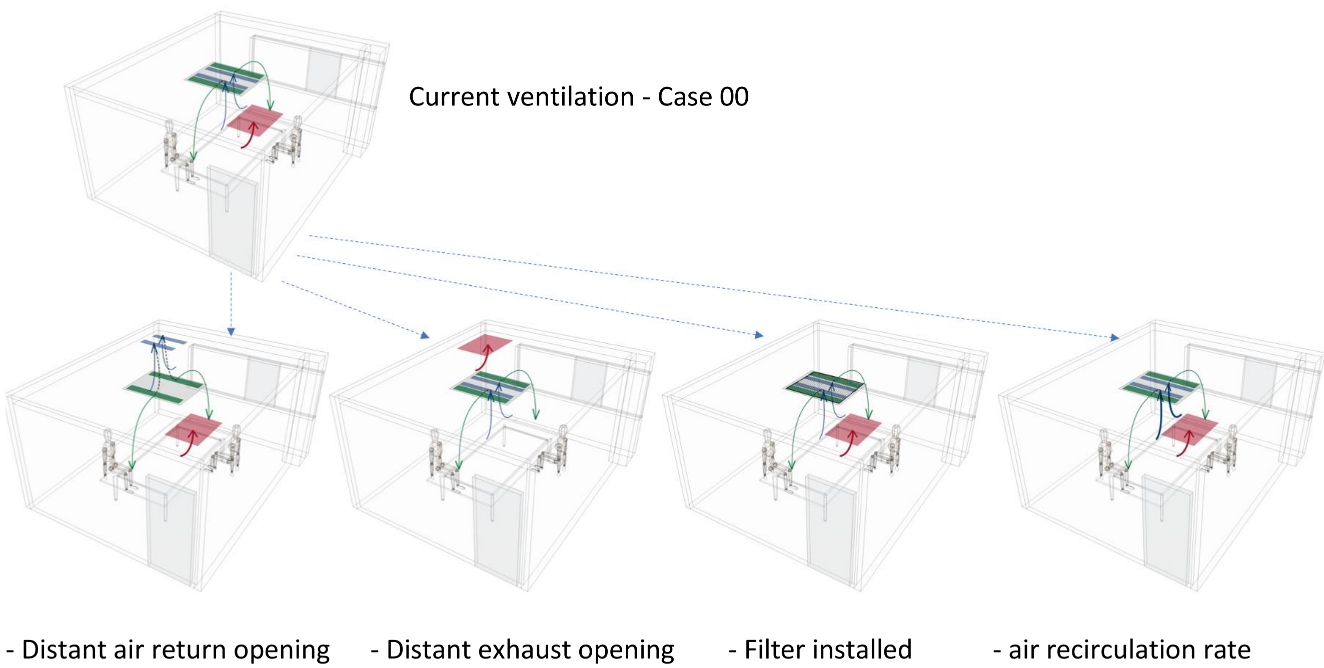


Figure 91 the variant detail for case developing

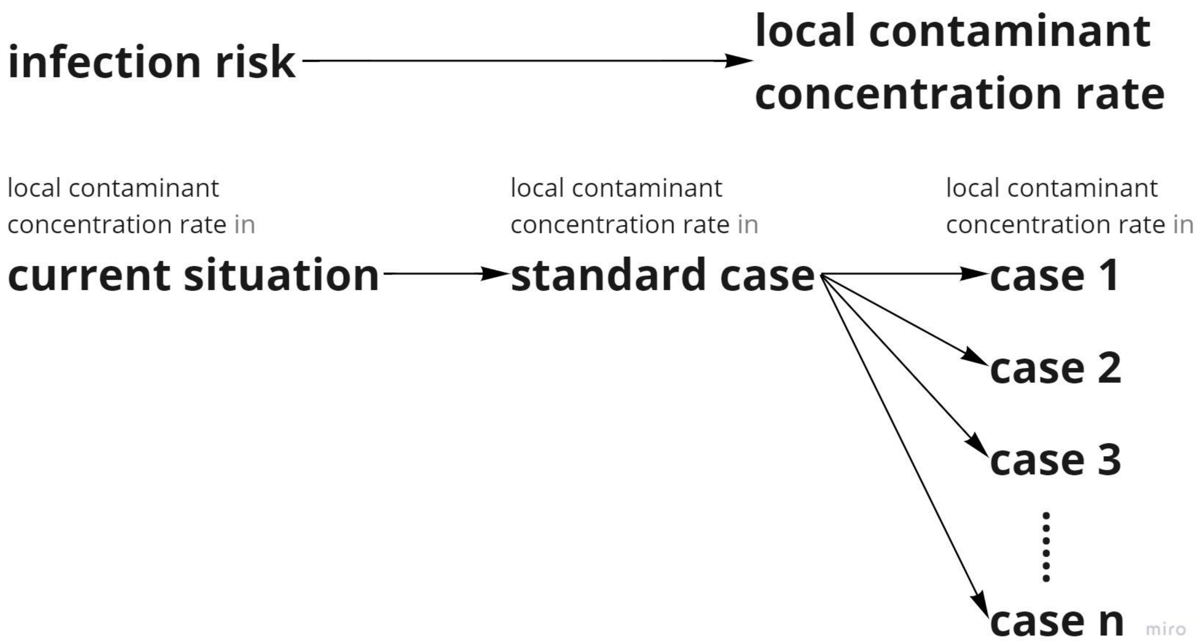


Figure 92 evaluation logics mapping for "corona-proof" performance of different cases

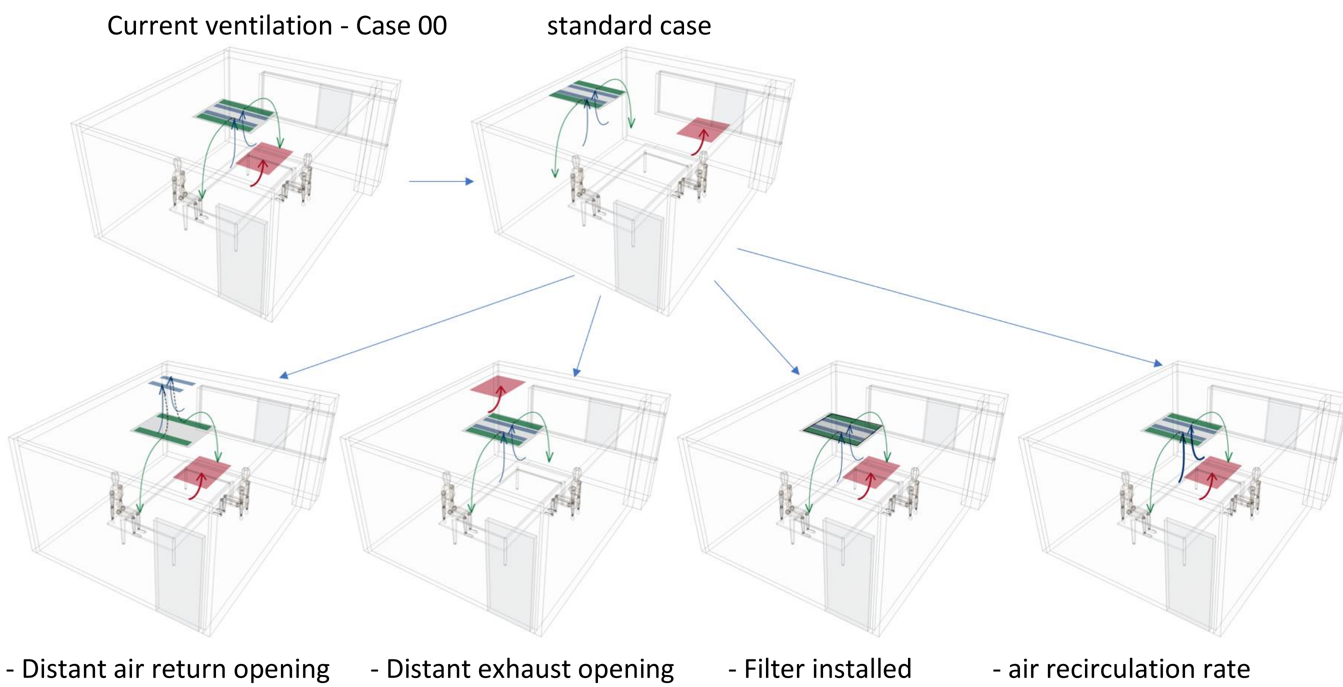


Figure 93 the variant detail for evaluation mapping for "corona-proof" performance of different cases

4.2.2 Standard case

To focus on the partial ventilation control level, the possible impacts from centralized ventilation control level and individual differences should be minimized.

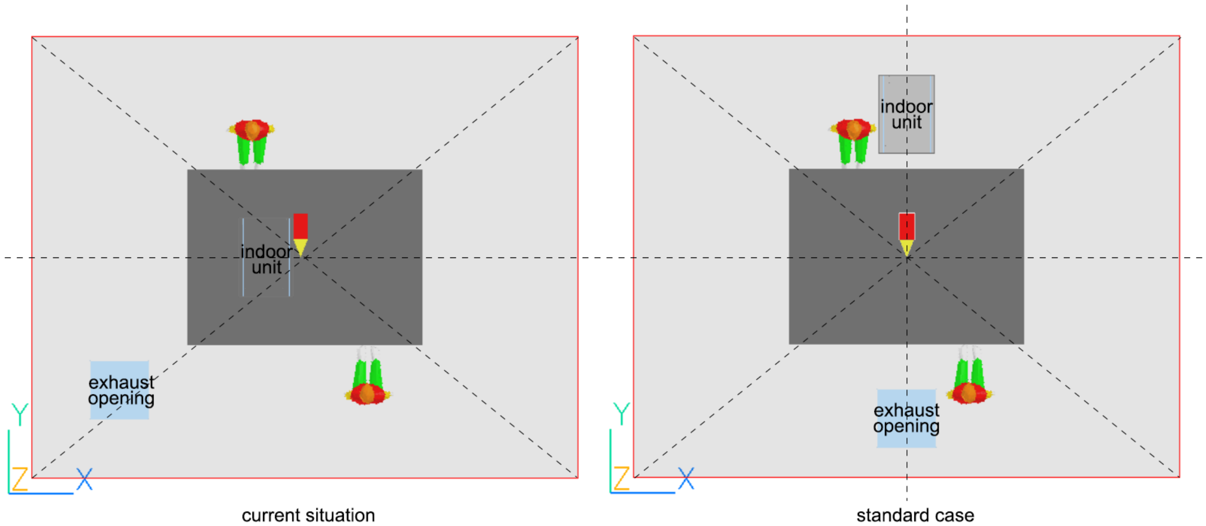


Figure 94 the centrosymmetric layout of the user locations & asymmetric layout of the ventilation facilities to equalize the pollutant distribution under current ventilation pattern for the standard case

- Parameter setting

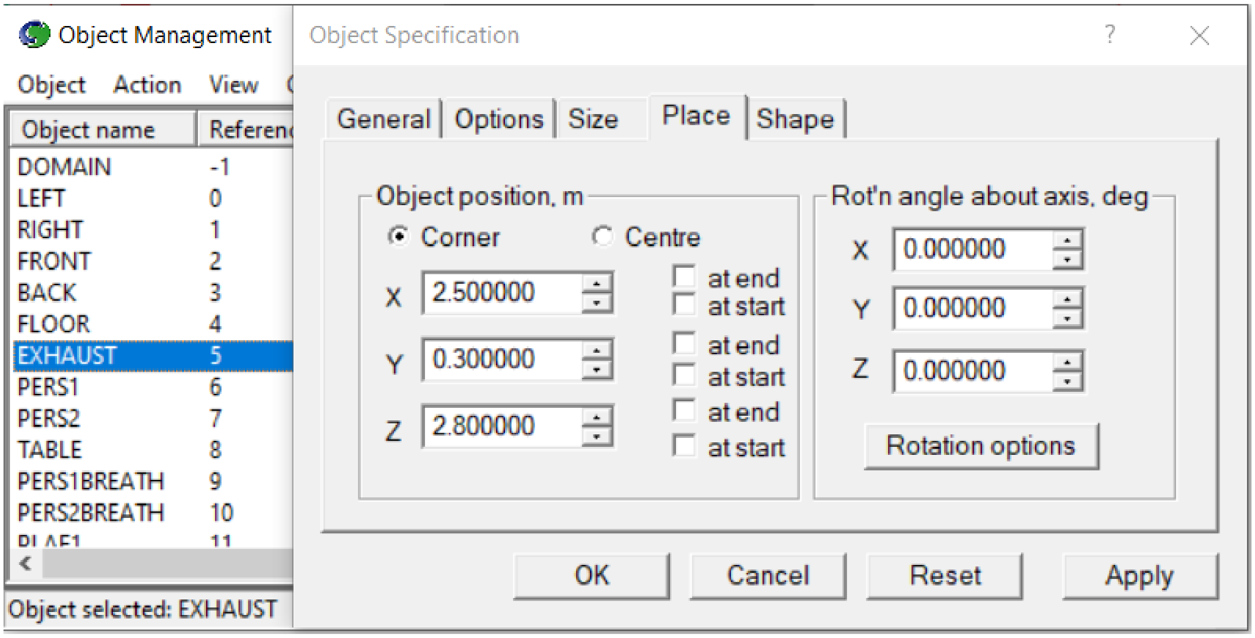


Figure 95 the changed "place" setting for the EVAHUST compared with Case 00

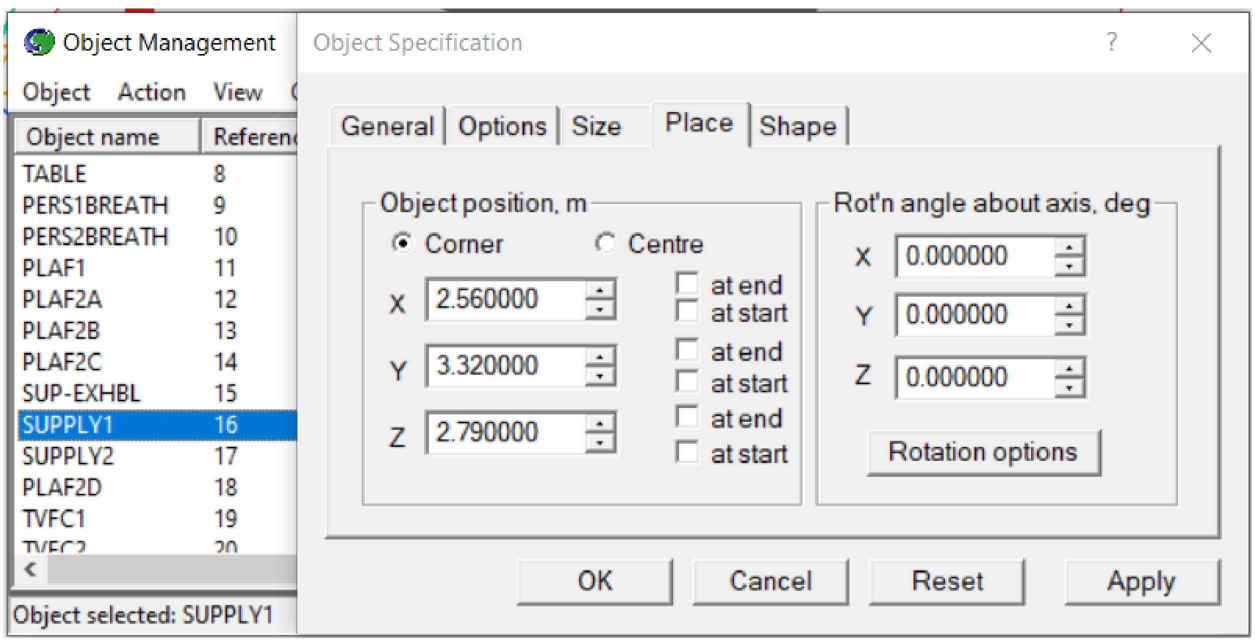


Figure 96 the changed "place" setting for the SUPPLY 1 compared with Case 00

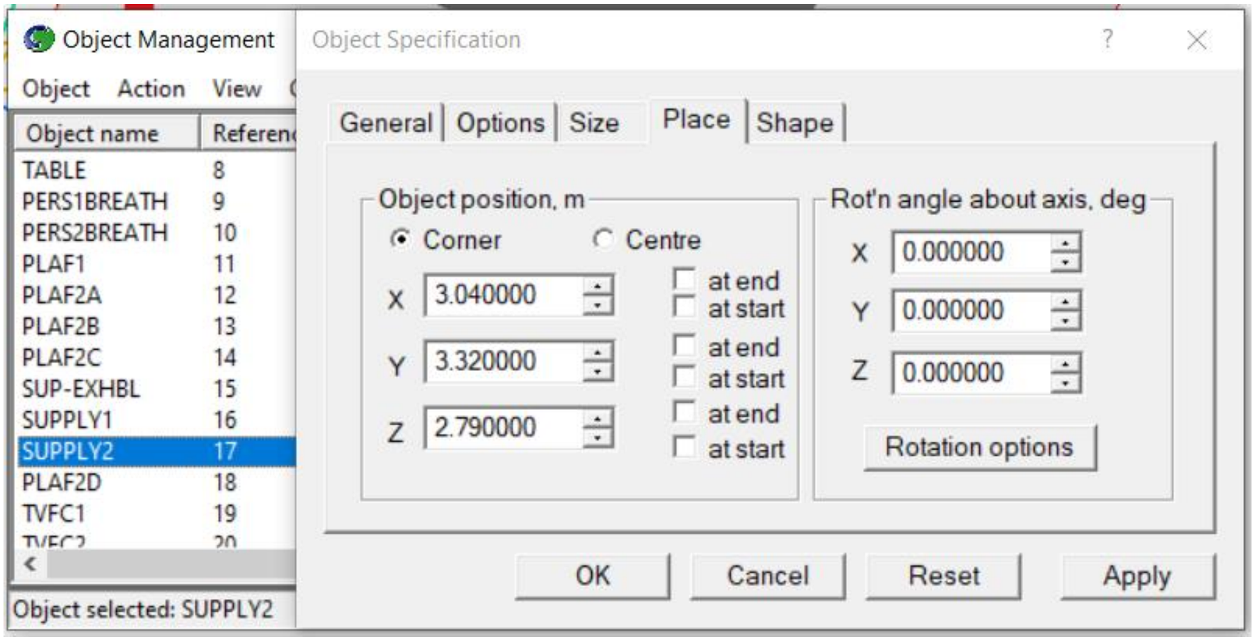


Figure 97 the changed “place” setting for the SUPPLY 2 compared with Case 00

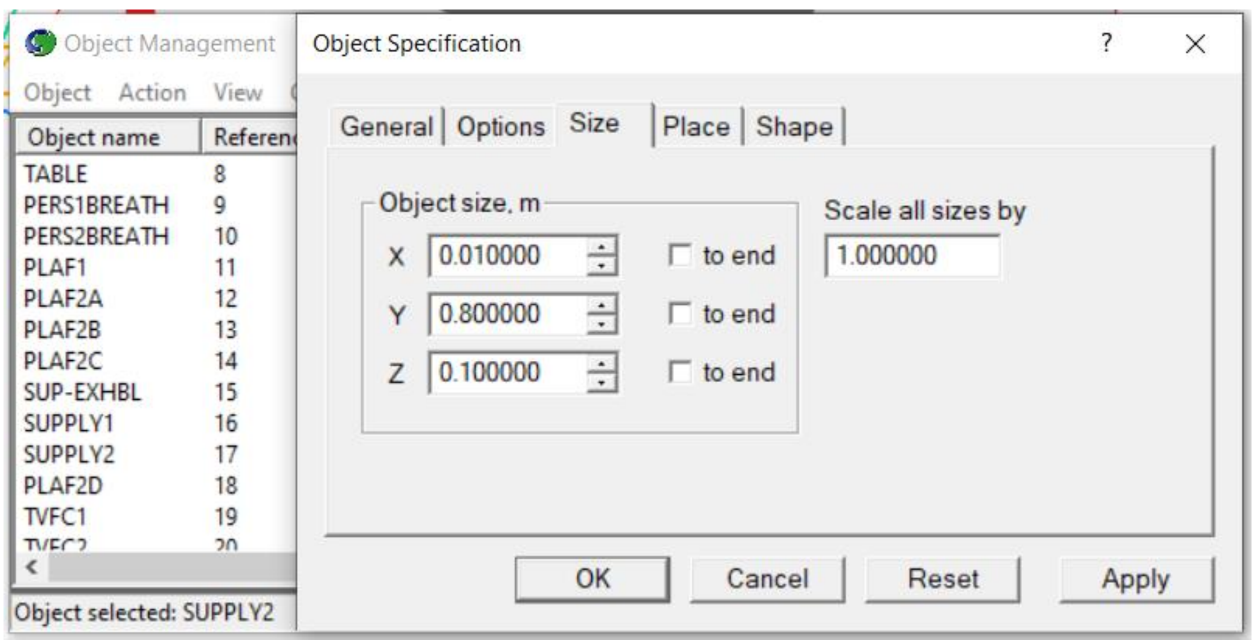


Figure 98 the changed “size” setting for the SUPPLY 2 (also for the SUPPLY 1) compared with Case 00

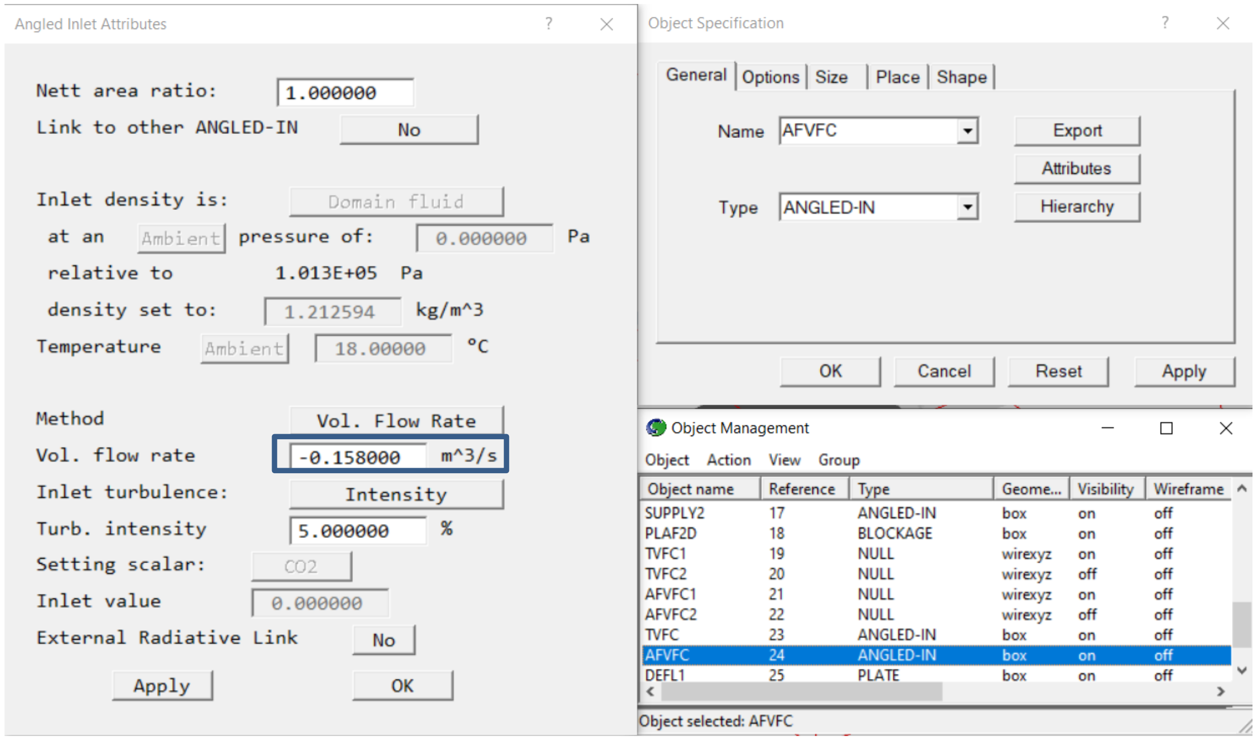


Figure 99 the changed "Attributes" setting for the AFVFC for the maximum fan coil setting compared with Case 00

- Accuracy of standard case compared to the real situation (see case 00 and case standard Figure 54)
  There is not much difference between current situation and standard case for "corona-proof" performance, but standard cases shows a relatively higher mixing level.

Calculation of the local infection risk

The calculation of the infection risk at the breathing height is based on the comparison ratio between the average CO2 concentration at the breathing height in this case and that in the standard case. Thus the calculation is:

PI(x)=cCO2(x)/ cCO2(0)*PI(0)
(0) referred to the initial reference value from standard case.
The CFD results of standard case as coordinate evaluation axis are:

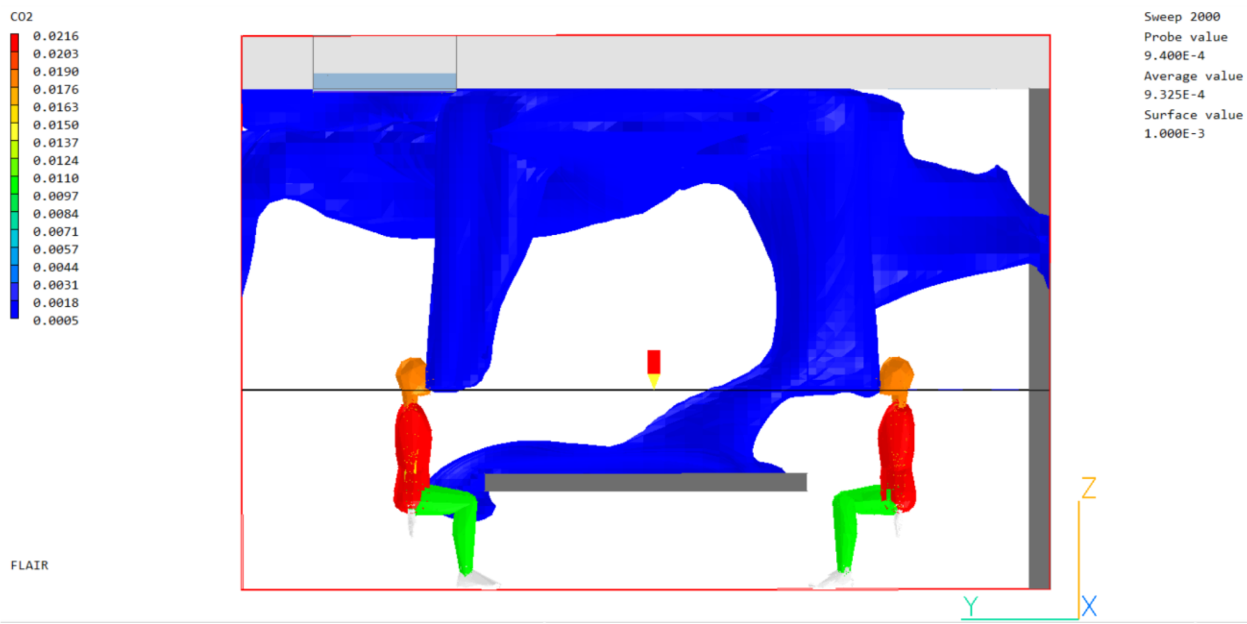


Figure 100 the modelling result of the standard case

4.3 CFD modelling of a variant matrix

4.3.1 Background

COIVD-19 crisis forced people to consider the other important aspect of ventilation system, the indoor air quality, not only from CO2 concentration rate, but also from organic pollutant. For most commercial buildings, like offices, transportation terminals and schools, are mainly focusing on the indoor thermal comfort thermal comfort, which directly determines cooling and heating loads, thus, impacting the capital and energy costs. While, with the advanced hygiene requirements from the users, the ventilation needs to be updated in no time to ensure that people are comfortable and safe indoors for various social activities.

The optimization includes two ventilation control levels: **general** and **partial** methods. The general methods include increasing the air exchange rate, enhancing the outdoor air ratio. The partial methods include updating the filter quality at the end unit and raising the recirculated air portion by increasing fan speed. The computational simulation research method allows outcomes based on different solutions in the sample room to be compared and evaluated at a relatively high accuracy to the realistic situations. To promote an optimal ventilation engineering control for the sample meeting room in Kuijpers, Leiden, the research question of this CFD modelling simulation is:

Therefore the research question for this experiment is:

What would the ventilation strategy be to maximize the epidemic prevention performance from engineering control aspect based on the current ventilation system for the small sharing rooms in standard Dutch offices?

To answer the above main question, the following sub-questions were defined to proceed with the research:

1. Why are the partial controls the optimal methods for short-term economic renovation in the commercial small shared rooms?
2. What are the partial control methods?
3. What is the relationship among partial, general and individual controls?
4. What are the variants in computational modelling for partial control in the small meeting room?
5. What is the general and local *air exchange efficiency* performances by applying **partial** control methods?
6. What is the general and local *particle removal efficiency* performances by applying partial control methods?
7. What is the role of **mixing level** in mixing air exchange efficiency and particle removal efficiency in the breathing zone by different partial control detail designs?
8. What is the relationship among infection risks, general and local air exchange efficiency, and general and local particle removal efficiency?
9. What are the partial control details that can be widely applied in small shared rooms in public commercial buildings?

4.3.2 Context

The overall graduate research project mainly includes three research methods: literature study, experiments and computational modelling. This report is based on the CFD modelling simulation, which is to provide the theoretical foundation of the further ventilation strategy designs for small shared rooms in public commercial buildings. Before the CFD modelling, the report discusses the controls in the realistic building system and figure out the variants worth for computational simulation. The CFD modelling is based on the exhaustive algorithm which lists all the permutation of each single variable. The evaluation of the modelling results is based on the parameters that applied in the ventilation engineering practice to discuss the relationship between the quantity and quality values in ventilation engineering and the infectious risks in epidemiology.

4.3.3 Excursion plan

For meeting-room it is necessary to know if it possible to realize an acceptable Covid infection-risk reduction in case there is one infected person in the room. Based on earlier literature study, the amount of infection quanta in a meeting room is 25 quanta per hour per person. The performance of the ventilation system should lead to an infection risk lower than **5 %. 25 quanta** per hour maybe a rather low estimation in view of the current delta-variant with an infection risk that may be 60 % higher. However, up to now the 25 quanta per hour is still the most common approach. Options to improve the situation are:

- Improving the mixing ventilation efficiency of the room by increasing the mixing level of the breathing zone.
- Adding a partial commercial filter within the indoor end unit out of user's vision in the room.

The differences of recirculation modes and exhaust opening locations may impact the ventilation efficiency or room air mixing level. And the filter is regarded as the extra effective method to explore the filter efficiency under different ventilation strategies.

Case no.	partial				
	ventilation pattern			additional method - filter	
	recirculation rate	distance between return and resupply openings [m]	distance between supply and exhaust openings [m]	filter level	ISO ePM1
exisitng 00	12.3	0	1.75	M5	0%
standard	14.6	0	3.12		0%
1	14.6	0	1.75	M5	0%
2	14.6	0	2.67	M5	0%
3	7.3	0	1.75	M5	0%
4	7.3	0	2.67	M5	0%
5	0	0	1.75	M5	0%
6	0	0	2.67	M5	0%
7	14.6	0	1.75	F7	50%
8	14.6	0	2.67	F7	50%
9	7.3	0	1.75	F7	50%
10	7.3	0	2.67	F7	50%
11	0	0	1.75	F7	50%
12	0	0	2.67	F7	50%
13	14.6	1.75	1.75	M5	0%
14	14.6	1.75	2.67	M5	0%
15	7.3	1.75	1.75	M5	0%
16	7.3	1.75	2.67	M5	0%
17	0	1.75	1.75	M5	0%
18	0	1.75	2.67	M5	0%
19	14.6	1.75	1.75	F7	50%
20	14.6	1.75	2.67	F7	50%
21	7.3	1.75	1.75	F7	50%
22	7.3	1.75	2.67	F7	50%
23	0	1.75	1.75	F7	50%
24	0	1.75	2.67	F7	50%
25	14.6	2.67	1.75	M5	0%
26	14.6	2.67	2.67	M5	0%
27	7.3	2.67	1.75	M5	0%
28	7.3	2.67	2.67	M5	0%
29	0	2.67	1.75	M5	0%
30	0	2.67	2.67	M5	0%

31	14.6	2.67	1.75	F7	50%
32	14.6	2.67	2.67	F7	50%
33	7.3	2.67	1.75	F7	50%
34	7.3	2.67	2.67	F7	50%
35	0	2.67	1.75	F7	50%
36	0	2.67	2.67	F7	50%

Table 36 excursion plan of the CFD modelling matrix

There are two run for the excursion plan. The RUN 1 is to figure out the local ventilation performance in the breathing zone. Because the impacts from the new object "ROOM" is unknown and the author lacks the experience in the convergence control, the results from "ROOM"-installed matrix, the RUN 2 is only for the general ventilation performance (AEE) of the whole space. There is the impact due to the new object "ROOM".

The standard deviation of different local contaminant concentrations is regarded as the mixing level to see the relationship between mixing level of the whole room and infection risks.

The parameter setting see Appendix 1 the CFD model inputs.

4.4 Modelling matrix results

The modelling matrix results are shown as below. In this result table, all the CO2 concentration results are the concentration above outdoor CO2 concentration.

Case no.	strategic variants						engineering parameters							(min) infection risk for 1 h			object
	general	partial					local					general		breathing zone			
	general	ventilation pattern			additional method - filter		human produced CO2 concentration			CO2 removal efficiency	mixing level in breathing zone	Standard deviation	CFD	wells-riley		optimization rate (compared to the existing case)	
	Air exchange rate	recirculation rate	distance between return and resupply openings [m]	distance between supply and exhaust openings [m]	filter level	ISO ePM1	breathing zone (2.8,2.26,1.1)	exhaust opening	average of breathing zone			mixing level for whole space = 1-SD/AVE	fresh air exchange effectiveness=ave outflow local age / ave local age in room	average virus concentration (quanta/m3)	average risk ratio		
1	1.1	14.6	0	1.75	M5	0%	498.4	481.3	483	103.5%	96.8%	98.4%	102.6%	0.12	11.2%	6%	CO2
2	1.1	14.6	0	2.67	M5	0%	458.7	478.7	424.2	95.8%	91.9%	95.0%	103.9%	0.11	10.3%	14%	CO2
3	1.1	7.3	0	1.75	M5	0%	419.3	480.2	436.9	87.3%	96.0%	94.3%	102.6%	0.10	9.4%	21%	CO2
4	1.1	7.3	0	2.67	M5	0%	474.3	481.9	442.8	98.4%	92.9%	96.4%	105.0%	0.12	10.7%	11%	CO2
5	1.1	0.0	0	1.75	M5	0%	468.8	478.9	457.3	97.9%	97.5%	98.1%	101.1%	0.11	10.6%	12%	CO2
6	1.1	0.0	0	2.67	M5	0%	469.0	480.9	476.1	97.5%	98.5%	99.0%	104.9%	0.11	10.6%	12%	CO2
7	1.1	14.6	0	1.75	F7	50%	358.3	337.1	341.5	106.3%	95.1%	97.4%	102.6%	0.09	8.1%	33%	CO2
8	1.1	14.6	0	2.67	F7	50%	332.9	352.6	295	94.4%	87.2%	92.7%	103.9%	0.08	7.5%	38%	CO2
9	1.1	7.3	0	1.75	F7	50%	371.0	433.7	386.2	85.5%	96.1%	93.3%	102.6%	0.09	8.4%	30%	CO2
10	1.1	7.3	0	2.67	F7	50%	407.3	420.5	379.2	96.9%	92.6%	95.7%	105.0%	0.10	9.2%	24%	CO2
11	1.1	0.0	0	1.75	F7	50%	472.1	485.4	461.2	97.3%	97.6%	97.9%	101.1%	0.12	10.6%	11%	CO2
12	1.1	0.0	0	2.67	F7	50%	492.7	487.4	478.4	101.1%	97.0%	98.8%	104.9%	0.12	11.1%	8%	CO2
13	1.1	14.6	1.75	1.75	M5	0%	482.9	491.2	488.8	98.3%	98.8%	99.3%	99.6%	0.12	10.9%	9%	CO2
14	1.1	14.6	1.75	2.67	M5	0%	501.6	488.3	520.4	102.7%	96.4%	97.4%	98.1%	0.12	11.3%	6%	CO2
15	1.1	7.3	1.75	1.75	M5	0%	486.9	489.5	489.5	99.5%	99.5%	99.7%	102.0%	0.12	11.0%	9%	CO2
16	1.1	7.3	1.75	2.67	M5	0%	497.0	490.9	499.3	101.2%	99.5%	99.3%	98.0%	0.12	11.2%	7%	CO2
17	1.1	0.0	1.75	1.75	M5	0%	442.3	495.1	456.5	89.3%	96.9%	95.2%	102.9%	0.11	10.0%	17%	CO2
18	1.1	0.0	1.75	2.67	M5	0%	444.6	487.5	466	91.2%	95.4%	96.2%	102.7%	0.11	10.0%	17%	CO2
19	1.1	14.6	1.75	1.75	F7	50%	99.3	108.3	106.2	91.7%	93.5%	96.3%	99.6%	0.02	2.2%	81%	CO2
20	1.1	14.6	1.75	2.67	F7	50%	107.1	101.4	127.4	105.7%	84.1%	90.0%	98.1%	0.03	2.4%	80%	CO2
21	1.1	7.3	1.75	1.75	F7	50%	183.1	177.3	187.4	103.3%	97.7%	97.7%	102.0%	0.04	4.1%	66%	CO2
22	1.1	7.3	1.75	2.67	F7	50%	189.8	175.9	190.2	107.9%	99.8%	96.4%	98.0%	0.05	4.3%	64%	CO2
23	1.1	0.0	1.75	1.75	F7	50%	464.4	517.7	479.2	89.7%	96.9%	95.4%	102.9%	0.11	10.5%	13%	CO2
24	1.1	0.0	1.75	2.67	F7	50%	444.7	487.9	467.1	91.1%	95.2%	96.2%	102.7%	0.11	10.0%	17%	CO2
25	1.1	14.6	2.67	1.75	M5	0%	513.7	489.9	513.2	104.9%	99.9%	97.8%	98.6%	0.13	11.6%	4%	CO2
26	1.1	14.6	2.67	2.67	M5	0%	485.2	481.4	490	100.8%	99.0%	99.3%	100.6%	0.12	10.9%	9%	CO2
27	1.1	7.3	2.67	1.75	M5	0%	483.0	486.8	500.8	99.2%	96.4%	98.4%	101.0%	0.12	10.9%	9%	CO2
28	1.1	7.3	2.67	2.67	M5	0%	487.1	489.1	488.6	99.6%	99.7%	99.8%	97.9%	0.12	11.0%	9%	CO2
29	1.1	0.0	2.67	1.75	M5	0%	444.7	495.7	458.9	89.7%	96.9%	95.4%	102.9%	0.11	10.0%	17%	CO2
30	1.1	0.0	2.67	2.67	M5	0%	446.0	488.3	466.1	91.3%	95.7%	96.3%	102.7%	0.11	10.0%	16%	CO2
31	1.1	14.6	2.67	1.75	F7	50%	118.8	93.8	118.1	126.7%	99.4%	89.4%	98.6%	0.03	2.7%	78%	CO2
32	1.1	14.6	2.67	2.67	F7	50%	104.9	107.0	110.8	98.1%	94.7%	97.7%	100.5%	0.03	2.4%	80%	CO2
33	1.1	7.3	2.67	1.75	F7	50%	173.3	165.7	188.7	104.6%	91.8%	94.6%	101.0%	0.04	3.9%	67%	CO2
34	1.1	7.3	2.67	2.67	F7	50%	175.2	176.9	172.8	99.0%	98.6%	99.0%	97.9%	0.04	3.9%	67%	CO2
35	1.1	0.0	2.67	1.75	F7	50%	444.7	495.7	458.9	89.7%	96.9%	95.4%	102.9%	0.11	10.0%	17%	CO2
36	1.1	0.0	2.67	2.67	F7	50%	468.0	510.2	487.9	91.7%	95.9%	96.5%	102.7%	0.11	10.5%	12%	CO2
00	1.1	12.3	0	1.75	M5	0%	507.8	484.6	486.8	104.8%	95.7%	97.9%	102.1%	0.13	12.0%	0%	CO2
standard	1.1	14.6	0	3.12	0%		533.0	485.8	528.2	109.7%	99.1%	95.9%	98.2%	0.13	12.0%	0%	CO2

Table 37 modelling results

4.4.1 Discussions about modelling matrix results

a. recirculation rate

In each block (see Figure 101 and Figure 102), the local CO2 concentration changes only due to recirculation ratio. When there is 50% filter effect in the ventilation system, higher recirculation rates help decreasing the local CO2 concentration. But, when there is no filter effect in the ventilation system, higher recirculation rates tend to decrease the local CO2 concentration. But the mitigation can’t be promised, especially when there is no recirculation distance.

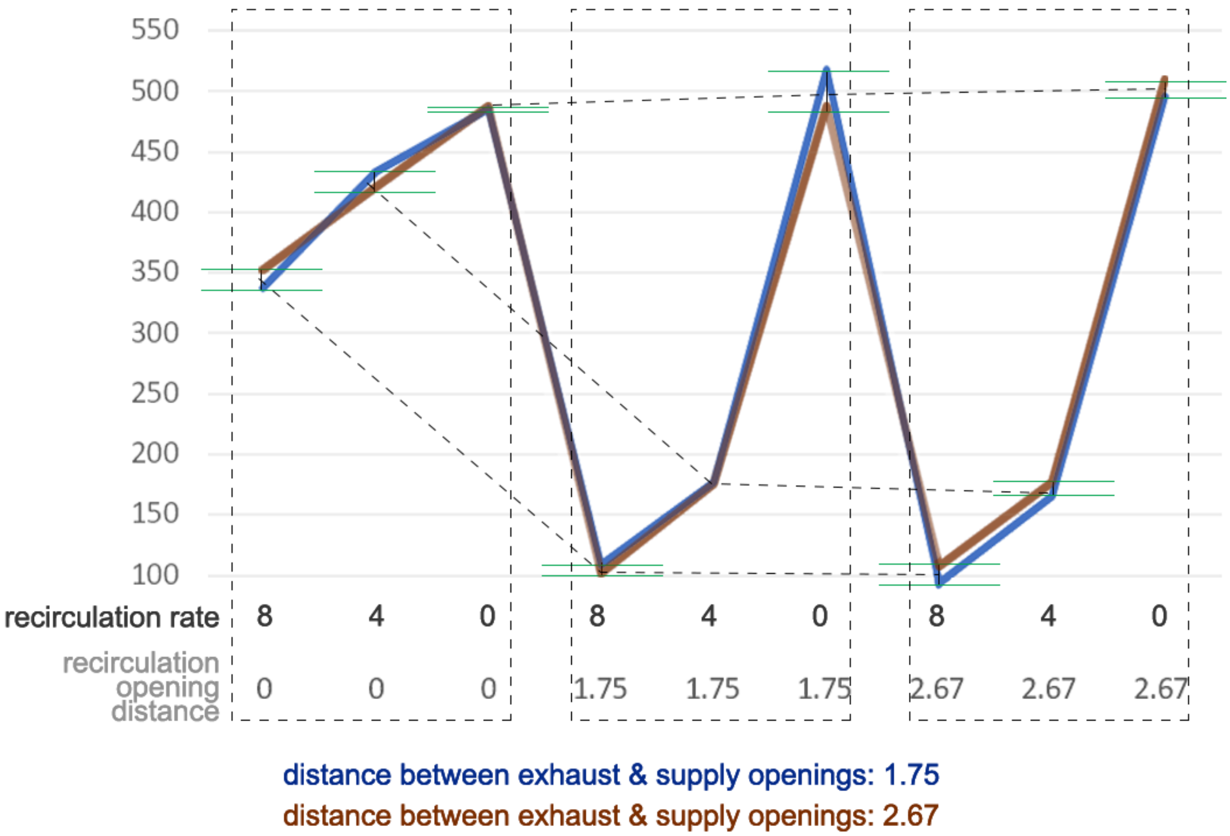


Figure 101 local CO2 concentration with 50% filter effect: for air recirculation rate analysis in each block; for air recirculating distance analysis in dash lines; for general ventilation distance analysis in the green gaps.

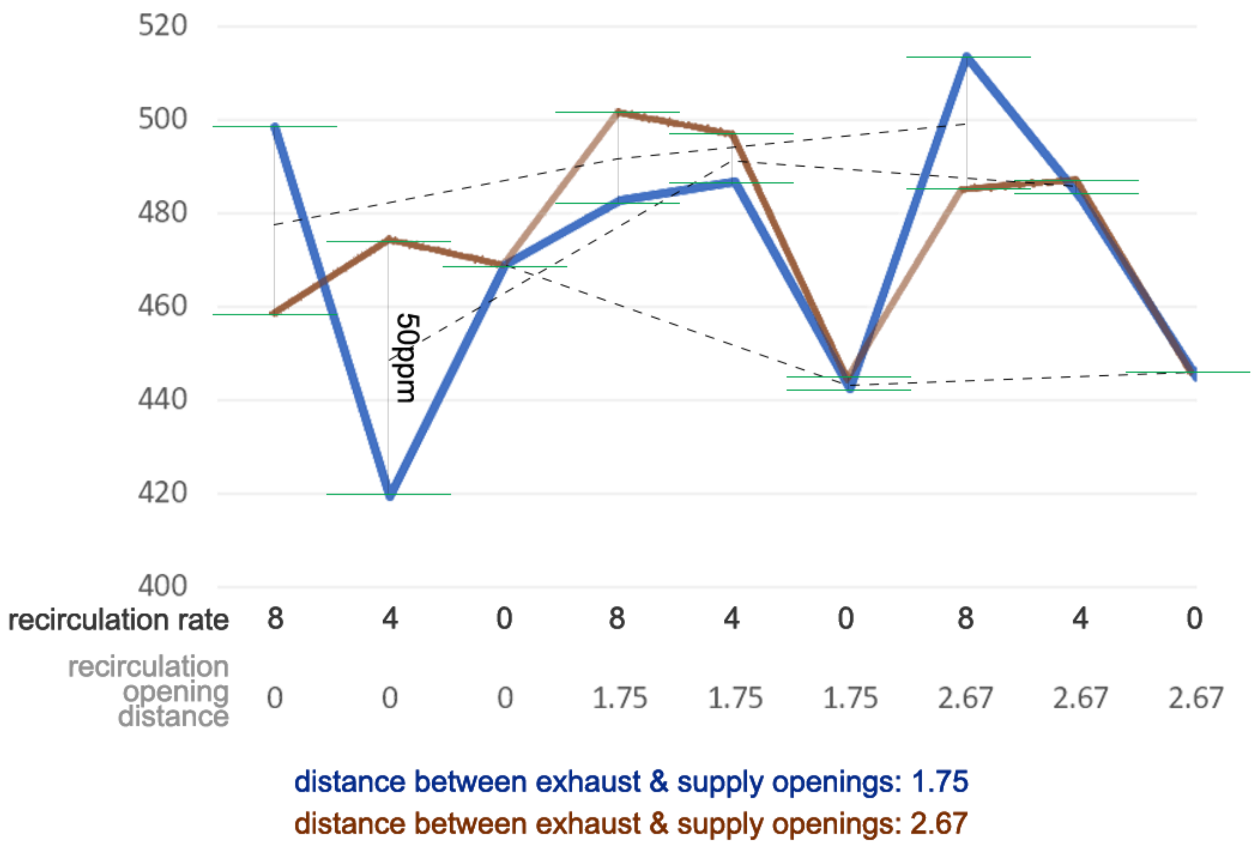


Figure 102 local CO2 concentration with no filter effect: for air recirculation rate analysis in each block; for air recirculating distance analysis in dash lines; for general ventilation distance analysis in the green gaps.

b. distance between return and resupply openings [m]

The dash lines in **Fout! Verwijzingsbron niet gevonden.** and **Fout! Verwijzingsbron niet gevonden.** show the fluctuations due to the recirculation distance, between return and resupply openings. When there is 50% filter effect in the ventilation system, longer recirculation distances help decreasing the local CO2 concentration. But, when there is no filter effect or no air recirculation rate in the ventilation system, higher recirculation rates may increase the local CO2 concentration.

c. distance between supply and exhaust openings [m]

The gaps (see **Fout! Verwijzingsbron niet gevonden.** and **Fout! Verwijzingsbron niet gevonden.**) between red and blue lines illustrate the impacts from general ventilation distance, between supply and exhaust openings. In both cases, when there is 50% filter effect or no filter effect in the ventilation system, longer general ventilation distances help decreasing the local CO2 concentration, but the differences are little, maximum around 50 ppm. Thus, enlarging the general ventilation distances may be a less effective way to enhance the “corona-proof” performance of the ventilation system in the medium-scale environment, compared with enlarging the recirculation ventilation distances.

d. the application of filter

There are obvious differences between the cases applied 50% filter effect and no filter applied (see Figure 103). With only 50% filter effect, the local CO2 concentration can drop to 1/5 of the precious non-application cases. application of filter is necessary and efficient in most cases, except the cases without air recirculation.

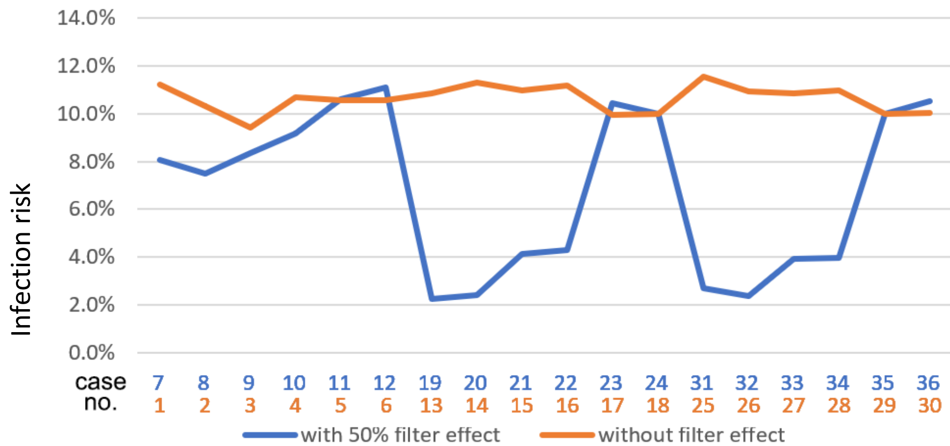


Figure 103 filter effect on infection risk decreasing analysis (by author)

e. Air recirculation mode

From the illustration above (see paragraphs a, b, c, d), there is no potential secondary pollution from the air recirculation mode in the indoor unit, if the filter is well maintained. The fluctuations of local CO2 concentration is very little (the maximum difference is 50 ppm) in the original ventilation pattern (see **Fout! Verwijzingsbron niet gevonden.**), which is also the ventilation pattern that has been widely applied in most offices. On the contrary, the air recirculation is the main role in enhancing anti-epidemic performance and have promising synergetic effects on filter performance, if the air recirculation airflow has been well directed in the room.

f. Ventilation efficiency

There is no promising ventilation efficiency parameter (the impact of filter effect on the ventilation pattern is omitted) can promise a low-infection-risk ventilation scenario, as the Figure 104, Figure 105 and Figure 106 shows, the fluctuations are obvious in all the three ventilation efficiency parameters that widely applied in the ventilation performance evaluation systems in ventilation designs and practices. Though, the advices drawn from in this research are:

- Controlling air change efficiency with 0.5 ± 0.01 (or AEE 1 ± 0.02) may provide a high possibility for "corona-proof" ventilation.
- A high mixing level (in this research above 97%, see Figure 105) of the indoor air may provide a high possibility for "corona-proof" ventilation.
- A high contaminant removal rate (in this research above 98%, see Figure 106) of the indoor air may provide a high possibility for "corona-proof" ventilation.

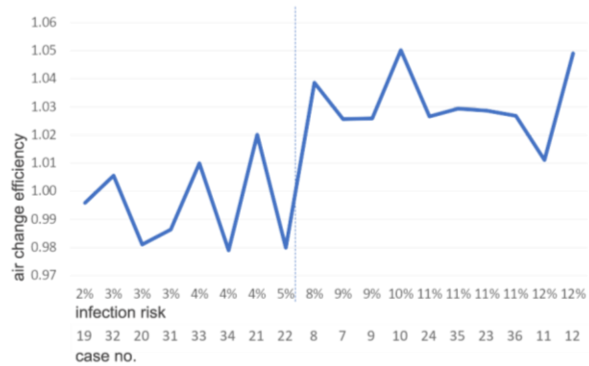


Figure 104 the possible relationship between infection risk and AEE in CFD (double the air change efficiency) (by author)

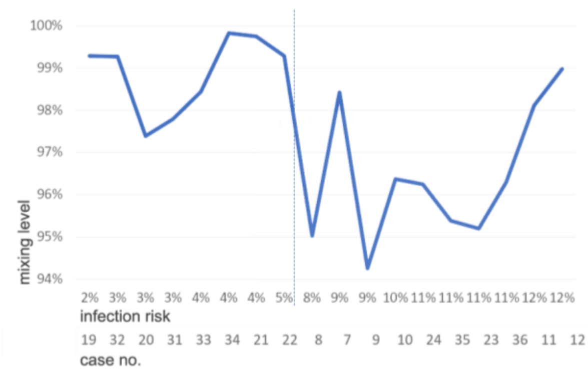


Figure 105 the possible relationship between mixing level and infection risk (by author)

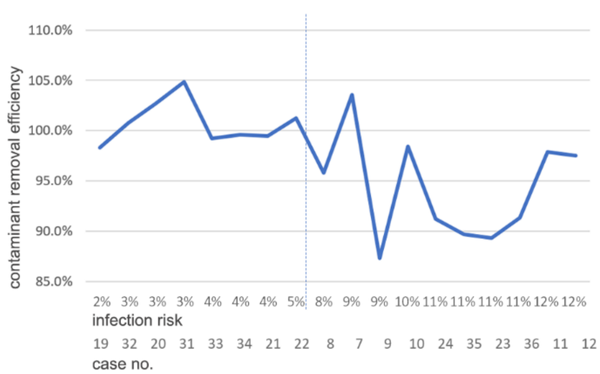


Figure 106 the possible relationship between infection risk and contaminant removal efficiency (by author)

4.4.2 Conclusions about modelling matrix results

1. There is an synergic effect based on the combination of optimal partial control methods with filter effect.

2. **Long-distance route** between *return* and *resupply* opening for air recirculation and **effective filter** is must to ensure that the infection risk is lower 1%.

3. The distance between distance between return and resupply openings [m] plays a more efficient role than distance between supply and exhaust openings [m] in most cases. Air recirculation plays a vitally positive role in "corona-proof" ventilation, because the airflow rate of recirculated room is normally 10 times larger than that of primary air (in this indoor end unit), which is the main force to direct the airflow throughout the room.

4. The wise application of air recirculation and filter effects are the must in the "corona-poof" ventilation design. The impacts from air recirculation mode is more obvious than the application of filter, but without filter, the indoor infection risk can never achieve design value.

5. To enlarge the distance between distance between return and resupply openings, remain the high speed of fan speed and apply the filter can maximize the "corona-proof" effects of single item.

6. There is no obvious parameters of ventilation efficiency can promise a low infection risk, the mixing level at 1.1 m can be referred as a parameter for further detail design based on already optimized partial design.

4.5 CFD modelling attempts for design

To practice the ventilation strategy, there are three attempts having been done to explore the feasibility of the distant opening(s) (see chapter 4.5.2) at ceiling level (see chapter 4.5.1) and the commercial application of filters (see chapter 4.5.3).

4.5.1 Exhaust and air return openings at the foot height

This CFD modelling attempt is to test if the design guidelines for cleanroom ventilation design can be applied in this medium-scale environment. The design guideline recommends to locate the exhaust opening close to the pollutant source at the foot height (see Figure 46). But in the medium-scale environment, with limited ACH adjustment range, the ventilation performance for hygiene purposes is hard to promise. Since all the research conclusions are based on the ventilation facilities at ceiling level, it is necessary to see if the foot-height openings will help with the "corona-proof" ventilation design in commercial medium-scale environment, and be another design option need further discussion.

Therefore the research question for this CFD modelling about exhaust and air return openings at the foot height is:

What is the infection risk in the medium-scale environment when the exhaust and return opening are distantly placed at foot height with a 50% filter effect applied and maximum air recirculation rate?

a. parameter setting

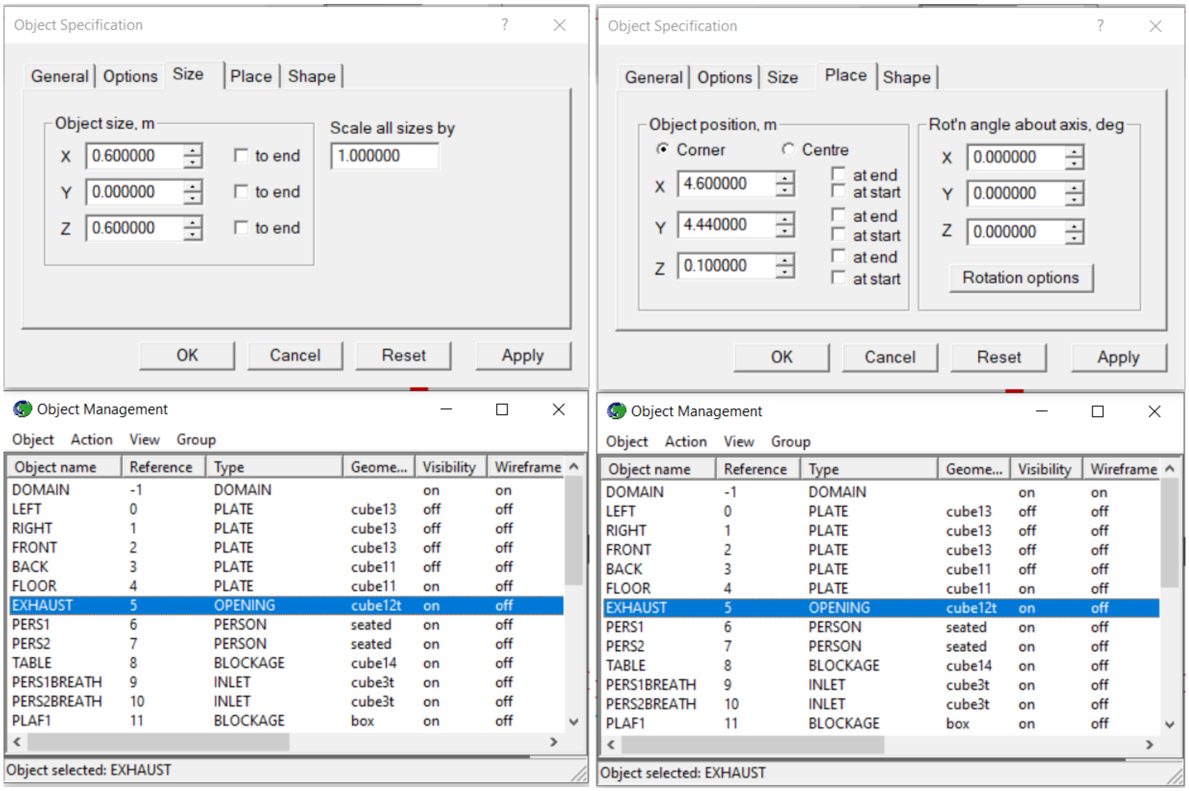


Figure 107 size & position setting for exhaust opening (by author)

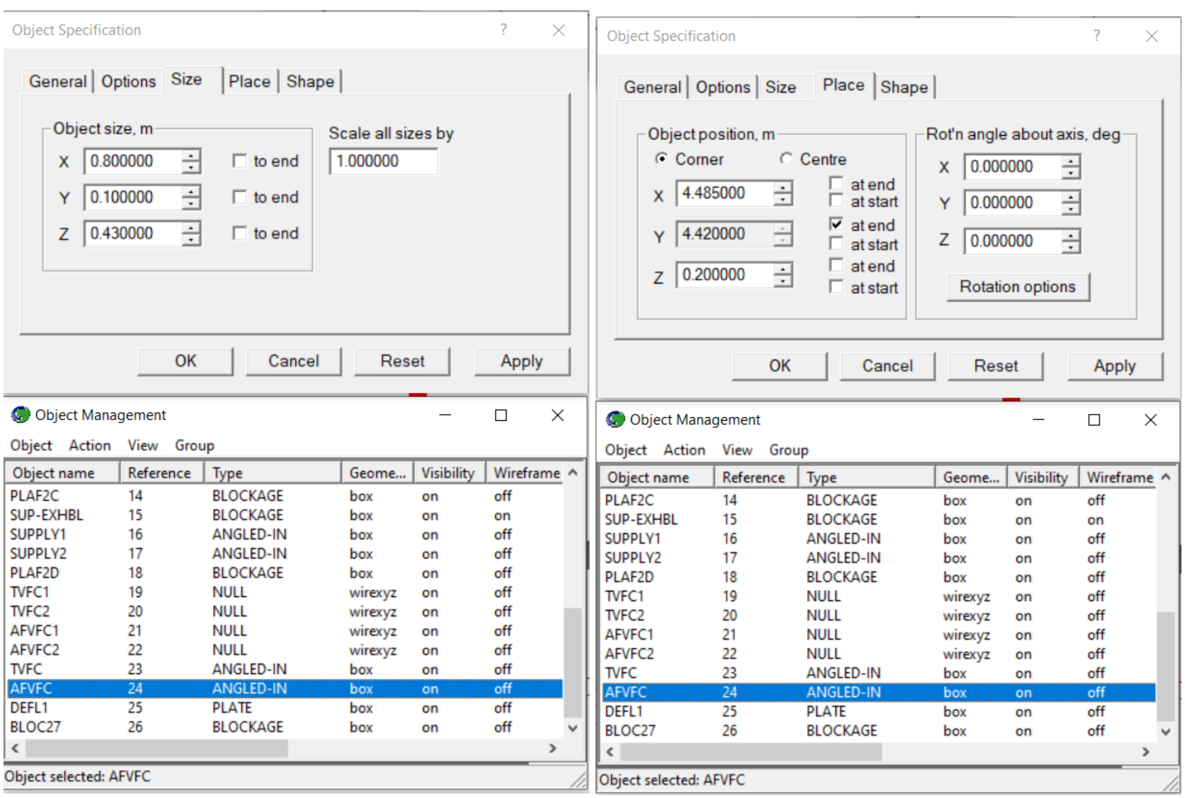


Figure 108 size & position setting for air return opening (object AFVFC) (by author)

b. Results and analysis

Instead of one-direction downwards airflow, there is upwards thermal plume in the mixing ventilation for a small meeting room. In this small enclosed area, the thermal plume plays a larger role than that in cleanrooms. The airflow direction is actually upwards in the micro-climate surrounding people. The low-height exhaust opening may be not efficient.

This impact can be simulated in CFD:

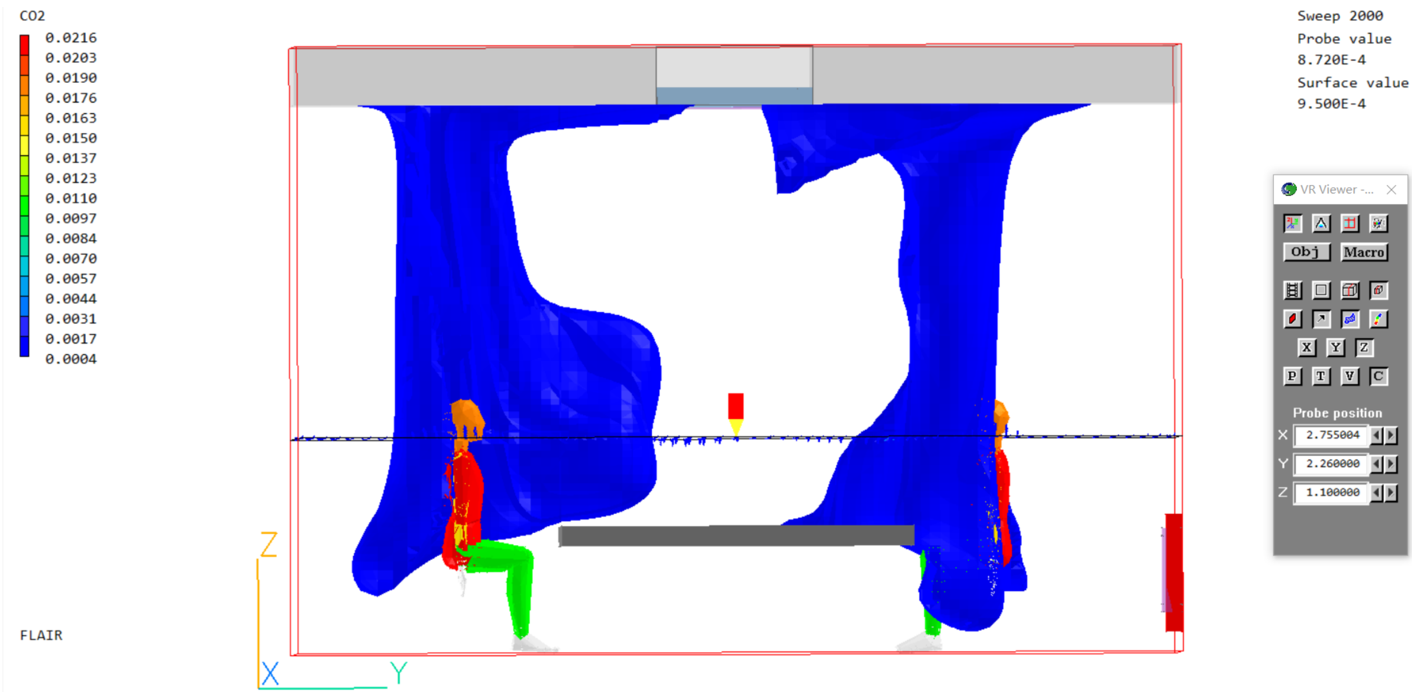


Figure 109 the simulation result of the CFD model with the exhaust & air return openings at foot height

The independent assemble panel system with cavity can be widely applied for fast renovation project.

Case no.	strategic variants						engineering parameters							(min) infection risk for 1 h			object
	general	partial					local					general		breathing zone			
		ventilation pattern			additional method - filter		human produced CO2 concentration			CO2 removal efficiency	mixing level in breathing zone	Standard deviation	CFD	wells-riley		optimization rate (compared to the existing case)	
	Air exchange rate	recirculation rate	distance between return and resupply openings [m]	distance between supply and exhaust openings [m]	filter level	ISO ePM1	breathing zone (2.8,2.26,1.1)	exhaust opening	average of breathing zone			mixing level for whole space = 1-SD/AVE	fresh air exchange effectiveness=ave outflow local age / ave local age in room	average virus concentration (quanta/m3)	average risk ratio		
<u>32</u>	1.1	8.0	2.67	2.67	F7	50%	104.9	107.0	110.8	98.1%	94.7%	97.7%	100.5%	0.03	2.4%	80%	CO2
vertical foot height	1.1	8.0	4.46	4.46	F7	50%	475.8	487.1808	500.3	97.7%	95.1%	97.9%	798.2%	0.12	10.7%	11%	CO2

Table 38 the CFD result data of the CFD model with the exhaust & air return openings at foot height

c. Conclusion

Different from the cleanroom ventilation design principle, creating a relatively one-direction ventilation airflow in the working area, the commercial medium-scale environment in offices usually is in the total mixing ventilation. The air is supplied with the coanda effect from the ceiling surface from the centre and drops on the sides. The body air and respiratory aid float up and are exhausted from the ceiling exhaust opening. Thus, the thermal plume can make the polluted air with high contaminant concentration rate still in the breathing zone, especially the foot-height exhaust opening inhibits the upward flow of contaminated air. Thus, the foot-height openings increase the infection risks in the medium-scale environment.

4.5.2 Multiple openings in the ceiling mixing ventilation pattern

In reality, the movement of indoor occupants is unpredictable. To equalize the ventilation airflow distribution in the sample room, the multiple openings at the ceiling level is put into consideration.

Therefore the research question for this CFD modelling about multiple openings in the ceiling mixing ventilation pattern is:

What is the "corona-proof" ventilation impact from the number of openings with the same efficient opening area in total, a 50% filter effect applied and maximum air recirculation rate?

a. parameter setting

The multi-opening proposal is to equalize the ventilation airflow distribution in the meeting room and to ensure the design output have the similar local performance, despite of the unpredictive indoor activities and occupant locations. Each pair of opening includes one exhaust opening and one air return opening, according to the prefabricated ceiling ventilation cavity design (see Figure 114).

Thus the opening locations need be geometric symmetry, like axial symmetry or centrosymmetric (see Figure 110).

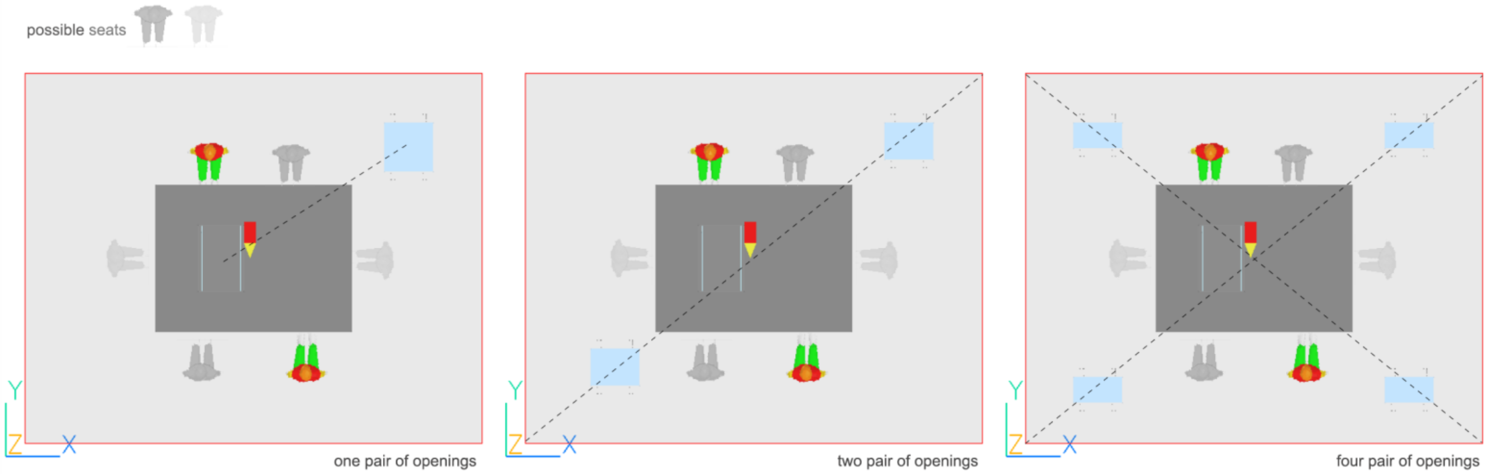


Figure 110 the possible seats and opening distribution

opening pair number	size				position (surface centre)			recirculated airflow rate [m3/s]
	x [m]	y [m]	S [m2]	efficient S [m2]	x [m]	y [m]	z [m]	
1	0.6	0.6	0.36	0.36	3.62	4.7	2.8	-0.158
2	0.6	0.42	0.252	0.356382	0.9	0.9	2.8	-0.079
	0.6	0.42	0.252		3.62	4.7		-0.079
4	0.6	0.3	0.18	0.36	0.9	0.75	2.8	-0.0395
	0.6	0.3	0.18		0.9	4.85		-0.0395
	0.6	0.3	0.18		3.62	0.75		-0.0395
	0.6	0.3	0.18		3.62	4.85		-0.0395

Table 39 the size and position of the multiple openings

b. Results and analysis

The multiple openings cannot always promise a lower infection risk, for example the two-pair-opening design. The four corner opening distribution shows better “corona-proof” ventilation performance and can decrease the infection risk to 2.3% with a 50% filter effect in the ventilation system.

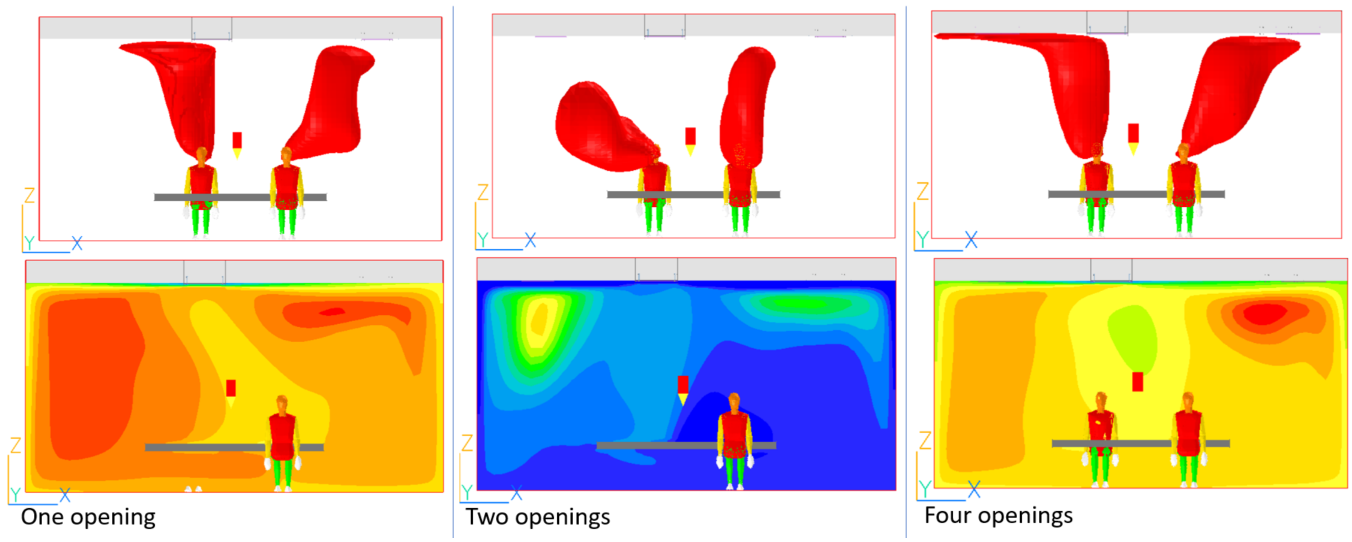


Figure 111 the simulation result of the CFD model with the multiple exhaust & air return openings

Case no.	strategic variants						engineering parameters							(min) infection risk for 1 h			object
	general	partial					local					general		breathing zone			
		ventilation pattern			additional method - filter		human produced CO2 concentration			CO2 removal efficiency	mixing level in breathing zone	Standard deviation	CFD	wells-riley		optimization rate (compared to the existing case)	
	Air exchange rate	recirculation rate	distance between return and resupply openings [m]	distance between supply and exhaust openings [m]	filter level	ISO ePM1	breathing zone (2.8,2.26,1.1)	exhaust opening	average of breathing zone			mixing level for whole space = 1-SD/AVE	fresh air exchange effectiveness=ave outflow local age / ave local age in room	average virus concentration (quanta/m3)	average risk ratio		
32	1.1	8.0	2.67	2.67	F7	50%	104.9	107.0	110.8	98.1%	94.7%	97.7%	100.5%	0.03	2.4%	80%	CO2
Two pairs of openings	1.1	8.0	1.75*1 & 2.67*1	2.67	F7	50%	158.0	152.4	158.5	103.7%	99.7%	98.2%	198.2%	0.04	3.6%	70%	CO2
Four pairs of openings	1.1	8.0	1.75*2 & 2.67*2	2.67	F7	50%	100.9	97.0	106.6	104.0%	94.7%	96.1%	298.2%	0.02	2.3%	81%	CO2

Table 40 the CFD result data of the CFD model with multiple exhaust & air return openings

c. Conclusion

The application of multiple opening in the hygiene ventilation design in this medium-scale environment should be careful about the possible shortcut for the ventilation airflow, like the “two pair of opening” case. Due to coanda effect, the amount of the supply air that has been directly exhausted out by the diagonal air exhaust opening on each air supply side (see Figure 110) increased compared to only one opening design or four small corner opening design. The four corner opening design is the optimal ventilation distribution pattern in this research.

4.5.3 Application of different commercial standard filter types

For design concept, the higher filter effect, the better “corona-proof” the ventilation system can be. But the installation of HEPA filter in realistic commercial public environment cost high and not always achievable for requiring the extra fan coil end unit. The commercial filter, like ePM 1 50%, 70%, 90%, may also be a sufficient choice to achieve the acceptable infection risk, 1%. It is necessary to find a economic sufficient filter standard for the fast renovation ventilation product promotion.

Therefore the research question for this experiment is:

What is the minimum ePM 1 filter effect required by this optimized ventilation design to achieve the acceptable infection risk in the commercial medium-scale environment in offices?

a. parameter setting

The CFD modelling attempt is based on the four-opening ventilation pattern and with a fully-working air recirculation mode. The setting process of filter effect refers to the Simulation of filter effect following air recirculation simulation. The removal rate is chosen as 50%, 70% and 90%, which are the common filter type in their filter standard level (see Table 5).

b. Results and analysis

The cost efficiency of higher standard filter decreases dramatically (see Figure 112) . There is no impacts for the modelling process or the ventilation to combine the air return opening and exhaust opening as one opening. The 90% filter effect under this ventilation pattern can achieve 1%, which meet the “corona-proof” ventilation. The economic 90% filter effect products can achieve the acceptable infection risk, which implying that the high-cost HEPA filter may not be the optimal choice for the fast renovation hygiene ventilation product design.

Case no.	strategic variants						engineering parameters							(min) infection risk for 1 h			object
	general	partial					local					general		breathing zone			
		ventilation pattern			additional method - filter		human produced CO2 concentration			CO2 removal efficiency	mixing level in breathing zone	Standard deviation	CFD	wells-riley		optimization rate (compared to the existing case)	
	Air exchange rate	recirculation rate	distance between return and resupply openings [m]	distance between supply and exhaust openings [m]	filter level	ISO ePM1	breathing zone (2.8,2.26,1.1)	exhaust opening	average of breathing zone			mixing level for whole space = 1-SD/AVE	fresh air exchange effectiveness=ave outflow local age / ave local age in room	average virus concentration (quanta/m3)	average risk ratio		
4open90 opening separate	1.1	8.0	1.75*2 & 2.67*2	1.75*2 & 2.67*2	F7	90%	51.48	49.98118	61.09	103.0%	84.3%	90.9%	398.2%	0.01	1%	90%	CO2
4open70 opening separate	1.1	8.0	1.75*2 & 2.67*2	1.75*2 & 2.67*2	F7	70%	67.06	65.34867	76.55	102.6%	87.6%	92.9%	498.2%	0.02	2%	87%	CO2
4open50 opening overlap	1.1	8.0	1.75*2 & 2.67*2	1.75*2 & 2.67*2	F7	50%	96.8	98.38801	103.2	98.4%	93.8%	97.3%	598.2%	0.02	2%	82%	CO2
4open50 opening separate	1.1	8.0	1.75*2 & 2.67*2	1.75*2 & 2.67*2	F7	50%	92.3	90.27285	102	102.2%	90.5%	94.6%	698.2%	0.02	2%	83%	CO2

Table 41 the CFD result data of the CFD model with the exhaust & air return openings with different filter effects

	filter effect	optimization rate
4open90	90%	*90%*
4open70	70%	*87%*
4open50	50%	*83%*
4open37	37%	*74%*

Table 42 the optimization rates under the different filter effects

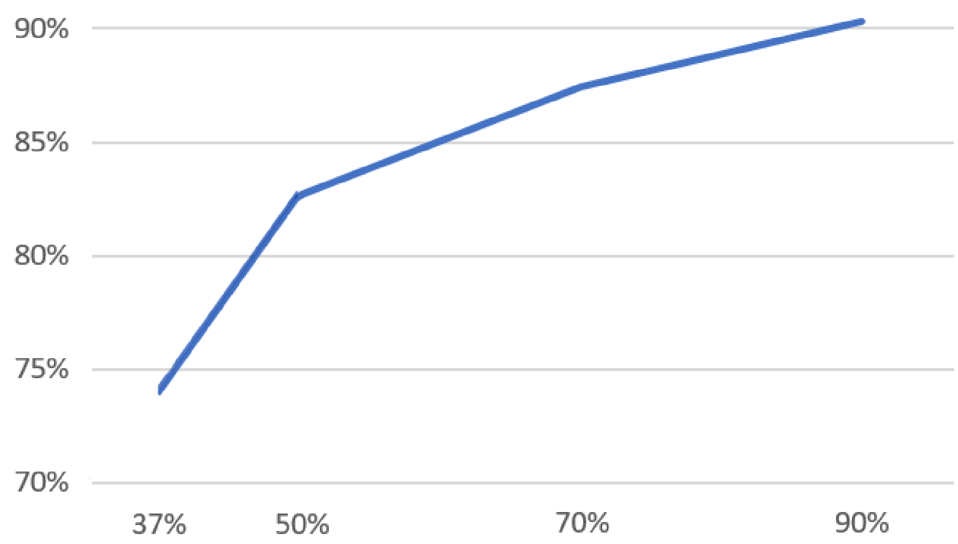


Figure 112 filter types and its optimization rate

c. Conclusion

HEPA filter is not a must in “corona-proof” ventilation design. Economic filters or purifiers that with filter effect higher than 90% in this ventilation pattern design can meet the “corona-proof” ventilation goal. The combine opening has no impacts on general ventilation or air recirculation patterns which make the ceiling ventilation cavity design more convincing.

4.6 CFD testing of the installable ventilation

This CFD modelling is to test the realistic "corona-proof" performance of the draft ventilation product model on site. The test modelling estimated the possible infection risk after the on-site installation of the fast renovation ventilation product, and simulate particle concentration, based on the om-site measurement in CFD modelling, instead of tracer gas, to see the gaps between reality and computational design.

Therefore the research question for this CFD modelling about draft model test is:

What is differences between the estimated "corona-proof" performance of the draft model of fast renovation hygiene ventilation in CFD modelling and its practical performance in the sample room?

a. parameter setting

estimation of the "corona-proof" performance of the ventilation design based on the CO2 concentration

The size and location settings refer to the on-site installation condition, see Table 21. The filter effect is set as 37%, referring to the experiment result of Experiment about model material qualification.

simulation of "corona-proof" performance of the ventilation design based on the 0.3 um particle concentration

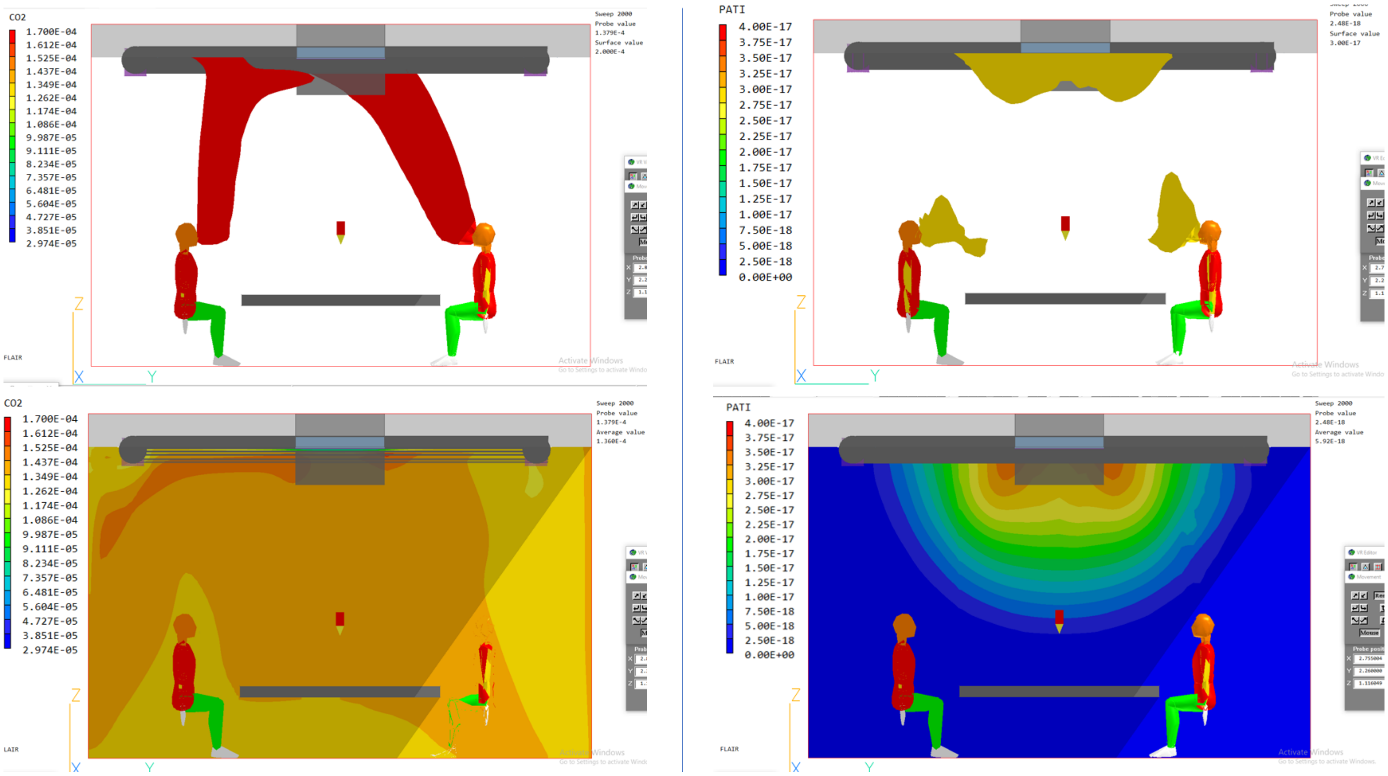
The contaminant setting refers to the setting for the tracer gas in Tracer air in the beginning of this chapter. And the values for the setting refers to the **Fout! Verwijzingsbron niet gevonden.**.

b. Results and analysis

The initial outdoor 0.3 um particle concentration is hard to be precisely simulated in the Phoenics. Thus, the local concentration constant is added to the local 0.3 um particle concentration rate caused by human pollution source only with the impacts from the designed ventilation pattern. Then CFD results matched the onsite measurement of my design. While the simulation of the non-installation case matched the measurement smoothly.

Thus, the estimation of the "corona-proof" performance of the ventilation design based on the CO2 concentration can be regarded as reliable, which is 3.1%. The optimization rate compared to the original situation is 74%. The infection risk with this draft ventilation model decreased to 1/4 of that of previous situation.

The modelling results based on particle is two orders of magnitude smaller than expectation based on experiences. Because the particle concentration produced by manikins are too small to calculate and the set calculation time is not long enough, the spreading of the particle in the space is slow, and the calculation results can be largely impacted by the calculation duration. The alien results are a temporary outcomes in a significant fluctuation of airflow in the room over time.



CFD testing in CO2 CFD testing in particle 0.3 um

Figure 113 the simulation result of the CFD model for the draft design model installed on site

Case no.	strategic variants					engineering parameters							(min) infection risk for 1 h			object
	general	partial				local					general		breathing zone			
		ventilation pattern			additional method - filter	human produced CO2 concentration			CO2	mixing level in	Standard deviation	CFD	wells-riley		optimization rate	
	Air exchange rate	recirculation rate	distance between return and resupply openings [m]	distance between supply and exhaust openings [m]	ISO ePM1	breathing zone (2.8,2.26,1.1)	exhaust opening	average of breathing zone	removal efficiency	breathing zone	mixing level for whole space = 1-SD/AVE	fresh air exchange effectiveness=ave outflow local age / ave local age in room	average virus concentration (quanta/m3)	average risk ratio	(compared to the existing case)	
realistic installation particle accuracy	1.1	8.0	1.75*2 & 2.67*2	1.75*2 & 2.67*2	37%	121238.36	120034.07	120486.85	101.0%	99.4%	99.6%					particle [(num.)/min]
realistic installation particle accuracy	1.1	8.0	0	1.75	0%	188582.89	241989.61	239390.42	77.9%	78.8%	89.0%					particle [(num.)/min]
realistic installation infection risk	1.1	8.0	1.75*2 & 2.67*2	1.75*2 & 2.67*2	37%	137.9	129.3996	136.3	106.6%	98.8%	97.3%	998.2%	0.03	3.1%	74%	CO2
existing 00	1.1	6.8	0	1.75	0%	507.8	484.6	486.8	104.8%	95.7%	97.9%	102.1%	0.13	12.0%	0%	0%

Table 43 the CFD result data of the CFD model with the exhaust & air return openings in the design-installed site

c. Conclusion

The limitation of the simulation is that the attributes of 0.3 um particle are different from those of CO2. Thus, the 0.3 um particle concentration rate is too small for the CFD modelling to simulate its indoor distribution. The precision of the calculation in the Phoenics has been highly impacted due to the unsuitable convergence control.

The CFD modelling of on-site installation matches the on-site experiment result. Thus, based on parameter CO2, the optimistic estimation of the infection risk after the draft ventilation product model installed is 3.1%.

4.7 Conclusion

About the application of CFD in ventilation design:

1. The necessity in CFD application exhaust opening. Since, none of the ventilation engineering indicators can promise a "corona-proof" ventilation, the application of CFD is a must.
2. The limitation of CFD in simulating the particle movements indoors
3. design details for without any predictable indicator referred need visualization at the beginning

the detail architectural design should be stay consistent with in the ventilation design phase:

1. based on the space layout, the supply opening should be placed in the centre area where the indoor actives are, and the exhaust & air return openings are recommended in the distant corner, in the medium-scale environment with ceiling mixing ventilation pattern.
2. The application of filter-effect facilities is a must for "corona-proof" ventilation design, a commercial type is possibly applied in the well optimized ventilation
3. The maximum running mode for fan coil unit is always strongly recommended for high air recirculation rate and good general ventilation pattern.

5 Design concept

According to Chapter 1.6 and 2.4.2. The requirements of the renovation ventilation product design would be to:

• Propose conceptual ventilation design and renovation installation solutions that respond to the hygiene ventilation optimization in small pubic shared room (area ≤ 30m2; height ≤ 2.8m).

- Propose conceptual ideas that are both product and system oriented.
- Design according to the ventilation process and to air recirculation patterns in the room.
- Take into consideration user's behaviours and the logistics behind the local ventilation control.

• Reflect the installation knowledge learned from the graduate internship in Leiden, Kuijpers, to apply them into a common commercial context.

• Evaluate the current ventilation and renovation solutions in CFD and have conclusions about the application of CFD analysis into practice based on the test results in the sample meeting room in Leiden, Kuijpers.

5.1 Strategy

The ventilation design strategy is based on the experiment and CFD researches (see pervious researches) for small build-in shared rooms (area ≤ 30m2; height ≤ 2.8m). With limited renovation of current space and building system, the possibility and feasibility to decrease the infection risk to an acceptable value and a balance based on the occupation condition of the specific place. The ventilation product is aimed at the built-in variable office from partial engineering control, conceptional design with CFD and cleanroom technical experience for the ventilation system installation:

• Partial control:
- Keep the max. fan speed in the indoor end unit
- Enlarge the distance between distance between return and resupply openings & distance between supply and exhaust openings
- Update the filter or install the purifier at least to 90%.

• Application of CFD:
- Predict the ventilation shadow and "corona-proof" efficiency of the new strategy in the room based on the existing location of indoor end unit for renovation
- The application of CFD to test the optimal strategy is essential and necessary for first construction to save energy and face with possible extreme situation

• Application of cleanroom technic
- Place the supply opening at the functionally central area (normally in the centre of the room) to the working area and can provide the direct airflow to the breathing openings of users.
- Application of assemble prefabricated modular panel system to create a cavity.

- Fast construction and wide feasibility for the ceiling mixing ventilation with air recirculation pattern.

5.2 Product

The ventilation product is developed based on the **optimization analysis in CFD** (see chapter 4.7) and **cleanroom technics for installation** (see chapter 2.5). During installation, the cleanroom facilities are pre-fabricated and installed on site following the tracks and sub-structure. Thus, the ventilation product design includes the ventilation design workflow, the facility modular and its possible installation system.

Design principle:

- From optimization analysis in CFD:
- Avoid shortcut for direct airflow from supply and exhaust openings
- Avoid shortcut for recirculation airflow from resupply and air return openings
- Maximise the local air recirculation rate
- Apply at least ePM1 90% filter-effect end facility for local air recirculation
- For the shared open space lower than 2.8m, the ventilation facilities should be installed at ceiling level

- From cleanroom technics for installation (see Figure 39):
- Fast construction
- Wide feasibility for different indoor ventilation with the ventilation type
- Locate the supply opening at the most closed area to the working area to provide the direct airflow to the breathing openings of users

In this sample case, the current location of the supply openings of indoor end unit is good enough, which is nearly located in the centre of room ceiling. The exhaust opening and air return opening should be multiple and distant at the corner on the ceiling level. The installation of the filter device at the end unit need to be careful about its pressure drop and extra installation of facilities, like fan coil and electricity source.

As Figure 114 the ventilation design product integrated celling shows, the ceiling element functions as the ventilation cavity to conduct the air at the ceiling level. The extended box cover connects the connection opening on the ceiling and the fan coil unit of indoor end unit and avoid the impact on supply airflow also. The central exhaust opening exists above the ceiling on the inner wall already, and will be directly connected to the ceiling ventilation cavity also. The distant air return openings and distant exhaust openings can be placed based on the layout of the room, in the sample meeting room in Kuijpers, the four air return & exhaust openings on the ceiling are as shown below.

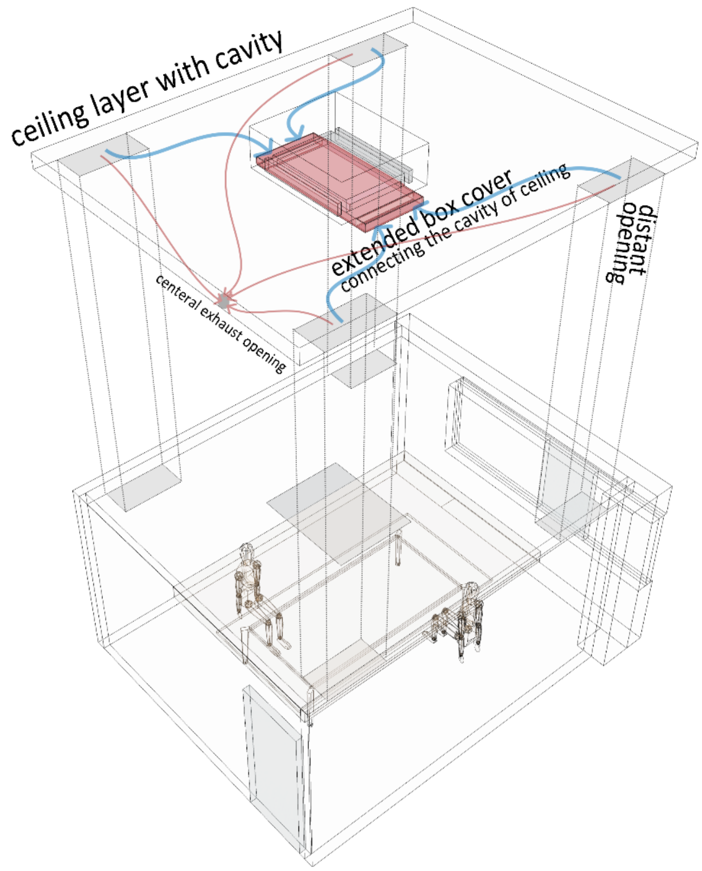


Figure 114 the ventilation design product integrated celling

5.2.1 Workflow

Based on the research process, a workflow design from design phase to prefabrication phase to integration with the building system for the hygiene ventilation is necessary for the wide application of the ventilation strategies provided in this research.

For **design**:

Space analysis → spatial scale definition → function area distribution → supply end in the central of main using area (see Figure 115) → exhaust & air return openings at the distant area from the supply end (see Figure 115) → layout drawing

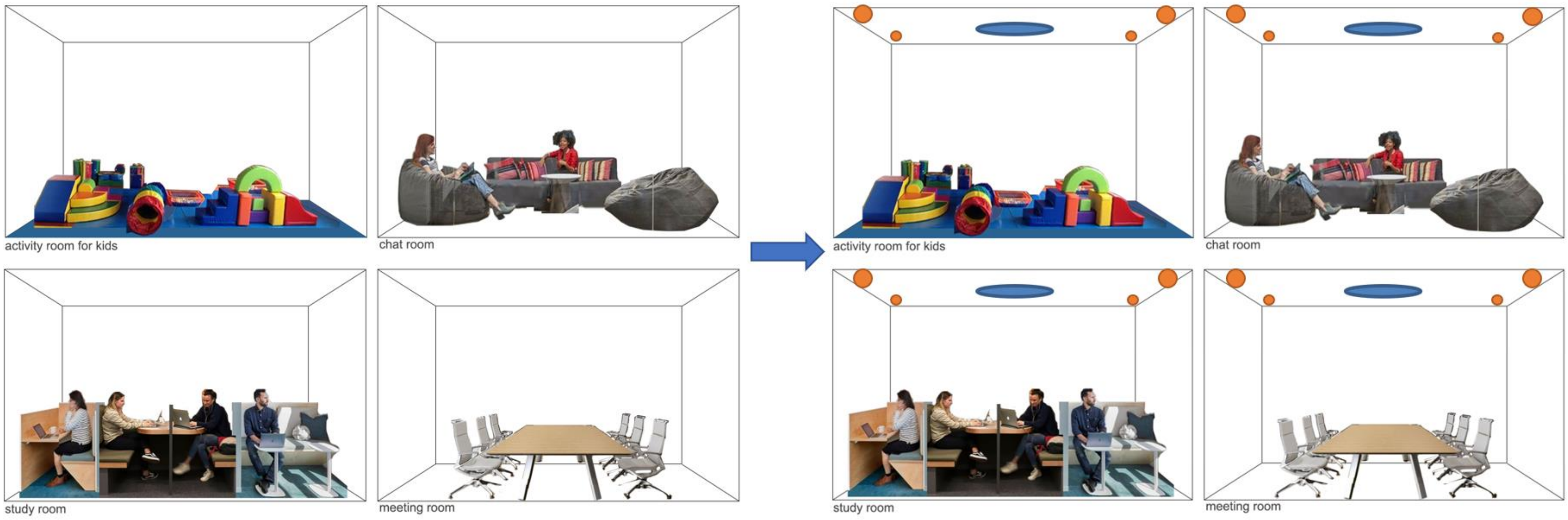


Figure 115 the possible scenarios that how the supply end (in blue) and exhaust & air return openings (in orange) in the central of main using area (by author)

For **prefabrication and installation**: (central modular + cavity modular)

Allowance of the spatial height → cavity thickness → facilities' positions (up or side) → purifier's connection with the indoor end unit (pressure resistance control: decreasing ducts) →the extra installation of end devices (electricity source, fan coil and purifier device)→ high flexibly for exhaust & return openings → maintenance accessory

For **long-term** hygiene ventilation needs:

Further smart building system design is necessary to explore to integrate the hygiene ventilation design. The smart building system design should be able to switch among working mode, hygiene working mode, resting mode and turn-off mode, and also allows the regular maintenance for the filter end device and frequent check of the ventilation performance in the real scenario.

5.2.2 Facility modular

After the investments of purifier devices, dry ESP is an optimal choice, especially for its relatively low price, convenience in maintenance and no need for low pressure drop impacts on the ventilation system. modular ventilation product design focuses on the integration with dry ESP at the indoor end unit and the structural to the ceiling element.

There is a lack of the commercial dry ESP product safety certification about its leakage risks of the poisonous bi-product during the filtering. The safety certification from authorities for its efficient filter performance and environmental safety is necessary for the widely commercial application. Later, the installation requirement for space and pressure is necessary to ensure during the architectural or structural designs.

The dry ESP chosen for the ventilation product in this research is **M-Care-ASPRA** from VFA-Solution company. The product information of **M-Care-ASPRA is:**

Facility size: 600mm * 307mm * ≥ 200mm (width, flexible for user's changes)

Pressure drop: 17 Pa

The installation space height should be at least around 350mm, which is the same installation requirement of VRF indoor end unit. Thus, the integration design with the M-Care-ASPRA is of high flexibility for the ventilation renovation in any space with a VRF indoor end unit.

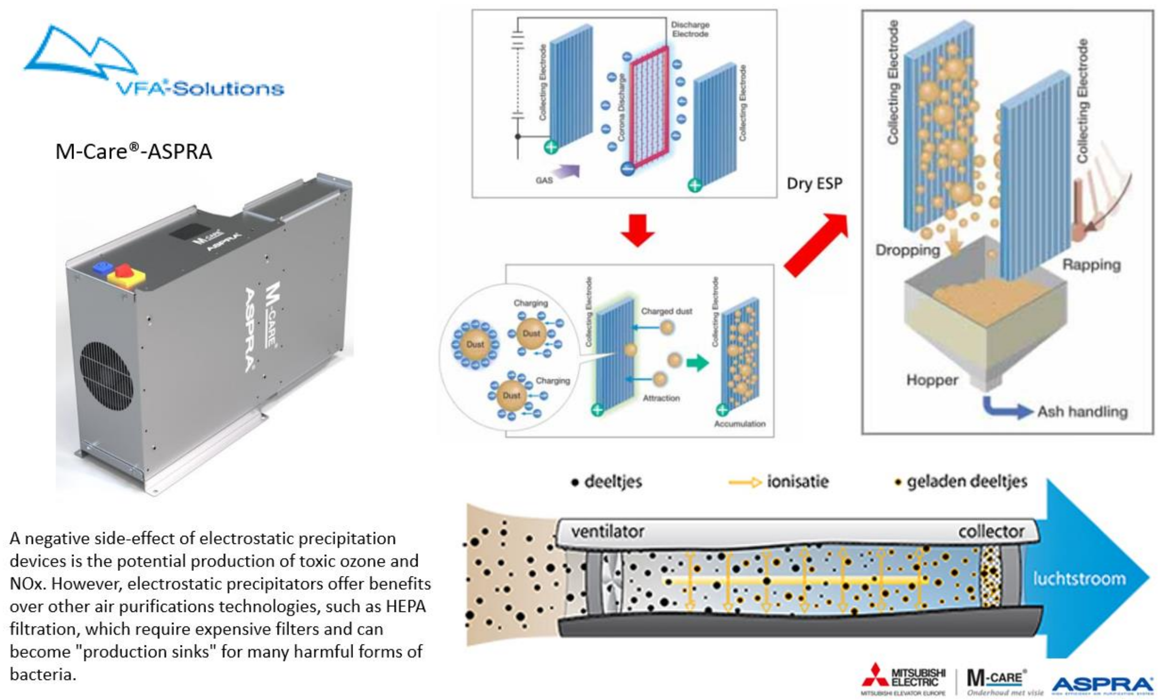


Figure 116 mechanic logics of M-Care-ASPRA (from VFA-Solutions)

Facility modular: a modular asking for certain area and a minimum height, with indoor supply end unit and purifier end or extra fan coil (if needed) facilities inside. The main element that need structural supports (see Figure 117).

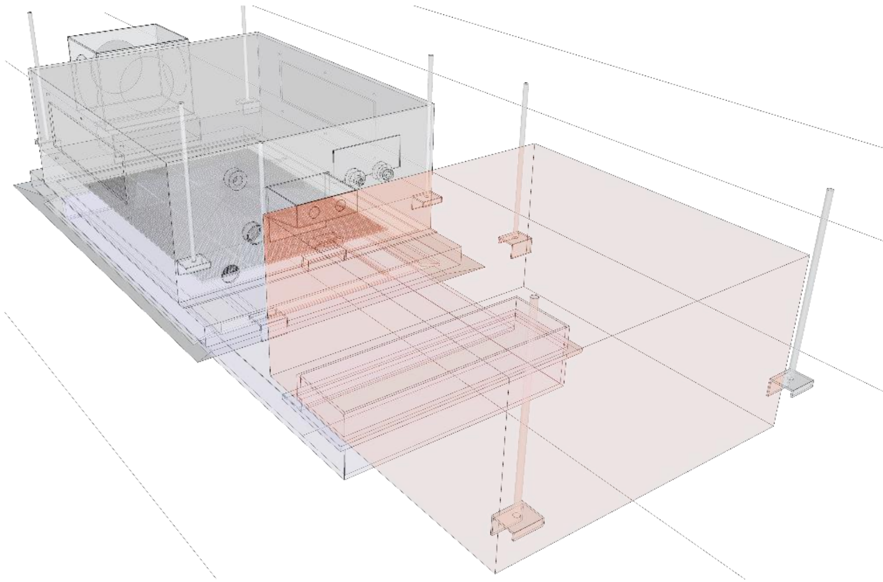


Figure 117 the connection between existing indoor end unit and M-Care-ASPRA (in light orange colour) via the cover box (in purple colour)

Cavity modular would be mostly open modular with high flexibility for opening needs and low air resistance

To figure out the realistic performance of the conceptional strategy, further experimental experience is needed for the more hygiene indoor environment:

1. Efficiency of the supply air amount
2. The ventilation design precision requirements based on the building attributes
3. Formal standards for specialized design accuracy data issued by authority rather than simple general strategic suggestion

5.2.3 Accessory structures

Based on the widely applied modular panel system and its ceiling sub-structure, the facility panel modular also based on the installation logics of the panels also. The common scale is 600 mm based.

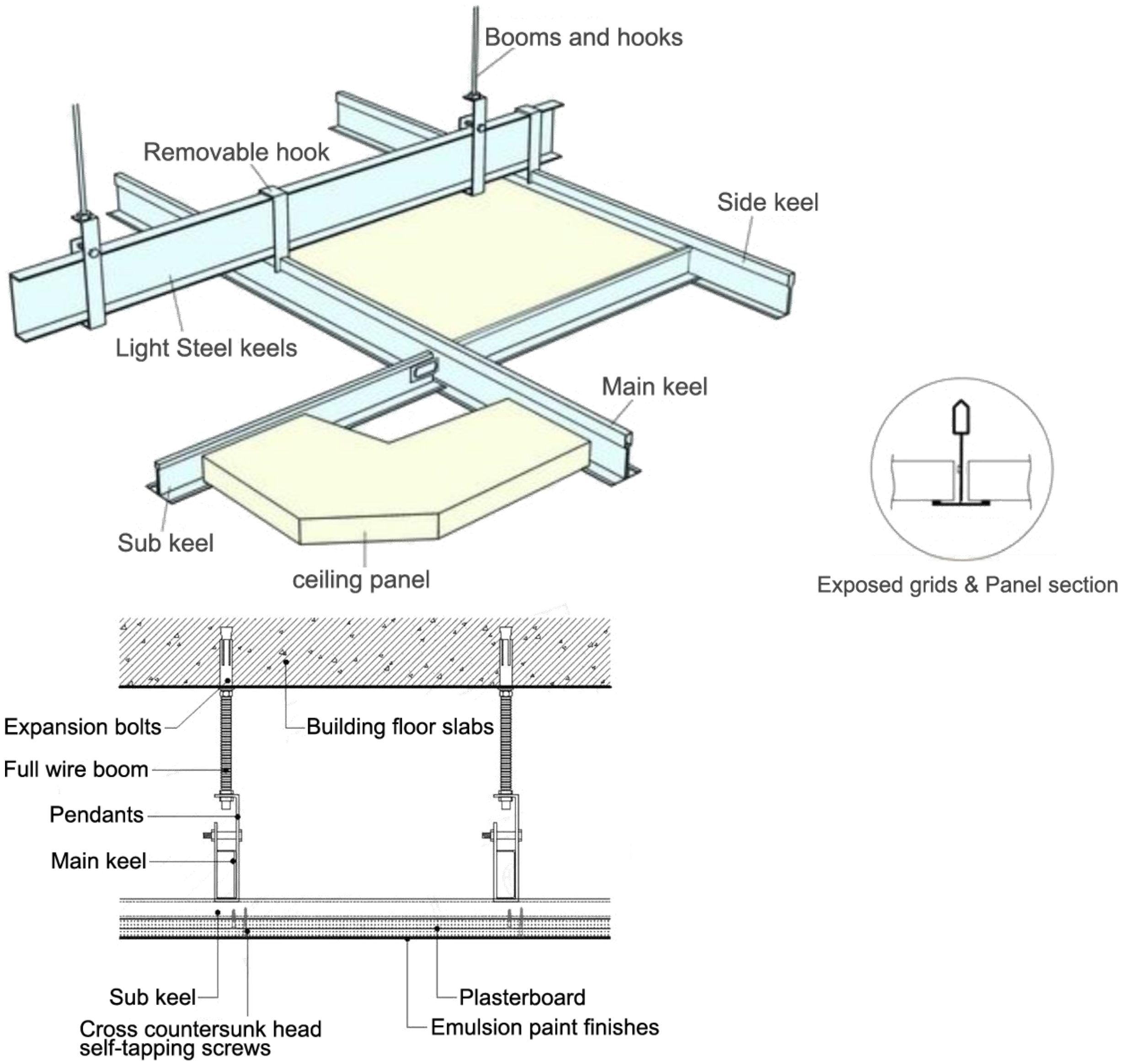


Figure 118 detail drawings of the possible ceiling modular in panel layout and its ceiling structure system

Figure 119 the existing separated structure for the indoor end unit in the sample room (photo by author)

The separated structure for facilities directly connecting to the building structure system is needed (see Figure 119). Extra rough filter for the open return opening on the dry ESP is needed, based on the on-site ventilation installation experience. To decrease air resistance caused by the ceiling ventilation cavity, the panel system should be low-air-resistance and double-sided dustproof design.

5.3 Testing

The testing phase of the draft ventilation product with a filter cloth (filter effect about 37%, see chapter 3.4) is proved by experiment (see chapter 3.3 and Figure 65) and CFD modelling (see chapter 4.6) at the same time the assumption of indoor infection after installing the design (with 37% filter effect).
The infection risk is **3.1% based on CFD modelling**, and **5%** based on the ideal assumption of the direct comparison of **measurement data** (the concentration decreasing rate of 33.43%). In conclusion, the draft ventilation product functions well.

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Appendix 1 the CFD model inputs

case	CO2 Inlet value in SUPPLY attributes	place of SUPPLY 1			size of SUPPLY 1			shape of SUPPLY 1 - geometry	Vol. flow rate of SUPPLY 1 attributes	place of SUPPLY 2			size of SUPPLY 2			shape of SUPPLY 2 - geometry	Vol. flow rate of SUPPLY 2 attributes	place of EXHAUST			size of EXHAUST			place of AFVFC			size of AFVFC			shape of AFVFC - geometry	Vol. flow rate in AFVFC attributes [m^3/s]	place of TVFC			size of TVFC			shape of TVFC - geometry	Source: % Removal in TVFC Attributes
		x [m]	y [m]	z [m]	x [m]	y [m]	z [m]			x [m]	y [m]	z [m]	x [m]	y [m]	z [m]			x [m]	y [m]	z [m]	x [m]	y [m]	z [m]	x [m]	y [m]	z [m]	x [m]	y [m]	z [m]			x	y	z	x	y	z		
standard	4.07E-04	2.56	3.32	2.79	0.01	0.8	0.1	box	0.010867	3.04	3.32	2.79	0.01	0.8	0.1	box	0.010867	2.5	0.3	2.8	0.6	0.6	0				0.43	0.8	0.1	box	-0.158	2.12	1.86	2.78	0.56	0.8	0.1	box	off (0)
0	4.07E-04	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	0.6	0.6	2.8	0.6	0.6	0	2.185	1.86	2.78	0.43	0.8	0.1	box	-0.133	2.12	1.86	2.78	0.56	0.8	0.1	box	off (0)
1	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	0.6	0.6	2.8	0.6	0.6	0	2.185	1.86	2.78	0.43	0.8	0.1	box	-0.158	2.12	1.86	2.78	0.56	0.8	0.1	box	off (0)
2	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	4.4	3.32	2.8	0.6	0.6	0	2.185	1.86	2.78	0.43	0.8	0.1	box	-0.158	2.12	1.86	2.78	0.56	0.8	0.1	box	off (0)
3	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	0.6	0.6	2.8	0.6	0.6	0	2.185	1.86	2.78	0.43	0.8	0.1	box	-0.79	2.12	1.86	2.78	0.56	0.8	0.1	box	off (0)
4	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	4.4	3.32	2.8	0.6	0.6	0	2.185	1.86	2.78	0.43	0.8	0.1	box	-0.79	2.12	1.86	2.78	0.56	0.8	0.1	box	off (0)
5	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	0.6	0.6	2.8	0.6	0.6	0	2.185	1.86	2.78	0.43	0.8	0.1	box	0	2.12	1.86	2.78	0.56	0.8	0.1	box	off (0)
6	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	4.4	3.32	2.8	0.6	0.6	0	2.185	1.86	2.78	0.43	0.8	0.1	box	0	2.12	1.86	2.78	0.56	0.8	0.1	box	off (0)
7	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	0.6	0.6	2.8	0.6	0.6	0	2.185	1.86	2.78	0.43	0.8	0.1	box	-0.158	2.12	1.86	2.78	0.56	0.8	0.1	box	50
8	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	4.4	3.32	2.8	0.6	0.6	0	2.185	1.86	2.78	0.43	0.8	0.1	box	-0.158	2.12	1.86	2.78	0.56	0.8	0.1	box	50
9	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	0.6	0.6	2.8	0.6	0.6	0	2.185	1.86	2.78	0.43	0.8	0.1	box	-0.79	2.12	1.86	2.78	0.56	0.8	0.1	box	50
10	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	4.4	3.32	2.8	0.6	0.6	0	2.185	1.86	2.78	0.43	0.8	0.1	box	-0.79	2.12	1.86	2.78	0.56	0.8	0.1	box	50
11	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	0.6	0.6	2.8	0.6	0.6	0	2.185	1.86	2.78	0.43	0.8	0.1	box	0	2.12	1.86	2.78	0.56	0.8	0.1	box	50
12	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	4.4	3.32	2.8	0.6	0.6	0	2.185	1.86	2.78	0.43	0.8	0.1	box	0	2.12	1.86	2.78	0.56	0.8	0.1	box	50
13	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	0.6	0.6	2.8	0.6	0.6	0	0.65	0.5	2.78	0.43	0.8	0.1	box	-0.158	2.12	1.86	2.78	0.56	0.8	0.1	box	off (0)
14	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	4.4	3.32	2.8	0.6	0.6	0	0.65	0.5	2.78	0.43	0.8	0.1	box	-0.158	2.12	1.86	2.78	0.56	0.8	0.1	box	off (0)
15	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	0.6	0.6	2.8	0.6	0.6	0	0.65	0.5	2.78	0.43	0.8	0.1	box	-0.79	2.12	1.86	2.78	0.56	0.8	0.1	box	off (0)
16	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	4.4	3.32	2.8	0.6	0.6	0	0.65	0.5	2.78	0.43	0.8	0.1	box	-0.79	2.12	1.86	2.78	0.56	0.8	0.1	box	off (0)
17	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	0.6	0.6	2.8	0.6	0.6	0	0.65	0.5	2.78	0.43	0.8	0.1	box	0	2.12	1.86	2.78	0.56	0.8	0.1	box	off (0)
18	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	4.4	3.32	2.8	0.6	0.6	0	0.65	0.5	2.78	0.43	0.8	0.1	box	0	2.12	1.86	2.78	0.56	0.8	0.1	box	off (0)
19	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	0.6	0.6	2.8	0.6	0.6	0	0.65	0.5	2.78	0.43	0.8	0.1	box	-0.158	2.12	1.86	2.78	0.56	0.8	0.1	box	50
20	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	4.4	3.32	2.8	0.6	0.6	0	0.65	0.5	2.78	0.43	0.8	0.1	box	-0.158	2.12	1.86	2.78	0.56	0.8	0.1	box	50

21	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	0.6	0.6	2.8	0.6	0.6	0	0.65	0.5	2.78	0.43	0.8	0.1	box	-0.79	2.12	1.86	2.78	0.56	0.8	0.1	box	50
22	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	4.4	3.32	2.8	0.6	0.6	0	0.65	0.5	2.78	0.43	0.8	0.1	box	-0.79	2.12	1.86	2.78	0.56	0.8	0.1	box	50
23	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	0.6	0.6	2.8	0.6	0.6	0	0.65	0.5	2.78	0.43	0.8	0.1	box	0	2.12	1.86	2.78	0.56	0.8	0.1	box	50
24	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	4.4	3.32	2.8	0.6	0.6	0	0.65	0.5	2.78	0.43	0.8	0.1	box	0	2.12	1.86	2.78	0.56	0.8	0.1	box	50
25	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	0.6	0.6	2.8	0.6	0.6	0	4.485	3.22	2.78	0.43	0.8	0.1	box	-0.158	2.12	1.86	2.78	0.56	0.8	0.1	box	off (0)
26	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	4.4	3.32	2.8	0.6	0.6	0	4.485	3.22	2.78	0.43	0.8	0.1	box	-0.158	2.12	1.86	2.78	0.56	0.8	0.1	box	off (0)
27	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	0.6	0.6	2.8	0.6	0.6	0	4.485	3.22	2.78	0.43	0.8	0.1	box	-0.79	2.12	1.86	2.78	0.56	0.8	0.1	box	off (0)
28	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	4.4	3.32	2.8	0.6	0.6	0	4.485	3.22	2.78	0.43	0.8	0.1	box	-0.79	2.12	1.86	2.78	0.56	0.8	0.1	box	off (0)
29	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	0.6	0.6	2.8	0.6	0.6	0	4.485	3.22	2.78	0.43	0.8	0.1	box	0	2.12	1.86	2.78	0.56	0.8	0.1	box	off (0)
30	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	4.4	3.32	2.8	0.6	0.6	0	4.485	3.22	2.78	0.43	0.8	0.1	box	0	2.12	1.86	2.78	0.56	0.8	0.1	box	off (0)
31	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	0.6	0.6	2.8	0.6	0.6	0	4.485	3.22	2.78	0.43	0.8	0.1	box	-0.158	2.12	1.86	2.78	0.56	0.8	0.1	box	50
32	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	4.4	3.32	2.8	0.6	0.6	0	4.485	3.22	2.78	0.43	0.8	0.1	box	-0.158	2.12	1.86	2.78	0.56	0.8	0.1	box	50
33	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	0.6	0.6	2.8	0.6	0.6	0	4.485	3.22	2.78	0.43	0.8	0.1	box	-0.79	2.12	1.86	2.78	0.56	0.8	0.1	box	50
34	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	4.4	3.32	2.8	0.6	0.6	0	4.485	3.22	2.78	0.43	0.8	0.1	box	-0.79	2.12	1.86	2.78	0.56	0.8	0.1	box	50
35	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	0.6	0.6	2.8	0.6	0.6	0	4.485	3.22	2.78	0.43	0.8	0.1	box	0	2.12	1.86	2.78	0.56	0.8	0.1	box	50
36	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	4.4	3.32	2.8	0.6	0.6	0	4.485	3.22	2.78	0.43	0.8	0.1	box	0	2.12	1.86	2.78	0.56	0.8	0.1	box	50
foot height	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	4.6	4.44	0.1	0.6	0	0.6	4.485	4.42	0.2	0.8	0.1	0.43	box	-0.158	2.12	1.86	2.78	0.56	0.8	0.1	box	50
2 openings	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	0.9	0.9	2.8	0.6	0.42	0	0.6	0.6	2.78	0.43	0.56	0.1	box	-0.79	2.12	1.86	2.78	0.56	0.8	0.1	box	50
																		3.62	4.7	2.8	0.6	0.42	0	4.485	3.22	2.78	0.43	0.56	0.1	box	-0.79	2.12	1.86	2.78	0.56	0.8	0.1	box	50
4 openings	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	0.9	0.75	2.8	0.6	0.3	0	0.6	0.6	2.78	0.43	0.4	0.1	box	-0.395	2.12	1.86	2.78	0.56	0.8	0.1	box	50
																		0.9	4.85	2.8	0.6	0.3	0	0.6	3.22	2.78	0.43	0.4	0.1	box	-0.395	2.12	1.86	2.78	0.56	0.8	0.1	box	50
																		3.62	0.75	2.8	0.6	0.3	0	4.485	0.6	2.78	0.43	0.4	0.1	box	-0.395	2.12	1.86	2.78	0.56	0.8	0.1	box	50
																		3.62	4.85	2.8	0.6	0.3	0	4.485	3.22	2.78	0.43	0.4	0.1	box	-0.395	2.12	1.86	2.78	0.56	0.8	0.1	box	50
70% filter	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	4.98	4.85	2.8	0.6	0.3	0	6.428	3.22	2.78	0.43	0.4	0.1	box	-0.395	2.12	1.86	2.78	0.56	0.8	0.1	box	70
																		6.068	5.67	2.8	0.6	0.3	0	7.982	3.744	2.78	0.43	0.4	0.1	box	-0.395	2.12	1.86	2.78	0.56	0.8	0.1	box	70
																		7.156	6.49	2.8	0.6	0.3	0	9.536	4.268	2.78	0.43	0.4	0.1	box	-0.395	2.12	1.86	2.78	0.56	0.8	0.1	box	70

																		8.244	7.31	2.8	0.6	0.3	0	11.09	4.792	2.78	0.43	0.4	0.1	box	-0.395	2.12	1.86	2.78	0.56	0.8	0.1	box	70
90% filter	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	0.010867	9.332	8.13	2.8	0.6	0.3	0	12.64	5.316	2.78	0.43	0.4	0.1	box	-0.395	2.12	1.86	2.78	0.56	0.8	0.1	box	90
																		10.42	8.95	2.8	0.6	0.3	0	14.2	5.84	2.78	0.43	0.4	0.1	box	-0.395	2.12	1.86	2.78	0.56	0.8	0.1	box	90
																		11.508	9.77	2.8	0.6	0.3	0	15.75	6.364	2.78	0.43	0.4	0.1	box	-0.395	2.12	1.86	2.78	0.56	0.8	0.1	box	90
																		12.596	10.59	2.8	0.6	0.3	0	17.31	6.888	2.78	0.43	0.4	0.1	box	-0.395	2.12	1.86	2.78	0.56	0.8	0.1	box	90
testing	0	2.16	1.86	2.79	0.01	0.8	0.1	box	0.010867	2.64	1.86	2.79	0.01	0.8	0.1	box	1.010867	9.332	8.13	2.8	0.6	0.3	0	0.9	0.3	2.63	0.2	0.2	0.25	cylinder	-0.395	2.12	1.86	2.78	0.56	0.8	0.1	box	37
																		10.42	8.95	2.8	0.6	0.3	0	0.9	3.92	2.63	0.2	0.2	0.25	cylinder	-0.395	2.12	1.86	2.78	0.56	0.8	0.1	box	37
																		11.508	9.77	2.8	0.6	0.3	0	4.7	0.3	2.63	0.2	0.2	0.25	cylinder	-0.395	2.12	1.86	2.78	0.56	0.8	0.1	box	37
																		12.596	10.59	2.8	0.6	0.3	0	4.7	3.92	2.63	0.2	0.2	0.25	cylinder	-0.395	2.12	1.86	2.78	0.56	0.8	0.1	box	37

Appendix 2 the CFD model results

Case no.	strategic variants						engineering parameters							(min) infection risk for 1 h			object
	general	partial					local					general		breathing zone			
	general	ventilation pattern			additional method - filter		human produced CO2 concentration			CO2 removal efficiency	mixing level in breathing zone	Standard deviation	CFD	wells-riley		optimization rate (compared to the existing case)	
	Air exchange rate	recirculation rate	distance between return and resupply openings [m]	distance between supply and exhaust openings [m]	filter level	ISO ePM1	breathing zone (2.8,2.26,1.1)	exhaust opening	average of breathing zone			mixing level for whole space = 1-SD/AVE	fresh air exchange effectiveness=ave outflow local age / ave local age in room	average virus concentration (quanta/m3)	average risk ratio		
1	1.1	14.6	0	1.75	M5	0%	498.4	481.3	483	103.5%	96.8%	98.4%	102.6%	0.12	11.2%	6%	CO2
2	1.1	14.6	0	2.67	M5	0%	458.7	478.7	424.2	95.8%	91.9%	95.0%	103.9%	0.11	10.3%	14%	CO2
3	1.1	7.3	0	1.75	M5	0%	419.3	480.2	436.9	87.3%	96.0%	94.3%	102.6%	0.10	9.4%	21%	CO2
4	1.1	7.3	0	2.67	M5	0%	474.3	481.9	442.8	98.4%	92.9%	96.4%	105.0%	0.12	10.7%	11%	CO2
5	1.1	0.0	0	1.75	M5	0%	468.8	478.9	457.3	97.9%	97.5%	98.1%	101.1%	0.11	10.6%	12%	CO2
6	1.1	0.0	0	2.67	M5	0%	469.0	480.9	476.1	97.5%	98.5%	99.0%	104.9%	0.11	10.6%	12%	CO2
7	1.1	14.6	0	1.75	F7	50%	358.3	337.1	341.5	106.3%	95.1%	97.4%	102.6%	0.09	8.1%	33%	CO2
8	1.1	14.6	0	2.67	F7	50%	332.9	352.6	295	94.4%	87.2%	92.7%	103.9%	0.08	7.5%	38%	CO2
9	1.1	7.3	0	1.75	F7	50%	371.0	433.7	386.2	85.5%	96.1%	93.3%	102.6%	0.09	8.4%	30%	CO2
10	1.1	7.3	0	2.67	F7	50%	407.3	420.5	379.2	96.9%	92.6%	95.7%	105.0%	0.10	9.2%	24%	CO2
11	1.1	0.0	0	1.75	F7	50%	472.1	485.4	461.2	97.3%	97.6%	97.9%	101.1%	0.12	10.6%	11%	CO2
12	1.1	0.0	0	2.67	F7	50%	492.7	487.4	478.4	101.1%	97.0%	98.8%	104.9%	0.12	11.1%	8%	CO2
13	1.1	14.6	1.75	1.75	M5	0%	482.9	491.2	488.8	98.3%	98.8%	99.3%	99.6%	0.12	10.9%	9%	CO2
14	1.1	14.6	1.75	2.67	M5	0%	501.6	488.3	520.4	102.7%	96.4%	97.4%	98.1%	0.12	11.3%	6%	CO2
15	1.1	7.3	1.75	1.75	M5	0%	486.9	489.5	489.5	99.5%	99.5%	99.7%	102.0%	0.12	11.0%	9%	CO2
16	1.1	7.3	1.75	2.67	M5	0%	497.0	490.9	499.3	101.2%	99.5%	99.3%	98.0%	0.12	11.2%	7%	CO2
17	1.1	0.0	1.75	1.75	M5	0%	442.3	495.1	456.5	89.3%	96.9%	95.2%	102.9%	0.11	10.0%	17%	CO2
18	1.1	0.0	1.75	2.67	M5	0%	444.6	487.5	466	91.2%	95.4%	96.2%	102.7%	0.11	10.0%	17%	CO2
19	1.1	14.6	1.75	1.75	F7	50%	99.3	108.3	106.2	91.7%	93.5%	96.3%	99.6%	0.02	2.2%	81%	CO2
20	1.1	14.6	1.75	2.67	F7	50%	107.1	101.4	127.4	105.7%	84.1%	90.0%	98.1%	0.03	2.4%	80%	CO2
21	1.1	7.3	1.75	1.75	F7	50%	183.1	177.3	187.4	103.3%	97.7%	97.7%	102.0%	0.04	4.1%	66%	CO2
22	1.1	7.3	1.75	2.67	F7	50%	189.8	175.9	190.2	107.9%	99.8%	96.4%	98.0%	0.05	4.3%	64%	CO2
23	1.1	0.0	1.75	1.75	F7	50%	464.4	517.7	479.2	89.7%	96.9%	95.4%	102.9%	0.11	10.5%	13%	CO2
24	1.1	0.0	1.75	2.67	F7	50%	444.7	487.9	467.1	91.1%	95.2%	96.2%	102.7%	0.11	10.0%	17%	CO2
25	1.1	14.6	2.67	1.75	M5	0%	513.7	489.9	513.2	104.9%	99.9%	97.8%	98.6%	0.13	11.6%	4%	CO2
26	1.1	14.6	2.67	2.67	M5	0%	485.2	481.4	490	100.8%	99.0%	99.3%	100.6%	0.12	10.9%	9%	CO2
27	1.1	7.3	2.67	1.75	M5	0%	483.0	486.8	500.8	99.2%	96.4%	98.4%	101.0%	0.12	10.9%	9%	CO2
28	1.1	7.3	2.67	2.67	M5	0%	487.1	489.1	488.6	99.6%	99.7%	99.8%	97.9%	0.12	11.0%	9%	CO2
29	1.1	0.0	2.67	1.75	M5	0%	444.7	495.7	458.9	89.7%	96.9%	95.4%	102.9%	0.11	10.0%	17%	CO2
30	1.1	0.0	2.67	2.67	M5	0%	446.0	488.3	466.1	91.3%	95.7%	96.3%	102.7%	0.11	10.0%	16%	CO2
31	1.1	14.6	2.67	1.75	F7	50%	118.8	93.8	118.1	126.7%	99.4%	89.4%	98.6%	0.03	2.7%	78%	CO2
32	1.1	14.6	2.67	2.67	F7	50%	104.9	107.0	110.8	98.1%	94.7%	97.7%	100.5%	0.03	2.4%	80%	CO2
33	1.1	7.3	2.67	1.75	F7	50%	173.3	165.7	188.7	104.6%	91.8%	94.6%	101.0%	0.04	3.9%	67%	CO2
34	1.1	7.3	2.67	2.67	F7	50%	175.2	176.9	172.8	99.0%	98.6%	99.0%	97.9%	0.04	3.9%	67%	CO2
35	1.1	0.0	2.67	1.75	F7	50%	444.7	495.7	458.9	89.7%	96.9%	95.4%	102.9%	0.11	10.0%	17%	CO2
36	1.1	0.0	2.67	2.67	F7	50%	468.0	510.2	487.9	91.7%	95.9%	96.5%	102.7%	0.11	10.5%	12%	CO2
00	1.1	12.3	0	1.75	M5	0%	507.8	484.6	486.8	104.8%	95.7%	97.9%	102.1%	0.13	12.0%	0%	CO2
standard	1.1	14.6	0	3.12	0%		533.0	485.8	528.2	109.7%	99.1%	95.9%	98.2%	0.13	12.0%	0%	CO2
2return50	1.1	8.0	1.75*1 & 2.67*1	2.67	F7	50%	158.0	152.4	158.5	103.7%	99.7%	98.2%	198.2%	0.04	3.6%	70%	CO2

4return50	1.1	8.0	1.75*2 & 2.67*2	2.67	F7	50%	100.9	97.0	106.6	104.0%	94.7%	96.1%	298.2%	0.02	2.3%	81%	CO2
4open90	1.1	8.0	1.75*2 & 2.67*2	1.75*2 & 2.67*2	F7	90%	51.48	49.98118	61.09	103.0%	84.3%	90.9%	398.2%	0.01	1.2%	90%	CO2
4open70	1.1	8.0	1.75*2 & 2.67*2	1.75*2 & 2.67*2	F7	70%	67.06	65.34867	76.55	102.6%	87.6%	92.9%	498.2%	0.02	1.5%	87%	CO2
4open50 overlap	1.1	8.0	1.75*2 & 2.67*2	1.75*2 & 2.67*2	F7	50%	96.8	98.38801	103.2	98.4%	93.8%	97.3%	598.2%	0.02	2.2%	82%	CO2
4open50 separate	1.1	8.0	1.75*2 & 2.67*2	1.75*2 & 2.67*2	F7	50%	92.3	90.27285	102	102.2%	90.5%	94.6%	698.2%	0.02	2.1%	83%	CO2
vertical foot height	1.1	8.0		1.75	F7	50%	475.8	487.1808	500.3	97.7%	95.1%	97.9%	798.2%	0.12	10.7%	11%	CO2
realistic installation particle accuracy	1.1	8.0	1.75*2 & 2.67*2	1.75*2 & 2.67*2		37%	121238.36	120034.07	120486.85	101.0%	99.4%	99.6%					particle [(num.)/min]
realistic installation particle accuracy	1.1	8.0	1.75*2 & 2.67*2	1.75*2 & 2.67*2		0%	188582.89	241989.61	239390.42	77.9%	78.8%	89.0%					particle [(num.)/min]
realistic installation infection risk	1.1	8.0	1.75*2 & 2.67*2	1.75*2 & 2.67*2		37%	137.9	129.3996	136.3	106.6%	98.8%	97.3%	998.2%	0.03	3.1%	74%	CO2
standard	1.1	8.0	0	3.12	0%		340.3	485.8	334	70.1%	98.1%	81.9%	98.2%	0.13	12.0%	0%	CO2
2return50	1.1	8.0	1.75*1 & 2.67*1	2.67	F7	50%	158.0	152.4	158.5	103.7%	99.7%	98.2%	198.2%	0.04	3.6%	70%	CO2

Reflection

The widely spreading of coronavirus brought a new angle for ventilation design in public commercial buildings. In addition to active outbreak prevention and control methods, the self-motivated efforts from individuals, like wearing masks, keeping 1.5m safety distance and avoiding offline group events, the passive methods, being protected from public infrastructure, are of high importance for public general goodness. And "corona-proof" ventilation is important for such kind of passive ventilation designs. It is novel and challenging because of the high requirements of customization and the high unpredictability of the real using condition. There is only few researches provides guiding advice about the ventilation principles to face the corona problems. It is valuable to explore the possible core ventilation principle for the small public space as the start point for the whole construction market.

Interdisciplinary research

Epidemiology, practical engineering and theoretical ventilation design consist of knowledge base of this interdisciplinary research. All these three objects are the obligative precondition for the research, the outcome was expected to have sufficient effects for epidemic prevention, high feasibility for a wide range of fast installation and high precision as a guideline for the spaces with same attributes. To achieve those qualities, the comprehension of all these aspects is of vital importance. I realized that different academic disciplines have different knowledge framework, glossaries and parameter systems. To develop a project based on all these differences, a cross-knowledge mapping with a scientific language translation system should be built by myself. This information digest capacity also requires years of related experiences and a broad vision, and I am still at the budding stage for this specialized career. I use my strong adaptability and learning ability to stumble through these challenges. Though there were falls and frustrations, I still feel the strong motivation when doing something practical and worthwhile. The interdisciplinary research process made me not only more skilled in this specialized area, but also more aware of my personal characters in professional performance, and in general, help me accept and develop myself in an effective way.

Systematic performance

When talking people-oriented built environment, there is a famous theory, the Organic Architecture, the architecture is treated as a living creature. In this way, ventilation system is the circulatory system for the whole body. There is always a deep interaction between each different systems for the macro-functional attribute in the organic existing. Thus, when talking about a specific performance of the cell unit, it is just the tip of the iceberg. There is always a high-variety of context behind a simple change which may cause a butterfly effect afterwards. Positive feedback among different function units can trigger unexpected synergies that result in an extremely efficient outcome. In my case, the anti-epidemic performance of the ventilation facility in the small enclosed space is the end edge of the whole building. It is impacted by the architectural layout of the room, the spatial functional attributes and the building system. The fundamental understanding about the whole building and its building system is essential for the identification of the research problem and further exploration of the optimal solutions, and widely practice for the projects that have the certain commons. A deep understanding of the building and its system also helps the achievability of the master research, and in return, promising a good quality of the research results. As the small peeps about the big, from the partial level design of a small meeting, certain consensus can be achieved to function as a ventilation design guidelines for the general public under the corona time.

Micro-climate control

Human being is always the uncontrollable elements in any people-oriented product design, especially in built environment. The ventilation as a spatial engineering product is to provide a healthy, safe and comfortable living environment for users. The dilemma between conceptual design and realistic practice is that the ventilation design is controlling the whole space, while the local experience is based on the micro-climate around the individual. Thus, the local air quality where the user stays may be quite different from the general design values. And there are also more disturbance elements in micro-climate surrounding the individual. Not only ventilation airflow, but also body airflow and respiratory airflow that decide the air condition surrounding an individual. The indoor activity should be restricted for a high precision of the research result. Luckily, there are some regulation about indoor behaviors in public buildings with same conscious from all over the world under the coronavirus time, like wearing mask and at least safety distance of 1.2m. These regulations allow the research to focus on the airborne transmission only, which is mainly impacted by ventilation airflow and possible to be simulated by CFD methods.

Methods & process

There three methods applied in this graduate program: literature study, on-site experiments and computational modelling. There are two main period: research and design. Based on the depth of the research, the research process has been detailed to four phases: knowledge base, exploration of current ventilation system, simulation of a variant matrix and practical design. During each phase, there combined with a different application level of the three methods. At the same time, a theory framework was continuously built up step by step. The results of literature study, on-site experiments and computational modelling in different phases come together and support each other and finally become a complete thesis.

Design & research

To produce a valuable and reasonable design, there is always combined with a solid research program in the process. Somehow, the sequence and weight of research and design are different. Some products are design-oriented, thus, all researches is based on the abstract image of the design and support the detail design afterwards. While, for research-oriented design, it is from the finding in the research that point out a potential issue for current situation, and the finding can support a novel design. In my case, the relationship between design and research is mixed, but on some level, more similar to the later one. Though I had an abstract image about the possible design based on my relevant experience, when I put my hands on the experiments, I have new finding about the current ventilation strategy – the role of air recirculation at the indoor end unit – and further research finding about it help me develop a ventilation strategy based on that new finding. And with the research results, I was able to combine the abstract image and strategic design and make it a ventilation product. In conclusion, design and research supplement each other, like two string twisted together as one strong rope. The priority of them is hard to clarify, but thesis become more convincing when the bonding is tighter.

Issues & limitations

Firstly, there are information asymmetries in interdisciplinary language translation. For example, when evaluating the indoor infection risk via airborne transmission, the Wells-Riley calculation is applied which is based on the Poison mathematical model, the virus in the air is regarded as homogeneously inactivated, and individual difference on sensitivity of infectious dose is ignored. While, the design context is set as two persons sitting in settled position to evaluate an abstract average infection risk. There is an unavoidable limitation of that between the realistic situation.

As for the issues from the Systematic performance. Currently, the relationship between general spatial environment and local micro-climate is still blur and need to be explored. In this research, I was unable to find a strong proof for the direct connection between general ventilation evaluation methods and the performance of the ventilation design in micro-climate. The application of CFD for the settle environment is of vital importance in both renovation and first-construction designs.

Last but not the least, the limitation from the computational simulation for a real dynamic system. The computational simulation is a stead condition based on the design value of the system. But the realistic situation is usually dynamic with a lot of unexpecting indoor occupation, especially in the "smart building" system that has been widely applicated in most building nowadays. The long-term metering about the indoor air quality condition and the comparison experiment for high accuracy model may help to decrease the gap, but it cannot be totally covered.

Next steps

For a mature and effective ventilation design, especially with high hygiene requirement for public anti-epidemics, the wide application of CFD in ventilation design is a must. It should be part of the documentation in every BIM document. It should be approved by specialists before the installation. To maximize the impact of specialists for system design, a high-productive integration working flow should be there from the very beginning of the project. The impacts from different ventilation strategies should be visualized and understandable for whole the relative works to accelerate the teamwork efficiency.

For different construction, with different time and financial budgets, the installation can achieve different detail level, but based on the same ventilation strategy based on the same attributes of the sample room in this research case.

Due to the wrong setting of the temperature of exhale air from manikin' mouth, further exploration about the thermal plume effect of uplift of exhaled gas airborne particles is needy for a more precise result.

Responds to sustainability and public health

The design is aimed to solve the current problems caused by COVID-19 by a fast, commercial and anti-epidemic effective ventilation strategy and design to protect the health of general public. The design priorities for low time and cost consuming well respond for sustainability requirements and also allow the design to be a speed pill for current emergency facing with the wide spreading of coronavirus and its varietals.