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Indoor Air Quality against COVID-19

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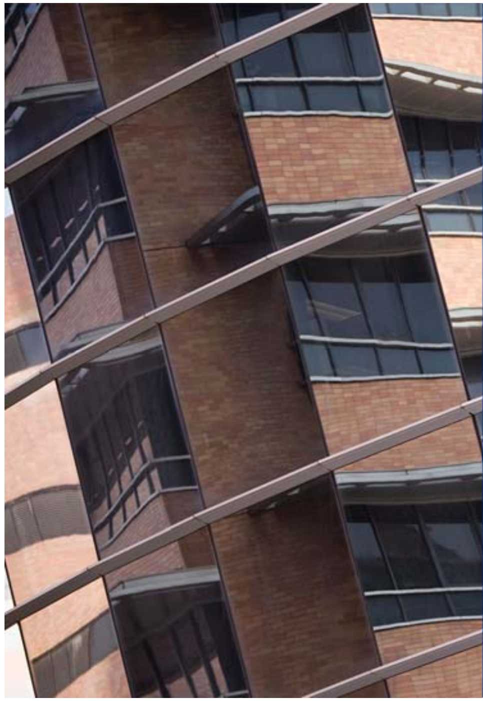

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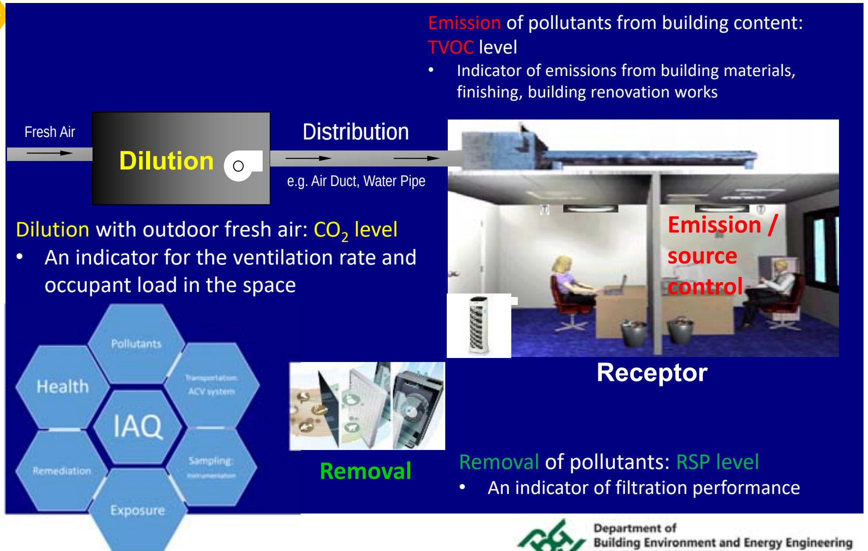
General Principles….

Generalization Principle

3 common IAQ control strategies



High Risk Premises

Mask Off
Close Proximity
Long Term Exposure
Enjoyable Loud Talking

Vulnerable Groups

Possible Out break if Teachers are infected and their offices become a hub

Schools and Elderly Homes: Physically vulnerable segment with long term close interaction

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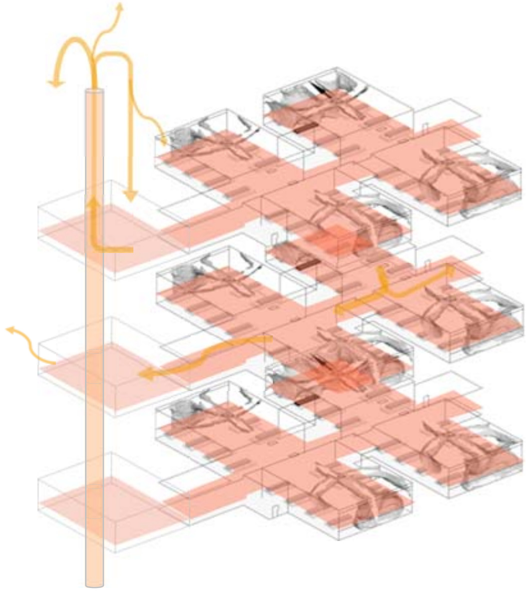
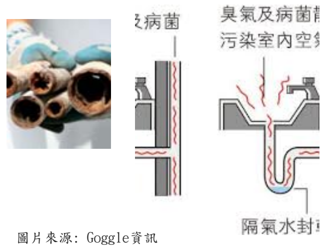
What we need to take care?



Air flow should never go from **dirty** to clean



圖片來源: Goggle資訊

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Any solutions?

Problems today

- COVID-19 Virus is more viable than SARS in normal thermal condition
- Transmission of the virus through carrier in air seems to be effective
- The most effective way of precaution is to cut off all possible connections between people (not desirable)
- All interpersonal activities are halt and caused damage to most schooling (classroom, teacher's office)
- Difficult to perform effective risk assessment (Hidden paths of transmission are very hard to determine)
- Situations change so rapidly. When emergency out break takes place, how to respond?
- Actual Virus test in real environmental is not desirable

What is needed?

- Simple assessment method
- Minimal disturbance to tenants and occupants
- Rapid response and deployment
- Provide all possible ways of dispersion profile
- Provide an easy-to-understand presentation of the current situation to the occupants
- Provide suggestions of remedy for effective precaution (i.e. seating plans modification, occupant allocation, operation scheduling, air purifications, system modifications)

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Ventilation & Transmission

Any Technologies?

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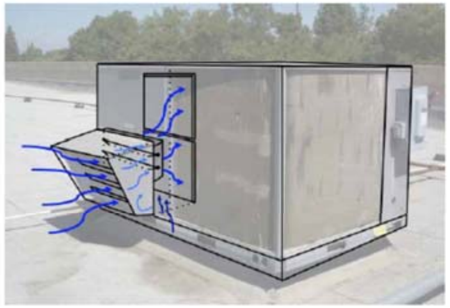
Ventilation Principles

- Ventilation is the supply of outdoor air to a building

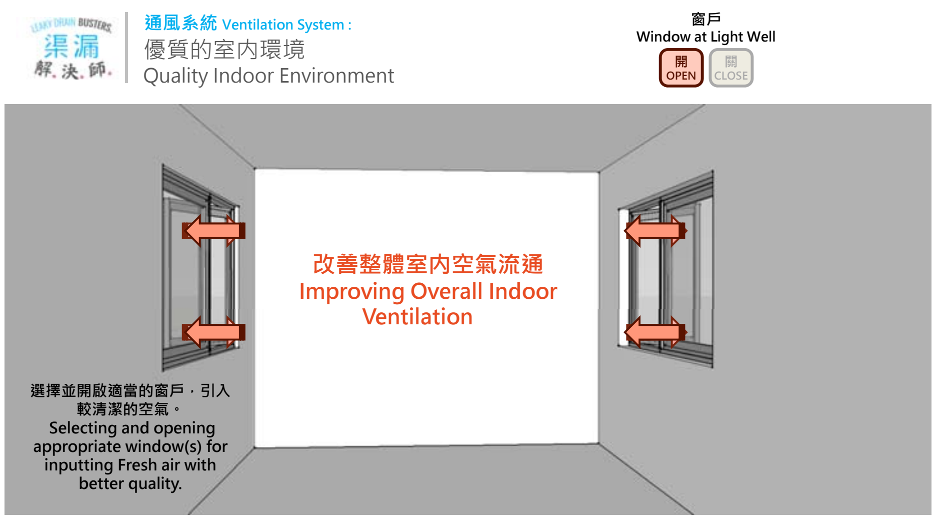


Ventilation Principles

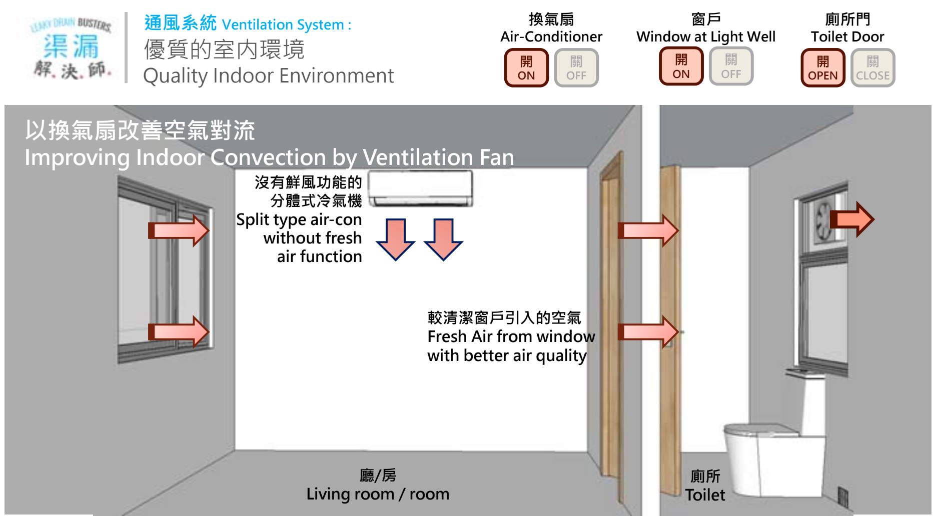
Why is building ventilation needed?

- Ensure comfort and satisfaction
  - Remove odor
  - Avoid stuffiness
- Maintain overall indoor air quality
  - Remove indoor air pollutants (e.g., formaldehyde emitted from building materials, furnishings)
- Support health and productivity of occupants

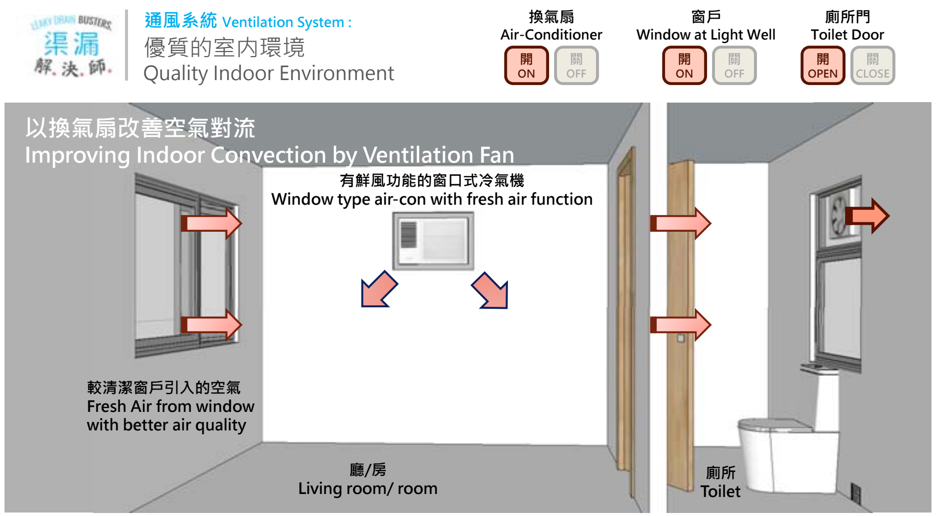
Ventilation Principles



Ventilation Principles



Ventilation Principles



Ventilation … any indicator?

Carbon Dioxide (CO_2) as Proxy for Ventilation Rates

- CO_2 concentrations are often used as an easily measured proxy for ventilation rates
  - When unoccupied, indoor CO_2 approaches outdoor background level (0.04%, or 400 parts per million (ppm))
  - When people enter the space, CO_2 increase over time because we exhale CO_2 (4%)
  - Peak indoor CO_2 concentration above **1,000 ppm** indicates ventilation rates less than 7 L/s (15 cfm) per person (building ventilation requirement)
- Research suggests exposure to elevated level of CO_2 can also impact cognitive performance

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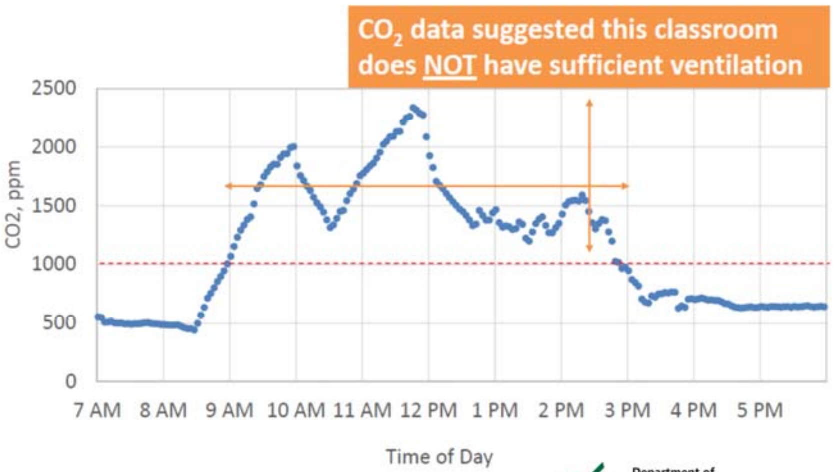
Ventilation … any indicator?

CO_2 Concentrations Measured in a Classroom



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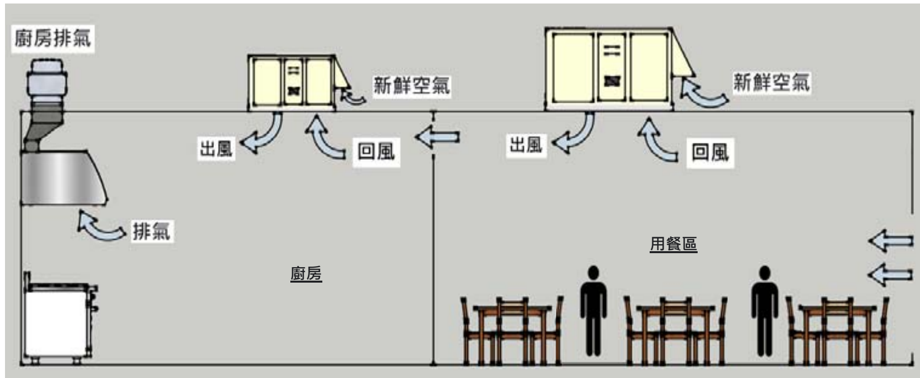
Restaurant Ventilation



換氣率 (Air Change Rate) = 每小時每人立方米新鮮空氣 (m^3/hour/person fresh air) x 人數 (person) / 餐廳的體積 (m^3)

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Restaurant Ventilation

A Guide to Application for Restaurant Licences (fehd.gov.hk)

HEALTH REQUIREMENTS FOR THE ISSUE OF PROVISIONAL GENERAL/LIGHT REFRESHEMENT RESTAURANT LICENCE

STANDARD REQUIREMENTS

1. **Ventilation** : When natural ventilation is insufficient (i.e., where openings and windows to the open air are less than 1/10th of the floor area), a ventilating system shall be provided to give not less than 17 cubic metres of outside air per hour for each person that the premises are designed to accommodate. A ventilating system, which shall be independent of any ventilating system provided for the seating accommodation, shall be provided for the kitchens and toilet rooms of the premises.

2. **Toilets** : At least one toilet compartment, one urinal and one wash-hand basin shall be provided on the premises for the use of customers and staff. If the premises are designed to accommodate more than 25 customers, at least 50% of the provision required for the issue of a full licence have been provided.

Ventilation

How to calculate the Air Change Per Hour (ACH)

Use	Factor used in determining the population
Seating Area	1 m^2/person
Food Room Area	4.5 m^2/person
Dancing Area	0.75 m^2/person

ACH

$$= \frac{\text{Number of occupants (person) x fresh air quantity } (m^3/h/person)}{\text{Volume of the space } (m^3)}$$

$$\text{換氣率 (Air Change Rate)} = \frac{\text{每小時每人立方米新鮮空氣 } (m^3/hour/person \text{ fresh air}) \text{ x 人數 (person)}}{\text{餐廳的體積 } (m^3)}$$

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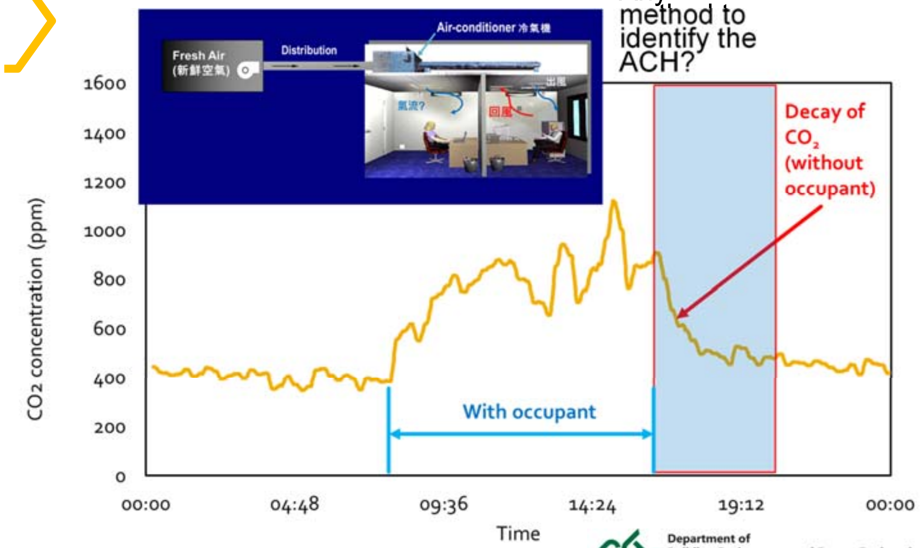
What is decay test??

Any method to identify the ACH?



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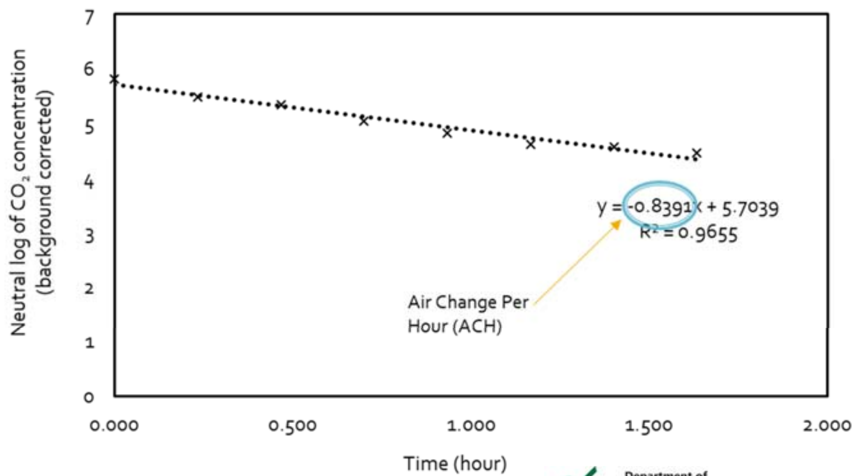
Ventilation calculation

Any method to identify the ACH?



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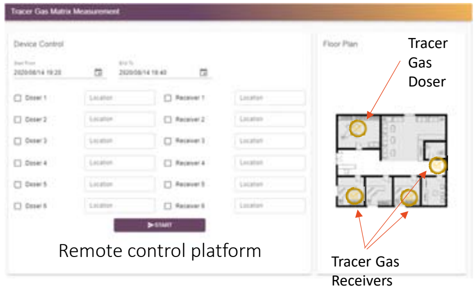
Ventilation calculation

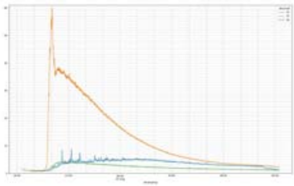


Tracer Gas Matrix Surveying System

- Rapid deployment for Instant response
- Minimal training required for deployment
- Remote real time analysis possible
- Environmentally friendly R134A applied as easily available tracer gas

- ACH analysis by Decay Mode
- Source apportionment analysis by Constant Injection Mode
- Cross Flow/Contamination analysis by Matrix Mode (Multi-Dosers/Receivers Sycnchronized Dosing Matrix)

Real Time Tracer Gas Profile at 3 defined locations



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Ventilation (Example)

Ventilation (Example)

Tracer Gas Doser

Tracer Gas Receiver

Tracer Gas Receiver

Tracer Gas Receiver

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Ventilation (Example)

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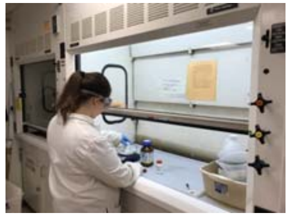
This is the update technology??

IAQ improvement methods

- Local exhaust ventilation
  - Chemical fume hoods to control critical emission sources of chemical vapours
  - Ensure adequate removal of the pollutant
  - Air cleaner with HEPA filter
- Ultraviolet light Irradiation
  - Upper-room irradiation
  - Duct irradiation
  - Mobile irradiation system



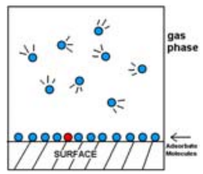
Different types of air purification system

- High efficiency particulate air filter (HEPA)
- Ultraviolet germicidal irradiance (UVGI)
- Carbon filters
- Photocatalytic oxidation (PCO)
- Ozone oxidation
- Ionization

Adsorption Mechanism

The adhesion of a gas to the surface of a solid by Van de Waals or forming new chemical bonds

- Physisorption
  - No any reaction between adsorbent and pollutant
  - No selection for adsorb which type of gas
- Chemisorption
  - The reaction is irreversible and selective
  - Temperature is direct proportion to the reaction velocity



Adsorption Mechanism

- Pollutants Treated by Adsorption
  - Gases
  - Odors
  - Fumes
- Common adsorbent
  - Active carbon
  - Silica gel
  - Activated aluminum oxide
  - Zeolite

Adsorption Advantages & Limitations

Advantages:

- High adsorption capacity & high removal efficiency for specific compounds
- Operation at room environment
- No harmful by-products.
- Good performance for gas-phase pollutants
  - e.g. activated carbon is effective in removing ozone

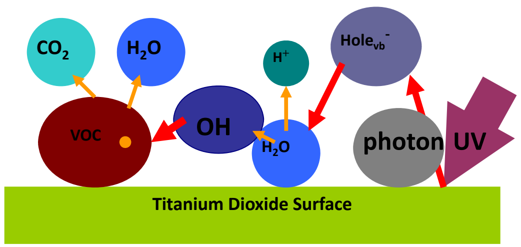
Disadvantages:

- Lose activity with time
- Post-treatment of adsorbent is required

What is TiO_2 and PCO?

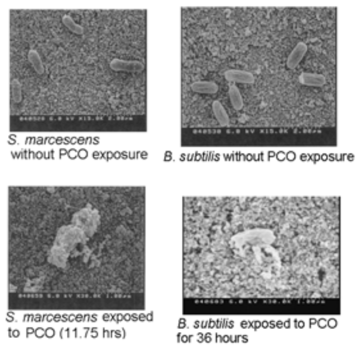
TiO_2 Chemical Reaction

- **Photocatalytic Oxidation occurs only if photons water molecules and the organic pollutants are all on the catalyst surface:**



What is TiO_2 and PCO?

SEM scanning of micro-organisms on TiO_2 disk…



- **The spore cells were broken…**
- **The bioaerosol was mineralized. [Goswami, 2003]**

Ozonation Mechanism

- Ozone can be generated by UV or NTP discharge
- Ozone is a strong oxidant
- To take reactions with pollutants and oxidizes them
- To oxidizes and decomposes the enzyme required by glucose to make the bacteria died
- To destroy the DNA structure and cellular of bacteria, virus and microorganisms

Ozonation Advantages & Limitations

Advantages:

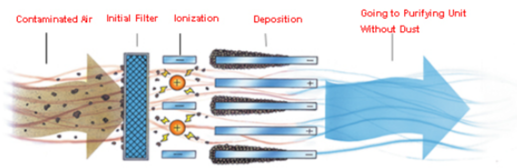
- Ozone can produce hydroxyl radicals
  - Highly reactive to the pollutants
- Ideal aerial disinfectant
  - Penetrate to everywhere of the room, include a small corner

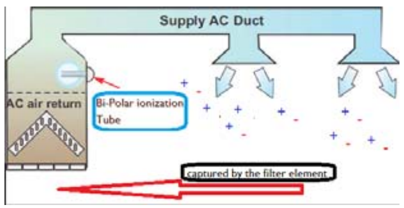
Disadvantages:

- Ozone output concentration needs to be strictly controlled
  - Health hazard
  - Slight: coughing, wheezing, headaches
  - Serious: lung diseases
- Damage some material
  - e.g. plastic

Bi-polar Ionization- Principles

Bi-polar ionization:
Positive (+) and negative (-) ions
generation by
Bi-Polar Generator &
Pulsed AC System

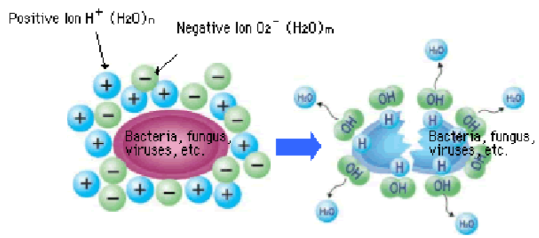




- Airborne particles then falls to the floor.
- These larger particles are also returned through the air conditioning system and captured by the filter element.

Bi-polar Ionization- Principles

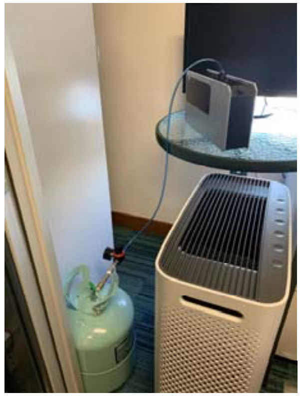
- Though positive and negative ions airborne the Microbiological (mold, bacteria etc)
- The organism was destroyed and deactivated



Ventilation and transmission path – How to measure?

Tracer Gas Matrix Measurement

Pathogen Source Dispersion Analysis
Contaminants Apportionment Analysis



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Identification of transmission path – How to measure?

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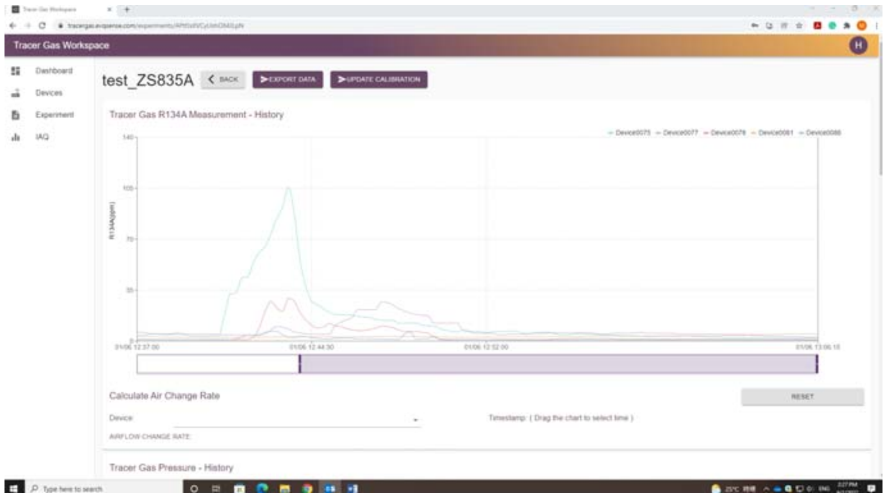
Identification of transmission path – How to measure?



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Identification of transmission path – How to measure?

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Identify the dispersion of COVID-19

- Applicable to special situation, for instant during a pandemic, to conduct monitoring in wet market and restaurants where transmissions are observed, even clean-up has been done
- Once the equipment is set-up, the system will release and track the tracer gas **remotely** without the presence of technician. Much less manpower and time are needed
- **No personnel is required** to be on-site. Data will be automatically transmitted to server for analysis
- Compare to traditional method which takes about half a day to collect and analysis the data, this **new approach takes only 2 hours** to report the pathogenic bioaerosol dispersion pathway

The Tracer Gas Measurement Exercise helps to

- Define better seating arrangement at with respect to the existing ventilation profile
- Determine the potential pathogen dispersion coverage
- Determine the existing risk level deduced by the ACH evaluating
- Determine the optimized occupation number
- Conduct cross platform analysis with long term IAQ monitoring data
- Define emergency control plan
- Define ventilation system modification plan

Any more examples?

On Stage Tracer Gas Air Flow Analysis
for
Risk Assessment of Potential Pathogen Dispersion Profile

In Association with
Hong Kong Philharmonic Orchestra

Objective for HK Phil On Stage Air Flow Analysis

- Determine the spreading path of potential pathogen from any player on stage
- Determine the potential risk level for other occupants on stage
- Determine the ventilation rate of the current system settings
- Help defining an optimized seating plan to minimize risk level
- Determine the best way of deployment of air purifiers if necessary
- Determine the best arrangement of barrier settings
- Evaluate the risk level at the common areas where the players may gather
- Define all possible measures that could provide a safe environment for the next performance

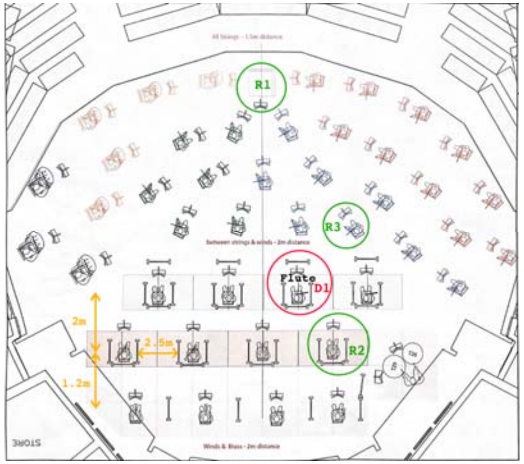
- https://pc.watch.impress.co.jp/docs/news/1282701.html

Tracer gas profile against Individual Barrier

Test Upon Individual Barrier Setting

Experimental condition

- Doser: Flute player
- Receiver
  - R1 – 54: conductor
  - R2 – 55: back-right
  - R3 – 56: front-left
- Tracer gas operation
  - Release at: 10:56:10
  - Stop at: 11:07:01



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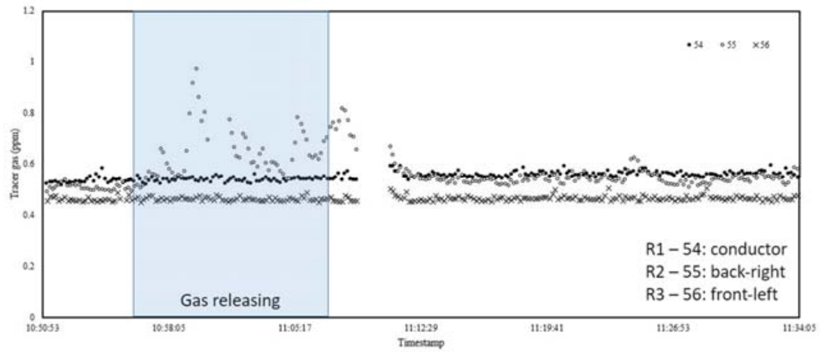
Tracer gas profile against Individual Barrier



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Tracer gas profile against Optimised Seatings with Inline Barriers

Test upon Optimized Seatings with Inline Barriers

Experimental condition

- Doser: Flute player
- Receiver
  - R1 – 54: front-right
  - R2 – 55: back-right
  - R3 – 56: further back-right
- Tracer gas operation
  - Release at: 14:53:00
  - Stop at: 15:03:36

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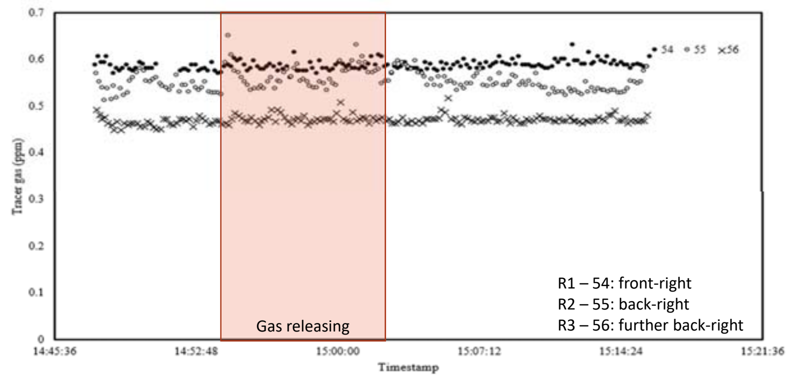
Tracer gas profile against Optimised Seatings with Inline Barriers



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So…?

Recommendation (1): Provide Adequate Ventilation

Fresh Air

Students more ***alert*** and ***focus***; Fewer respiratory symptoms and illness absence

Students tired, loss of concentration; Increase ***respiratory symptoms*** and ***illness absence***

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Any other high-risk area?

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Airborne transmission causing healthcare-associated infections (HAIs)

- A number of viruses and bacteria are known to be spread by air
  - e.g. Tuberculosis, influenza virus, SARS-CoV-1, MERS-CoV and COVID-19
- Aerosol-generating procedures such as tracheal intubation, nebulized therapy and bronchoscopy enhance risk of healthcare-associated infections


THE AGE

COVID-19 hospital worker infections prompt ventilation audit


The Guardian

News Opinion Sport Culture Lifestyle

Coronavirus

Up to 20% of hospital patients with Covid-19 caught it at hospital

NHS England figures reveal some infections were passed on by hospital staff unaware they had virus

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Clinics / health centres or hospital in Hong Kong?

- Whole building
  - Provide various services including general and specialist out-patient clinic services, pharmacy, diagnostics and imaging, dental service, etc.
  - Served by *mechanical ventilation and air conditioning (MVAC) system*
- Part of the existing commercial building
  - Provide several medical services, mostly general out-patient clinic services, pharmacy, diagnostics and imaging
  - On one or several floors
  - Served by *MVAC system*
  - *Share public facilities* (e.g. lift, toilet, lobby) with other businesses
  - Patients may need to travel for several floors for various services
- Small local clinics in residential areas
  - Usually provide only out-patient clinic services and pharmacy
  - In mall or on the street in residential areas
  - Served by *MVAC, window type or split type air-conditioner*

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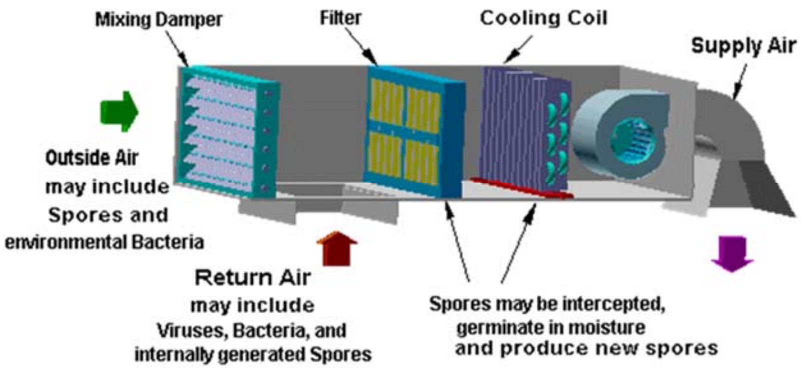
Airborne Pathogens in relation to a Typical Air Handling Unit (MVAC)



IAQ pollutants in clinics / health centres or hospital

Common IAQ pollutants:

- Carbon dioxide (CO_2)
- Carbon monoxide (CO)
- Formaldehyde (CH_2O)
- Volatile organic compounds (VOCs)
- Respirable suspended particulates (PM)
- Radon

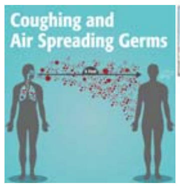
IAQ pollutants specific to healthcare facilities:

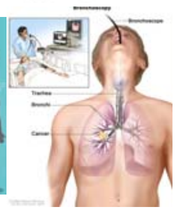
- Glutaraldehyde ($C_5H_8O_2$)
- Nitrous oxide (N_2O)
- Latex allergens
- Airborne bacteria/ mould

Reference: Leung, M., & Chan, A. H. (2006). Control and management of hospital indoor air quality. Medical Science Monitor, 12(3), 23.

Cause of IAQ problems

- Use of *disinfectant/ chemicals* which contain volatile organic compounds (VOCs)
- *Patients* as sources of airborne particles (e.g. airborne viruses and bacteria and fungus spores)
- Specific *medical procedures* (e.g. endoscopic procedures, tracheal intubation, nebulized therapy and bronchoscopy)
- Poor *design of MVAC system* originally for office usage
- *Recycled air* for energy efficiency
- Poor *filtration* performance
- *Improper maintenance/ lack of cleaning* of HVAC system





Consequences of poor IAQ

- Sick hospital syndrome (SHS)
  - Headache, fatigue, eye and skin irritation
  - Lower productivity
- Hospital acquired infections
  - Patient-patient and healthcare worker-patient cross-infection
- Spreading of diseases among different floors through common building facilities
  - Lift, door, toilet, MVAC system, etc.

Patients and healthcare workers

- Higher risk for vulnerable populations
  - Elderly and children
  - Patients with long-term illnesses
  - Patients with immunodeficiency disorder
- Healthcare workers are also prone to health risks due to prolonged exposure to IAQ pollutants and occupationally harmful biological pollutants

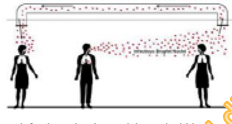

Hong Kong's classic example - SARS

In 2003, SARS outbroke in General Inpatient Ward caused by a SARS patient be given with nebulized treatment

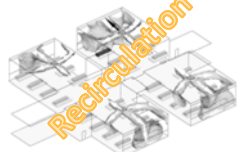
- Aerosolized coronavirus particles re-circulated in the whole ward, infecting 277 staff and patients, leading to the community outbreak in HK

In 2004, HK Government approved the construction of the 1st Infection Disease Control centre in HK

- 17-storeys with 108 negative pressure isolation beds
- Started operation in 2007



Infections droplet nuclei travel within environment

Transmission paths for the pathogenic between general inpatient ward cubicle

1st Infection disease centre in HK

Existing solutions

Problem solved?

- Design references
- A minimum of total 6 ACH for existing settings (without specifying the % for fresh air or recirculated air)
- Deploy ward with air handling unit exhaust out to ambient having 3-meter away from fresh air intake
- Enhanced ventilation at A&E, General Out-Patient Clinic (GOPC) & Specialist Out-patient Clinics (SOPC) waiting areas
  - Widest opening of the fresh air dampers

Temporary segregation on A&E area

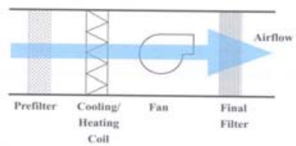
HEPA unit is placed at A&E area

Reference: Hospital Authority communication kit – COVID-19 version 6.3 (27 Oct 2020)

IAQ improvement methods

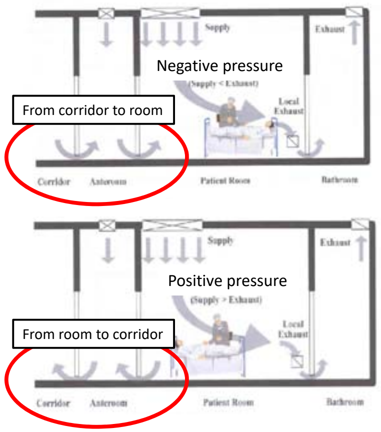
- Mechanical ventilation
  - Diluting indoor air pollutants
  - Exhaust the contaminated indoor air
  - Introduce clean outdoor air into an air-conditioning building
  - Air change rates for outdoor air and total air are recommended by ASHRAE (1999,2001,2004,2007), AIA (2001) and CDC (1994)
- Filtration
  - Trap particulate contaminants
  - Various grade of filters can be used to achieve different degrees of cleanliness
    - Prefilter of 25% dust spot efficiency to remove large particles
    - Final filter should have at least 90% efficiency to collect nearly all fungal spores of 2-5µm diameter and bacteria in colony-forming units of 1µm diameter
  - Filtration requirements of some hospital areas are provided by ASHRAE (1999) and AIA (2001)

Area	Outdoor ACH	Total ACH	Outdoor air requirement	
	ACH	ACH	Cfm/p	L/s/p
Patient room	2	4	25	13
Operating theatre	15	15	30	15
Infectious isolation room	2	6		
Laboratory	2	6		
Pharmacy	2	4		
Darkroom	2	10		



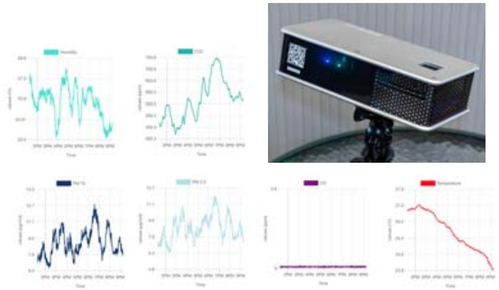
IAQ improvement methods

- Differential pressure control/ Directional airflow control
  - Maintain a differential pressure between two adjacent areas can restrict the air leakage in a single direction through the door undercut
  - Ensure **clean-to-less-clean airflows**: air movement should be from clean zones to zones of progressively greater contamination



IAQ monitoring

- IoT real-time monitoring
  - Automatic, low cost and manpower required
  - All-in-one multiple sensor module for representative pollutants
  - Compact design, mobile and easy to set-up
  - Real-time and smart analysis
- IAQ Certification Scheme



My research in improving IAQ in hospitals

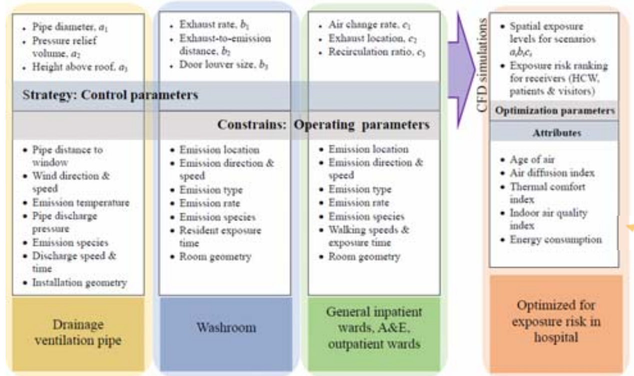
Project Title: ***Effective Ventilation Strategies for Mitigating Infection Risks in Hospitals***

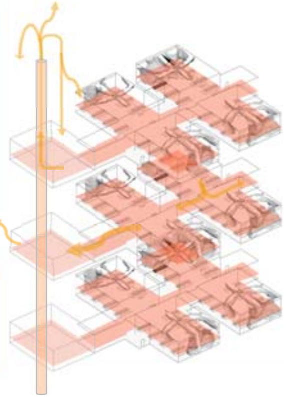
Objectives:

- Understand the spatial distribution of pathogenic bioaerosols in General Human Occupied Areas (GHOAs)
- Identify the temporal influence of possible combinations of control and operational parameters on the estimation of infection risk within the mechanically ventilated enclosure in hospital
- Evaluate and update current air change requirements (ACH) in hospital
- Provide proper ventilation strategies which mitigate the risk of airborne infection transmission for GHOAs

What we need to take care of?

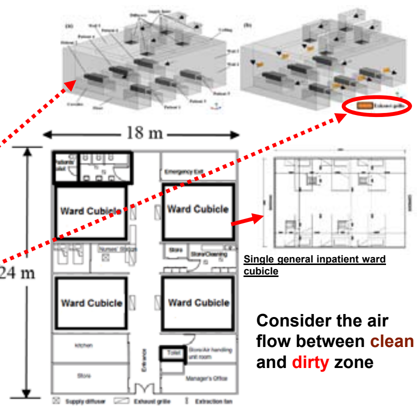
Air flow should never go from dirty to clean





Task 1: Hospitals layout and ventilation strategies data collection

- Arrangement drawings and technical details of GHOAs in hospitals (e.g. dimensions, ventilation rates and outlet locations)
- 27 ventilation scenarios for general inpatient ward (the most complicated one) will be simulated using
  - (a) ach (3, 9 and 13h^{-1})
  - (b) exhaust locations
    - EXISTING: no exhaust
    - low level exhaust near the beds
    - low level exhaust on the window side; and
  - (c) recirculation ratios (10, 30 and 50%)



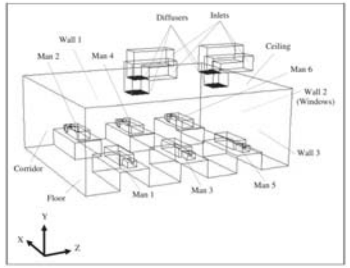
Single general inpatient ward cubicle

Layout of general inpatient ward

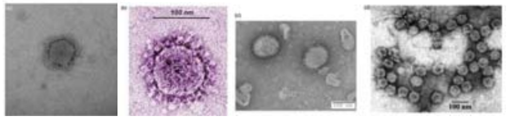
Consider the air flow between clean and dirty zone

Research into the ventilation of general hospital wards for mitigating infection risks

- A typical semi-enclosed six-bed general ward -7.5 m (L) x 6m (W) x 2.7 m (H)
- 3 respiratory viruses (MERS-CoV, SARS-CoV and H1N1 influenza virus)
- Computational fluid dynamics (CFD) simulation of airflow field and virus dispersion inside the ward with various ACH



CFD configurations of a six-bed general ward cubicle

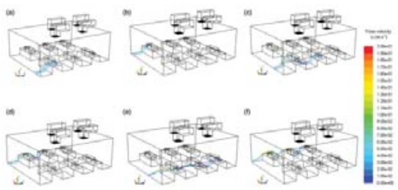


Electron micrograph of reference viruses. (a) MERS-CoV19 (b) SARS-CoV20 (c) H1N1 influenza virus21 and (d) Bacteriophage Phi X174

Reference: Yu, H.C., Mui, K.W., Wong, L.T. and Chu, H.S., 2017. Ventilation of general hospital wards for mitigating infection risks of three kinds of viruses including Middle East respiratory syndrome coronavirus. *Indoor and Built Environment*, *26*(4), pp.514-527.

Potential risks of cross infection with through air pathways

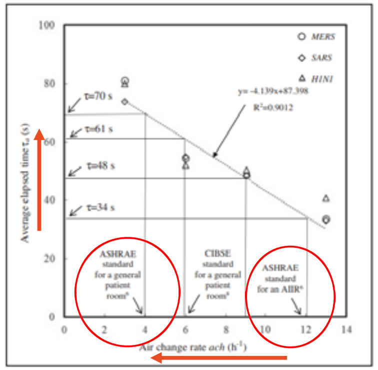
- Patients staying on the same side of an infected patient, especially the one located next to the corridor (i.e. Man 1 or Man 2), would have a higher chance of cross infection
- Two different virus pathway flows in the simulation due to the asymmetric diffuser locations
- The virus moved along floor surface of the ward but in cases shown in Figure d and f, virus would pass over nearby patients' heads, then flew to the corridor [Figure c and e]



MERS-CoV pathways for six source locations with ach=6 h^{-1} (a) Man 1, (b) Man 2, (c) Man 3, (d) Man 4, (e) Man 5 and (f) Man 6

Optimal ACH for hospital

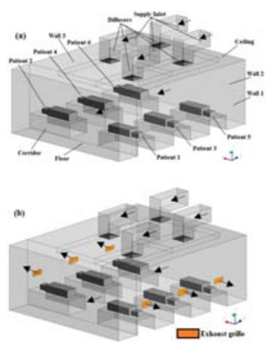
- The average elapsed time against ACH could be significantly shortened by increasing the air change rate in the ward
- The elapsed time doubled when ACH dropped from 12 to 4 h^{-1}, and thus doubling the potential inhalation risk
- Based on the median value in accordance with both ASHRAE and CIBSE standards, the maximum ACH in a general hospital ward should be <u>*9 h^{-1} (elapsed time=48 s)*</u> for the needs of maximizing energy efficiency and minimizing infection risk



Average elapsed time with various design standards. AIIR: airborne infection isolation room.

Research into ventilation strategies and the use of local exhaust grilles for infection risk mitigation

- To evaluate the combined impacts of air change rate and exhaust airflow rate on the airflow and infection risk distributions of droplet nuclei of size 0.167 μm (i.e. MERS-CoV) within an air-conditioned general inpatient ward cubicle using CFD
- To develop a simple yet cost-effective ventilation system design that can minimize the risk of infection in an existing hospital ward

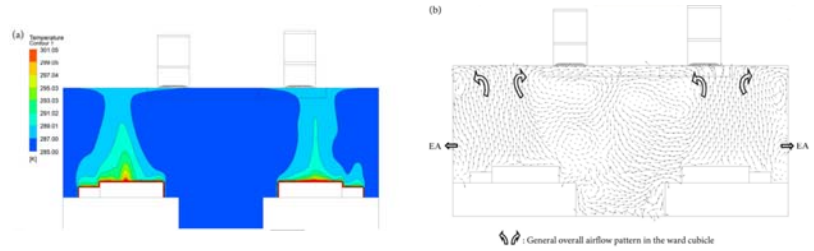


Inpatient ward cubicle with patients: (a) without exhaust grilles; (b) with local exhaust grilles

Reference: Satheesan, M.K., Mui, K.W., and Wong, L.T., 2020. A numerical study of ventilation strategies for infection risk mitigation in general inpatient wards. *Building Simulation*, 13, pp. 887-896.

Use of local exhaust grilles

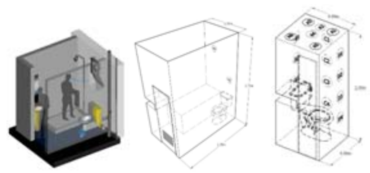
- The local exhaust grilles not only facilitated the removal of a portion of exhaled virus particles but also tended to increase the particle deposition in the source patient's body and thereby reduced the residual viral load present in the air



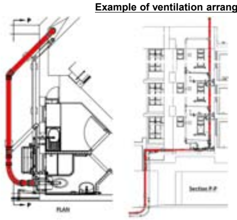
Simulation results of ward cubicle with exhaust grilles at 6ACH and exhaust air (EA)=50%: (a) temperature distribution; (b) velocity vector plot

Task 3b: CFD simulation for dynamic water and airflow in drainage system in relation with washroom

- Potential infection risk associated with toilet flushing and the influence of pathogen in common areas such as corridor or ward cubicle have not been sufficiently addressed in the design of residential washroom exhaust system
- A two-phase flow CFD model for air and water flows inside the drainage system will be developed
- Verification and application of CFD simulation using drainage test rig



Example of ventilation arrangement for Washrooms

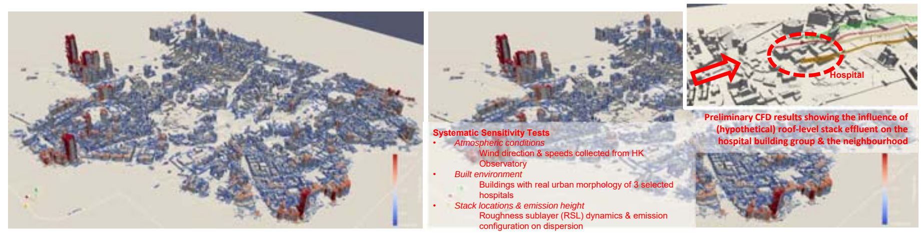


Layout of drainage pipe

Drainage test rig at PolyU

Task 3c: CFD simulation for spatial exposure levels at drainage ventilation pipe discharge

- Dynamic of airflow fields and spatial distribution of aerosols from the toilet exhaust and ventilation pipe discharge at hospital roof will be simulated
- Roof configuration, surrounding built environment, atmospheric conditions, stack location and emission height causing the risk of short circuit of contaminants from discharge to fresh air intake will be identified



Overall strategy and collaborative effort

- Data collection (Control and Operational parameters) and Computational Fluid Dynamics (CFD) simulation to understand spatial and temporal distribution of pathogenic bioaerosols under different ventilation strategies and emission scenarios
- Exposure Risk Assessment that helps to identify high risk zone in hospital
- Optimization of ventilation energy usage based on exposure risk

Deliverable: formulating ventilation strategies that minimize the risk of exposure to airborne infections in hospitals

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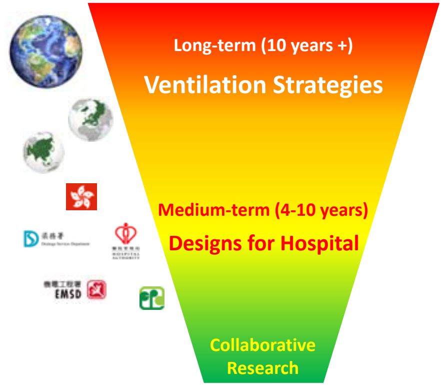
Pathway to impact

- Inter-institutional collaboration locally and internationally
- Policy and regulations
- Improve international ventilation standards, codes of practice
- Ventilation strategies
- Reference and guideline
- Better hospital design



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Media Exposure

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In conclude …

Embrace more health-conscious design, and work cooperatively as an international community to solve problems, pave the way for a healthier future

Question & answer?

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