A STUDY OF BIO-RISK ASSESSMENT, CONTROL AND EVALUATION (BRACE) FOR INDOOR ENVIRONMENT

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A Study of Bio-risk Assessment, Control and Evaluation (BRACE) for Indoor Environment

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Certificate of Originality

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Abstract

A better understanding of the exposure and deposition of bioaerosols in indoor environment is crucial for the improvement of indoor air quality (IAQ) and the minimization of the airborne infection. The information on exposure assessment of indoor bioaerosols in Hong Kong, however, is scare. Unlike the non-biological aerosols, the phenomenon of deposition of bioaerosols indoors is still unclear and not well investigated. Therefore, this study aims to provide important information on the exposure and control strategies of indoor bioaerosols through assessment, evaluation and investigation of the control factors of bioaerosols in the indoor environment of Hong Kong. Three principal objectives are (a) to assess the exposure of bioaerosols by investigating the abundance and composition of bioaerosols in various types of indoor environments in Hong Kong; (b) to evaluate the importance of bioaerosols in aspect of indoor air quality and identify the possible factors (e.g. ventilation) affecting the bioaerosols exposure in indoor spaces; and (c) to develop a method to investigate the deposition of some common bioaerosols in order to provide insights for the control of their occurrence in indoor environment .

In this study, regional cross-sectional database of indoor airborne bacteria and fungi were developed by collecting samples from typical naturally ventilated residential apartments (N=103) and air-conditioned commercial offices (N=239). For the apartments, seasonal effects on the indoor airborne bacteria and fungi were revealed. Significantly higher average indoor airborne bacteria count (ABC) and significantly lower average airborne fungi count (AFC) were recorded in summer when compared with winter. Investigation of indoor airborne fungi at different locations within the same apartment revealed that the highest concentration was recorded in the kitchen, followed by the living room and the bedroom. For the offices, it was observed that both ABC and AFC in offices with excellent IAQ were significantly lower than those typical offices in Hong Kong. In general, *Micrococcus*, *Staphylococcus*, *Aspergillus*, *Penicillium*, *Cladosporium* are commonly found airborne bacteria and fungi in both apartments and offices. Higher indoor ABC in apartments and lower indoor ABC in air-conditioned offices, and lower indoor AFC in both apartments and air-conditioned offices were observed in Hong Kong when compared with other countries.

This is the first study to use mathematical expression to reveal the importance of

indoor bioaerosols assessment in the IAQ investigations of air-conditioned commercial buildings. It was found that AFC and ABC are the 2nd and 3rd ranked contributors for the unsatisfactory rates of IAQ in the offices. Furthermore, the positive effects of the existing IAQ policy in Hong Kong were observed in the significant decrease of indoor ABC and AFC in air-conditioned offices in the past decade. Furthermore, this study proposed several indices and models for the evaluation of the indoor bioaerosols. A relative index of fungal exposure (RIFE) was proposed to measure the relative exposure risk associated with an indoor environment compared with the outdoor one. A higher relative exposure risk was found indoors compared with that of the outdoors for both apartments and offices. Mathematical expressions on the relationship between the indoor bioaerosols levels and the temperature and relative humidity were developed; hence, under certain thermal environmental conditions, the excepted ABC and AFC can be rapidly estimated. In addition, a statistical model was developed for the prediction of pre-assessed unsatisfactory failure rate of air-conditioned public spaces over the local region.

Several case studies on the evaluation of bioaerosols exposure were also conducted. The impact of indoor bioaerosols and some common air pollutants on the quality of life (QOL) of patients with Chronic obstructive pulmonary disease (COPD) was investigated. The patients' QOL were found to be strongly associated with the indoor environmental parameters recorded in their apartments, although the evidence of a causal relationship between them necessitated further research. Case studies investigation of the indoor bioaerosols exposure in the unoccupied office area and washroom under different ventilation conditions confirmed the strong effects of ventilation on bioaerosols exposure level.

Therefore, an experimental facility was designed and built with the objective of understanding the deposition of bioaerosols in indoor environments. Five commonly isolated bioaerosols i.e. *Micrococcus*, *Staphylococcus*, *Aspergillus*, *Penicillium*, and *Rhizopus* were selected. The average diameter of bacterial cells and fungal spores ranged from 1 to 10 μm. It was found that the deposition of bioaerosols was significantly affected by the ventilation rate, mixing condition of the chamber, and the size of the bioaerosols. It was demonstrated that small-sized bioaerosols were chiefly influenced by the ventilation rate, while large-sized bioaerosols were mainly affected by gravity.

A numerical model using the Eulerian-Lagrangian approach was developed to

predict the deposition of bioaerosols in the chamber. The experiment results agreed with the numerical results quite well despite some discrepancies were observed. And the inclusion of the drag with particle sphericity was found to improve the prediction of bioaerosols deposition at low ventilation rate by using this model.

The study provides some important information on the assessment, exposure evaluation, and control of indoor bioaerosols. Further work is needed to improve the numerical models for a better prediction and understanding the dynamics of bioaerosols in different indoor environments.

List of publications arising from the thesis

SCI and EI Journal papers

Fong KNK, Mui KW, Chan WY, Wong LT. Air quality influence on chronic obstructive pulmonary disease (COPD) patients' quality of life. Indoor Air 2010; 20(5): 434–441.

Lai ACK, Wong LT, Mui KW, Chan WY, Yu HC. An Experimental Study of Bioaerosol (1-10μm) deposition in a ventilated chamber. Building and Environment 2012 56: 118–126.

Mui KW, Chan WY, Wong LT, Hui PS. Fungi–an indoor air quality assessment parameter for air-conditioned offices. Building Services Engineering Research and Technology 2007; 28(3): 365–274.

Mui KW, Chan WY, Wong LT, Hui PS. Scoping indoor airborne fungi in an excellent indoor air quality office building in Hong Kong. Building Services Engineering Research & Technology 2010; 31(2): 191–199.

Mui KW, Wong LT, Chan WY. Energy impact assessment for the reduction of carbon dioxide and formaldehyde exposure risk in air-conditioned offices. Energy and Buildings 2008; 40(8): 1412–1418.

Mui KW, Wong LT, Hui PS, Chan WY. Formaldehyde exposure risk in air-conditioned offices of Hong Kong. Building Services Engineering Research and Technology 2009; 30(4): 279–286.

Wong LT, Chan WY, Mui KW, Hui PS. An assessment of airborne fungi exposure risk level in air-conditioned office. Indoor and Built Environment 2009; 18(6): 553–561.

Wong LT, Chan WY, Mui KW, Lai ACK. An experimental and numerical study on deposition of bioaerosols in a scaled chamber. Aerosol Science and Technology 2010; 44: 117–128.

Wong LT, Mui KW, Chan WY, Hui PS. Residential lifetime exposure risk of formaldehyde in residential buildings in Hong Kong. Architectural Science Review 2008; 51(1): 66–70.

Wong LT, Mui KW, Hui PS, Chan WY. Bayesian assessments for acceptable airborne bacteria levels in air-conditioned spaces. Indoor and Built Environment 2008; 17(1): 80–86.

Wong LT, Mui KW, Chan WY. An energy impact assessment of ventilation for indoor airborne bacteria exposure risk in air-conditioned offices. Building and Environment 2008; 43(11): 1939–1944.

Wong LT, Mui KW, Hui PS, Chan WY, Law AKY. Thermal environmental interference with airborne bacteria and fungi levels in air-conditioned offices. Indoor and Built Environment 2008; 17(2): 122–127.

Wong LT, Mui KW, Hui PS, Chan WY. An implementation choice of assessment parameters for indoor air quality (IAQ) in air-conditioned offices. Facilities 2009; 27(5/6): 202–210.

International and local conference papers

Chan WY, Mui KW, Wong LT. A microbiological assessment for drinking water quality. The 1st Hong Kong – Taiwan Workshop on Water systems in High–rise Buildings, 25 Jun 2007, Hong Kong SAR, Proceedings, pp. 28–35.

Chan WY, Wong LT, Mui KW. Microbiological drinking water quality in a high-rise office building of Hong Kong. Water Supply and Drainage for Buildings CIB W062 2007–The 33rd International Symposium, 19–21 Sep 2007, Brno, Czech Republic, Proceedings, pp. 149–155.

Chan WY, Mui KW, Wong LT. A pilot study of microbiological water quality in an institutional building, Joint Symposium 2007 on Building Services Engineering for a World Class City, 13 Nov 2007, Hong Kong, pp. 123–128.

Chan WY, Mui KW, Wong LT. Fungal exposure risk in indoor environment. In Indoor Air 2008: Proceedings of the 11th International Conference on Indoor Air Quality and Climate. Eds.: Strøm-Tejsen P, Olesen BW, Wargocki P, Zukowska D, Toftum J, Indoor Air 2008, Copenhagen, Denmark, paper ID: 4. ISBN 9788778772701.

Chan WY, Mui KW, Wong LT. Indoor airborne fungi levels in air-conditioned offices of Hong Kong. The 9th International Symposium on Building and Urban Environmental Engineering (BUEE), 7–10 Jul 2008, Hong Kong SAR, Proceedings, pp. 147–151.

Chan WY, Mui KW, Wong LT. An investigation of microbiological potable water quality in high-rise residential buildings of Hong Kong. Water Supply and Drainage for Buildings CIB W062 2008 – The 34th International Symposium, 8–9 Sep 2008, Hong Kong SAR, Proceedings, pp. 189–195.

Chan WY, Wong LT, Mui KW. Exposure risk for indoor airborne fungi in residential buildings of Hong Kong. ROOMVENT 2009 Conference, 24–27 May 2009, Korea, Proceedings, pp. 651–656.

Chan WY, Wong LT, Mui KW. Airborne fungi in air-conditioned offices of Hong Kong: Changes in the past decade. 2009. First International Postgraduate Conference on Infrastructure and Environment, 5–6 Jun 2009, Hong Kong SAR, Proceedings, pp. 70–74.

Chan WY, Mui KW, Wong LT. Airborne bacteria assessment in an office washroom. 2009 Conference on Green Building – Towards Eco-city, 11–14 Oct 2009, Taipei, Taiwan.

Mui KW, Wong LT, Chan WY, Law LY. Energy benchmarks for ventilation systems in air-conditioned offices, The 6th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings, 28–31, Oct 2007, Sendai, Japan. Proceedings Volume 3, pp. 417–423.

Mui KW, Wong LT, Chan WY. Screening analysis of unsatisfactory airborne bacteria level in air-conditioned offices of Hong Kong, Joint Symposium 2008 on Shaping our Future Environment, 18 Nov 2008, Hong Kong, pp. 31–38.

Wong LT, Mui KW, Hui PS, Chan WY. Indoor air quality of air-conditioned offices of Hong Kong: An IAQ policy influence. In Indoor Air 2008: Proceedings of the 11th International Conference on Indoor Air Quality and Climate. Eds.: Strøm-Tejsen P, Olesen BW, Wargocki P, Zukowska D, Toftum J, Indoor Air 2008, Copenhagen, Denmark, paper ID: 5. ISBN 9788778772701.

Wong LT, Mui KW, Chan WY. Efficiency assessment of indoor environmental policy for air-conditioned offices. Healthy Buildings 2009, 13–17 Sep 2009, Syracuse, New York, USA, Proceedings, Paper 632.

Wong LT, Mui KW, Lai ACK, Chan WY, Longjie Z. Comparisons between experiments and CFD predictions for deposition performance with 1 μm aerosols, *Staphylococcus* and *Micrococcus* in a forced ventilated chamber. Indoor Air 2011, The 12th International Conference on Indoor Air Quality and Climate, 5-10 Jun, Austin, Texas, Paper A193_3.

Yu HC, Mui KW, Wong LT, Chan WY. Numerical study of 10μm bioaerosols (*Rhizopus*) deposition in a forced-ventilated chamber. Healthy buildings 2012, The 10th International Conference, 8-12 Jul, Brisbane, Queensland.

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This thesis is dedicated to my grandmother, Ms Wai TANG, in heaven. You are forever in our hearts.

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List of abbreviations

ABC	airborne bacteria count
AC	air change
ACGIH	American Congress of Governmental Industrial Hygienists
ACH	air exchange rates
ADL	Moser’s activities of daily living
AFC	airborne fungi count
AHU	air handling unit
AM	arithmetic means
ASD	arithmetic standard deviation
API	air pollution index
ASI	Andersen six-stage impactor
BSI	Burkard single-stage impactor
CAV	constant air volume
CCRQ	(Chinese) chronic respiratory questionnaire
CFD	computational fluid dynamics
CFU	colony forming unit
CI	confident interval
CN	concordant negative
CO	carbon monoxide
CO_2	carbon dioxide
COPD	chronic obstructive pulmonary disease
CP	concordance positive
CRQ	chronic respiratory questionnaire
DG18	dichloran glycel 18
DN	discordant negative
DP	discordant positive
DRW	discrete random walk model
EAP	express assessment protocol
F	force
FCU	fan coil unit
FC	fractional count
FEV	forced expiratory volume

FEV1	forced expiratory volume in one-second
FVC	forced vital capacity
GCI	grid convergence index
GM	geometric means
GSD	geometric standard deviations
HCHO	formaldehyde
HKEPD	Hong Kong Environmental Protection Department
HRQOL	health-related quality of life
IAQ	indoor air quality
I/O	indoor-to-outdoor
MEA	malt extract agar
MVAC	mechanical ventilation and air conditioning
NIOSH	National Institute for Occupational Safety and Health
NO_2	nitrogen dioxide
NRFP	no rain-front period
O_3	ozone
OSHA	Occupational Safety and Health Administration
L_r	likelihood ratio
N	number
P	probability
PCA	plate count agar
PCR	polymerase chain reaction
PEF	peak expiratory flow
PM	particulate matter
PRP	pulmonary rehabilitation programme
QOL	quality of life
RH	relative humidity
Rn	radon
RCS	reuter centrifugal sampler
RIFE	relative index of fungi exposure
RMS	root mean square
RNG	renormalization group
RSP	respirable suspended particulates
SaO_2	arterial oxygen saturation
SARS	severe acute respiratory syndrome

SAS	surface air sampler
SBS	sick building syndrome
RFU	fractional particle concentration
SP	airborne particulates
SRFP	seasonal rain-front period
T	temperature
TSA	tryptone soya agar
TSB	tryptone soya broth
TVOC	total volatile organic compounds
V	air velocity
V_R	ventilation rate
VAV	variable air volume
VOCs	volatile organic compounds
WHO	World Health Organization

List of symbols

C	constant
C_c	Cunningham slip correction
C_D	drag coefficient
β	relative abundance
β^*	relative abundance ratio
d	diameter
g	gravitational acceleration
G	distribution functions
η	air viscosity
ε	error
ς	uncertainty ratio
p	p value
ρ	particle density
$\hat{p}$	unsatisfactory rate
R	correction coefficient
Q	Yule’s Q statistic
r	radius of particle
t	time
$t_{distribution}$	t-distribution
$t_{satistic}$	t-statistic
v	terminal velocity
δ	unit increment
α	occurrence frequency
α^*	occurrence frequency ratio
Φ	concentration
ϖ	relative index of bacteria/fungi exposure
ω	deposition ratio
ϕ	CRQ sub-score
ψ	relative index of bacteria/fungi exposure
ϕ_i	environmental parameter i

ϕ^*	error limits
θ	odds ratio for the specified limit
φ	indoor-to-outdoor ratio
μ	mean
σ	standard deviation
τ	sphericity
$\overline{X}$	the root mean square particle displacement
F_s	safety factor
Re_p	Reynolds number
ν	kinematic viscosity
ξ_i	zero-mean, unit-variance-independent Gaussian random numbers
Δt	time step
k_B	Boltzmann constant

Subscripts

0,1,2,...	of conditions 0,1,2,...
a, b, c,...	of conditions a, b, c...
B	of airborne bacteria
F	of airborne fungi
in	of indoor
ou	of outdoor
i	of parameter i

Chapter 1 Introduction

Background of the research

Air quality problems in the indoor environment

Since the outbreak of severe acute respiratory syndrome (SARS) in 2003 (swine flu is yet another concern currently), research interests in the control of airborne microorganisms indoors have been mounting (Chao et al. 2008; Mui et. al. 2009a). Studies show that airborne transmission of infectious agents in an indoor space is related to ventilation airflow patterns (Wan and Chao 2007; Li et al. 2007). These agents are usually carried in by the building occupants or via ventilation air supply (Otten and Burge 1999).

As early as the 1960s, occupational health related problems related to indoor air quality (IAQ) were identified, with many organizations, such as the US Occupational Safety and Health Association (OSHA), the US National Institution of Safety and Health (NIOSH), the American Congress of Governmental Industrial of Hygienists (ACGIH), and the World Health Organization (WHO) conducting studies. And these sick symptoms suffered by occupants in non-industrial workplaces coined the term 'Sick Building Syndrome' (SBS) in 1970s.

Unfortunately, despite the continuous effort and availability of a great deal of information by researchers and professionals, indoor air quality (IAQ) remains a major source of problem in the problem buildings especially for the air-conditioned buildings. Apart from adverse health effects due to indoor bioaerosols exposure, the IAQ of the working environments also affects other aspects such as the staff productivity. Wyon (2004) reported that poor IAQ in buildings can decrease productivity in addition to causing visitors to express dissatisfaction. It would reduce the performance of office work by 6% to 9%. Increase in outdoor airflow rate, decrease in emissions and improvement on ventilation efficiency (e.g. displacement ventilation) would increase the productivity (Kosonen and Tan 2004).

Assessment and evaluation of the IAQ in Hong Kong

In Hong Kong, many commercial buildings equipped with Mechanical Ventilation and Air Conditioning (MVAC) systems are provided with indoor environmental controls for air temperature, humidity, ventilation rate and particulate content in

order to maintain good IAQ (Mui 2002). The development of the current IAQ policy could be traced back to the early 1990's. In 1993, the Hong Kong Government recognized the IAQ issue in the second review of the '1989 White Paper on Pollution' and a study on Indoor Air Pollution in Offices and Public Places was initiated in 1995 (HKEPD 1997), and the IAQ Management Group was set up to coordinate the development and implementation of IAQ policy in Hong Kong. As a consequence of the review, the Hong Kong Environmental Protection Department (HKEPD) launched an IAQ Certification Scheme for Offices and Public Places in 2003 to promote an acceptable IAQ in workplaces. The scheme audited most of the major indoor pollutants and emission sources recognized for indoor environment (HKEPD 2003). Two IAQ ranks, namely the Excellent IAQ level and the Good IAQ level, were used as a classification of the IAQ status by auditing 12 independent IAQ and related parameters, including 3 physical parameters for thermal comfort (temperature (T), relative humidity (RH) and air velocity (V)), 8 chemical parameters (carbon dioxide (CO_2), respirable suspended particulates (RSP), nitrogen dioxide (NO_2), ozone (O_3), formaldehyde (HCHO), total volatile organic compounds (TVOC), and radon (Rn)), and 1 bioaerosols parameter (airborne bacteria (ABC)) (HKEPD 2003).

In other countries, IAQ pollutants and bioaerosols monitoring have been conducted at different environments, such as commercial buildings, clinics and hospitals, schools, residential buildings, transportation systems, etc. (Blondeau et al. 2005; Lee and Jo 2006; Tsai et al. 2007). In Hong Kong, apart from the HKEPD study in 1995, a regional cross-sectional measurement of airborne bacteria and other 11 HKEPD listed indoor pollutant levels in 422 air-conditioned offices were conducted during 1998 and 2003 (Wong et al. 2006a). Apart from commercial offices, IAQ at car parks, libraries, recreation places, restaurants, shopping malls, sport centers, schools and residential buildings were also conducted (Lee et al. 1999; Lee and Chang 2000; Lee et al. 2002a).

Assessment and evaluation of the indoor bioaerosols in Hong Kong

Hong Kong is a subtropical region with warm and hot climate favourable for indoor microbial growth. In the current IAQ certification scheme, airborne bacteria are the only assessed parameter of bioaerosols (HKEPD, 2003). Airborne fungus is another important indoor bioaerosols. WHO (2009) conducted a comprehensive review on the scientific evidences obtained from the epidemiology, clinical and toxicological studies associated with indoor fungi and building dampness. Based on the qualitative

assessments of dampness related factors (visible dampness, mould, water damage or mould odour), sufficient epidemiology evidence of association between indoor fungi or dampness and respiratory symptoms like asthma development, asthma exacerbation, current asthma, respiratory infections (except otitis media), upper respiratory tract symptoms, cough, wheeze and dyspnoea are revealed. Sufficient clinical evidence also concluded the associations between indoor fungi and other dampness-associated microbiological agents and hypersensitivity pneumonitis, allergic alveolitis and mould infections in susceptible individuals, as well as humidifier fever and inhalation fever. Moreover, both atopic and nonatopic people are susceptible to adverse health effects due to indoor fungi and dampness exposure. There is no sufficient epidemiology evidences, however, to conclude causal relationships between indoor dampness, mould, and any specific human health effect, except the epidemiological findings suggesting dampness or mould could exacerbate asthma in children. Furthermore, the results obtained from the toxicological studies also provided insights into the multiple biological mechanisms supporting the associations between indoor fungi and dampness and the adverse health effects. Diverse inflammatory, cytotoxic and immunosuppressive responses were observed after exposure to indoor fungi found in damp buildings (included spores, metabolites, components) in vitro and vivo studies.

Studies of indoor airborne fungi in Hong Kong were scarce with only a few assessments conducted; and the quantity, identity, distribution and importance of indoor airborne fungi were also poorly described (HKEPD 1997; Law et al. 2001). The sampling sizes of previous studies are not large enough to represent the overall picture of the indoor bioaerosols of Hong Kong. Nevertheless, the exposure assessment of airborne fungi has not been mandatory in the IAQ certification. Although various guidelines on indoor airborne bacteria level have already been established by different organizations (ACGIH 1989, HKEPD 2003), an international threshold for indoor airborne fungi level regarding the assessment of an acceptable IAQ has yet to be defined. Furthermore, despite the availability of some useful information in some nearby countries like Taiwan, it is believed that there are geographical differences in the abundance and composition of indoor bioaerosols due to the different geographical distribution, vegetation, climate condition, sampling methods, etc (Gots et al. 2003).

Deposition of indoor bioaerosols

Deposition and concentration of indoor aerosol particle are known to influence the IAQ significantly. In an indoor environment, the movement of aerosol particles are affected by many factors, such as airflow pattern, particle properties, geometry configurations, ventilation rates, supply and exhaust diffuser locations, internal partitions, thermal buoyancy due to the heat generated by occupants and/ or equipment, etc. (Hinds 1999; Lai 2002).

Aerosol particles may be suspended in an occupied area so that they may be inhaled by the occupants and deposited on the nasal passage and induce adverse health effects. In addition, these particles may also be deposited on interior surfaces of the building, causing a soiling problem and further leading to damage. However, there are only limited experimental and modelling studies on deposition of aerosol particles (Lai 2002). Most of these experiments are conducted in chambers with rough or smooth surfaces, ventilated or non-ventilated (Lai 2002). It is reported that the deposition velocity of aerosol particles onto a smooth surface decreased when the particle size increased from 0.9 μm to 3 μm, and then increased to saturation when the size increased from 3 μm to 7 μm (Lai 2002; Lai and Nazaroff 2005). Studies only forced on assessing the mechanism of bioaerosols deposition in the airways. However, the deposition of bioaerosols in an indoor environment is still unknown. It is therefore important for us to be able to predict the bioaerosols deposition indoors and to find out how to minimize the total exposure.

Rationale of the study

Despite the increasing number of evidences regarding the bioaerosols

exposure-related health effects reported information on the exposure assessment of bioaerosols in Hong Kong is still scarce – for instance, their quantity, identity, distribution and importance are poorly described. Unlike the non-biological aerosols, the phenomenon of deposition of bioaerosols indoors is still unclear and not well investigated. Therefore, it is necessary to investigate the assessment, exposure, and possible controlling factors for the indoor bioaerosols. The results of this study would provide very important information with a number of practical implications –some effective methods to reduce indoor bioaerosols exposures, estimate and prevent the dispersion of pathogenic bioaerosols can be developed by understanding the bioaerosols depositions onto surface.

Aims and Objectives

This study aimed to assess, evaluate and investigate the possible controlling factors for indoor bioaerosols in order to provide important information for the exposure and control strategies.

By taking Hong Kong as an example, three principal objectives were:

a. Assessment of bioaerosols

   To assess the exposure of bioaerosols in Hong Kong by investigating the abundance and composition of bioaerosols in non air-conditioned apartments and air-conditioned commercial offices

b. Evaluation of exposure to bioaerosols

   To evaluate the importance of bioaerosols in aspect of indoor air quality and identify the possible controlling factor (e.g. ventilation) affecting the bioaerosols exposure in the indoor spaces

c. Control of bioaerosols

   To develop a method and experimental setup to investigate the deposition of some common bioaerosols in order to identify the possible factors controlling their occurrence in the indoor environment

Research scope

This study included three parts.

Part I Assessment of bioaerosols

A database of indoor bioaerosols was developed by reviewing the published data and collecting the air samples from naturally ventilated residential and air-conditioned commercial office buildings.

Part II Evaluation of exposure to bioaerosols

Based on the database results, the importance of assessing indoor bioaerosols for the IAQ investigated was discussed. The possible effects of IAQ policy on the indoor bioaerosols exposure were investigated. Several index and mathematical models were developed to investigate the indoor bioaerosols exposure. A relative index of exposure was proposed to evaluate the relative risk of exposure to bioaerosols in the indoor environment. Mathematical models were developed to predict pre-assessed unsatisfactory failure rate of air-conditioned public spaces over the local region. In addition, a case study was conducted on the effects of IAQ on a the patient with chronic obstructive pulmonary disease were studied.

Part III Control of bioaerosols

A method and experimental setup was designed and constructed to investigate the deposition of the commonly isolated bioaerosols. The effects of ventilation rate, mixing condition and size of bioaerosols were investigated.

Organization of thesis

This introductory chapter has examined the background and the motivation for this research. The aim of this study is to develop an indoor airborne bioaerosols model in order to provide important information for exposure and control strategies. The

objectives and scope of the research were also defined. Figure 1.1 shows a flowchart summarizing the organization of the thesis.

The major structures and findings of this study are presented in the following chapters.

Chapter 2 states the importance of investigating different aspects of the indoor bioaerosols. Previous studies are reviewed and the research gaps have also been identified in this part. Then, the theories, previous studies on monitoring the indoor bioaerosols, international guidelines or standards for indoor bioaerosols exposure, and the different alternatives in sampling strategies are reviewed thus research gaps have also been identified in this part.

Chapter 3 describes the development of an indoor bioaerosols database in typical residential buildings, presents evaluation results between different areas in typical apartments, proposes the use of the relative index for exposure of indoor bioaerosols and presents the influence of indoor bioaerosols and other IAQ parameters on patients with COPD.

Chapter 4 reveals the indoor bioaerosols as dominant contributors to unsatisfactory IAQ of typical air-conditioned office in Hong Kong. The development of an indoor bioaerosols database in typical commercial office buildings is described. The possible interaction between the indoor bioaerosols and other IAQ parameters are evaluated. Case studies are conducted on evaluating the possible effects of different ventilation conditions in an unoccupied office and occupied washrooms.

In order to investigate the possible parameters affecting the deposition of the commonly isolated indoor bioaerosols, Chapter 5 proposes a novel experiment on understanding the deposition of indoor bioaerosols in a ventilated chamber and delves into the influence of various airflow rates and mixing conditions on the deposition. This chapter also investigates the size effects of indoor airborne bacteria and fungi on the deposition. In addition, it describes the development of a computational fluid dynamics (CFD) model which simulates the particle movement under the same condition by using an Eulerian-Lagrangian approach and compares the results with the experimental one. Finally, conclusions and recommendations for future work are presented in Chapter 6.

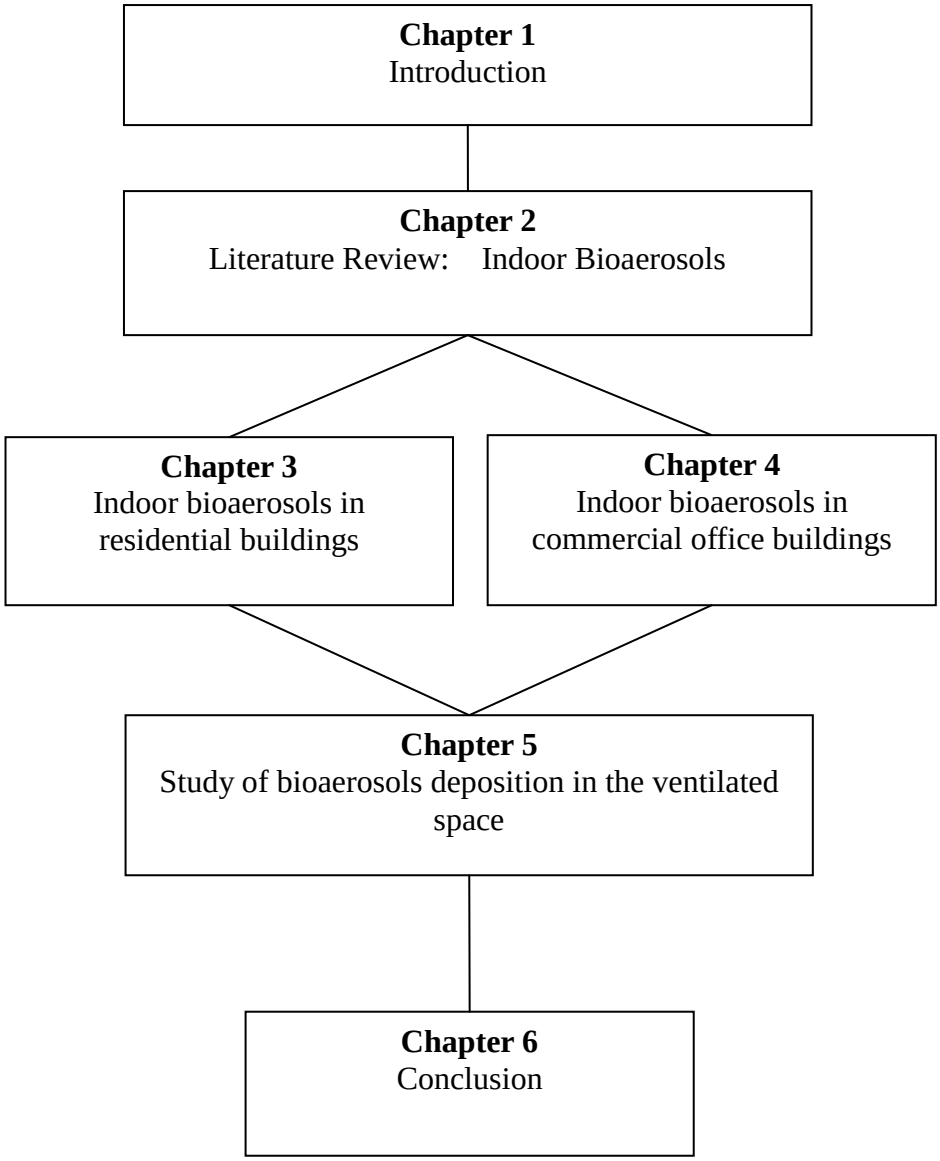


Figure 1.1: Organization of the thesis.

Chapter 2 Literature review – Bioaerosols and their dynamic in indoor environments

Introduction

Bioaerosols are defined as aerosols of biological origin, which can be artificially generated or naturally occurring (Lacey and Dutkiewicz 1994; Hinds 1999). It consists of pathogenic or non-pathogenic viable or dead fungi, bacteria, virus, protozoa and pollen (Cox and Wathes 1995). These particles are ubiquitous components of the atmospheric aerosol and cover a large size range from viruses to large pollens (Cox and Wathes 1995). Once present in the atmosphere, these particles can be transported by atmospheric turbulence and in some cases over long distances (Fuzzi et al. 1996). Two commonly assessed bioaerosols are focused in this study, which are airborne bacteria and fungi.

Bacteria are grouped on the basis of the prokaryotic cells. The group is multiphyletic and is categorized based on the structure of the cell wall and biochemical characteristics. *Aeromonas* spp., *Bacillus* spp., *Chryseobacterium* spp., *Micrococcus* spp. and *Staphylococcus* spp., are commonly isolated from the indoor air samples (Su et al. 2002; Seino et al. 2005; Kim and Kim 2007; Aydogdu et al. 2010). The common types of indoor bacterial contaminants, *Micrococcus spp.* and *Staphylococcus epidermidis*, were originated from human (Pastuszka et al. 2000).

Fungi are unique group of microorganisms which are omnipresent in our natural environment such as in air, soil, marine and fresh water, plant and decaying organic materials. Around 1.5 million fungal species are estimated to present in the world with only about 70000 are identified, while human are usually exposed to 200 fungal species in outdoor and indoor environments (Cox and Wathes 1995; Hinds 1999; Su et al. 2001; Su et al. 2002; Gots et al. 2003; Chan 2006). Three top most predominant airborne fungal genera are *Aspergillus, Cladosporium* and *Penicillium* in both indoor and outdoor environments (Salonen et al. 2000; Ren et al. 2001; Su et al. 2001; Lee and Jo 2006; Shelton et al. 2000). According to Lacey (1991), *Cladosporium* is the most abundant genus identified from outdoor sampling in most parts of the world. The concentration may exceed 200,000 spores m^{-3}, and may form over 90% of total spore load. *Alternaria*, *Penicillium* and *Aspergillus* are also dominant fungi in many

countries. Furthermore, other common airborne fungi are *Curvularia, Nigrospora, Aureobasidium, Stemphylium, Trichoderma, Fusarium, Acremonium,* and *Mucor*.

Exposure to airborne bacteria and fungi are known to pose health risk to human beings. Early experimental inhalation studies demonstrated effects including fever, cough, diffuse aches, nauseas, shortness of breath, and cute air flow obstruction (Pernis et al. 1961; Cavagna et al. 1969). Some bacteria species are also known to induce aerosol-transmitted infectious disease and are described as human pathogens, such as turberculosis, legionellosis, and anthrax as well as the systemic hyper-inflammatory that subsequently (leads to multiple organ failure, catastrophic circulatory collapse and lethality) due to exposure to endotoxin (lipopolysaccharide in the outdoor membrane) of gram-negative bacteria (Simpson and Martinez 2010). *C*hest tightness and bronchial catarrh were firstly described by Blackley after inhalation of fungal spores (*Penicillium* sp.) in the 1870s. Strong correlations between the occurrences of mould in indoor environment and reported respiratory symptoms (e.g. asthma, rhinitis, hypersensitivity pneumonitis, extrinsic allergic alveolitis, infections, toxicoses, etc.) were revealed by a number of large-scale epidemiological clinical and toxicological investigations (WHO 2009; Cabral 2010). WHO (2009) summarized the findings in the appendix I of ‘WHO guidelines for indoor air quality: dampness and mould.

Sampling methods of bioaerosols

Reliable sampling devices are very important for bioaerosols monitoring, as it can provide more accurate information on conducting epidemiological investigations, monitoring biohazardous procedures, understanding the transmission of bioaerosols, investigating the control strategies as well as applying as a quality control measure. Therefore, the efficiency of the sampling method should be higher in order to reflect the real picture of bioaerosols in the environments.

In general, the sampling methods can be divided into culturable and non−culturable. Culturable air sampling allows the identification of viable bioaerosols to species level, such as differentiation of *Aspergillus* and *Penicillium*, determination of viability and thermotolerance. Although cultural sampling method is commonly used, it is limited by the short duration of sampling time and their dependence on the variable success of the culture step. For example, there is no ideal sampling medium nor incubation conditions (e.g. temperature) to support all types of bioaerosols; however, both non-culturable and non-viable bioaerosols, and the fragments present

in environment are also found to be associated with allergic reaction, or as a source of endotoxins from bacteria causing health problems (Robbins et al. 2000; Gorny et al. 2002; Peccia et al. 2006; WHO 2009).

Moreover, it is reported that only 1 to 25% of fungal spores in air are viable and non-viable spores are also capable for inducing allergies or irritation (Eduard 2009). Therefore, more quantitative results can be obtained by non–culturable air sampling method as both viable and non-viable bioaerosols species can be captured.

Selection of suitable sampling medium (e.g. agar or broth) is very important in culturable air sampling. Sampling media that favor the growth of most bioaerosols and yield the highest number of colonies from the air are considered the ideal choice in most circumstances. Different media may be required under different environmental conditions and selective medium can be used for isolating species with species interests (Wu et al. 2000). Traditionally, malt extract agar (MEA) and dichloran glycel 18 (DG 18) agar have been used extensively as a broad spectrum medium for fungal sampling and enumeration while plate count agar (PCA) have been used for bacteria sampling and enumeration (ACGIH 1989).

A wide range of samplers have been used for monitor different types of bioaerosols, which are categorized based on the operation principles (Table 2.1). The most common air sampling method is by inertial impaction. Collecting bioaerosols by impaction principle relies on the tendency of a particle to separate from the air and settle onto a solid (i.e. agar) or semi-solid surface (i.e. containing water and nutrients that foster the growth of collected viable particles) (Hinds 1999). Collection of bioaerosols by using sieve sampler, slit samplers and cascade impactor are based on this principle and bioaerosols are collected onto the agar plate. Mehta et al. (1996) revealed that Andersen two-stage and Burkard air samplers retrieved equivalent airborne fungi count (AFC).

Impaction of bioaerosols into a liquid medium is also frequently used. The liquid medium for collection includes water, buffered saline solution, or nutrient broth. The most commonly used impringers are all-glass impingers, such as AGI-4 and AGI-30. By using liquid as a sampling medium, the desiccation of collected bioaerosols can be prevented thus increased the viability. However, the shear forces in the jet and in the turbulent liquid would induce a loss of viability (Hinds 1999).

Impaction of bioaerosols onto agar-coated plastic strip around the rim of the wheel by using centrifuging force is the working principle of centrifugal sampler, such as Reuter Centrifugal Sampler (RCS). It facilitates the collection of airborne

microorganisms from the sample volume ranging from 10 to 1000L. Laflamme and Miller (1992) demonstrated that RCS sampler collected fungal spores of different sizes and shapes with approximately equal efficiency over the useful range of the device. However, Mehta et al. (1996) reported that RCS recovered similar AFC as surface air sampler (SAS) Super-90, but was significantly lower when compared with Andersen two-stage and Burkard air sampler.

Impaction of bioaerosols onto the filter (e.g. membrane filter, fibrous filter, etc.) is also commonly used due to its simplicity and cost effectiveness. The collected filters can be examined directly under microscope, or by putting the filter onto the culturing medium (particles face up) and then incubated at suitable conditions.

Table 2.1: Common air sampling methods.

Sampler type	Principle of operation	Examples	Sampling rate ($L\ min^{-1}$)	Recommended sampling time (min)	Reference
Centrifugal sampler	Impaction of bioaerosols onto a plastic agar strip	Reuter centrifugal air sampler	50 or 100	5-10	Wong 1997, Chan et al. 2003; Haegreaves et al. 2003; Chow et al. 2005; Leung et al. 2005
Filtration	Impaction of bioaerosols onto the filter by air current	Fibrous filter, membrane filter, flat filter, cassette filter	1–2	15–60 or 480	Wu et al. 2010
Gravitational sampler	Passive collection simply by the gravitational force	Open Pertric dish method	NA	15–30	Sen and Asan 2009
Impactor	Impaction of bioaerosols onto the agar surface or adhesive surface by applying air current	Spore Traps, Whirling Arm, Rotorod sampler, Silt–to–Agar sampler	10	10	Calderon et al. 2002
Impinger	Impaction of bioaerosols into a liquid medium by applying air current	AGI - 30 impinge, Porton impinger, Midget impinge, glass midget impringer	12.5	30	Springorum et al. 2011
Sieve sampler	Impaction of bioaerosols onto agar after passing through perforated plates or sieve with holes of defined size	Single-stage impactor (Andersen), Surface air sampler, MAS-100, Burkard	10, 20, 28	1–9	Garrett et al. 1997 ; Wong 1997; Kalogerakis et al. 2005 ; Lee and Jo 2006
		Single-stage impactor (Rodac plate)	90 or 185	0.5 or 0.3	
		Two-stage impactor (Andersen)	28	1–5	

Recently, the application of molecular technique in microbiology has dramatically expanded (Peccia et al. 2006; West et al. 2008). It is believed that the sensitivity of molecular techniques and the unambiguous bioaerosol detection and identification that can be made independent of culturing, may overcome the limitations of the culturing methods (Rinsoz et al. 2008; Lee et al. 2010; Kim et al. 2011; Li 2011). The detection and identification of microorganisms can be achieved by comparing the DNA or RNA sequence (Pace 1997). By applying the polymerase chain reaction (PCR), a sequence of DNA (usually a specific gene or portion of a gene) is amplified to generate thousands to millions of copies. For subsequent PCR analysis, bioaerosols can be collected onto nonagar surfaces such as tape, foam, or glass slides, liquid medium, as well as membrane and gelatin filter (Peccia et al. 2006). Therefore, the samples can be identified by comparing the existing database, or processed for population fingerprinting, microarray analysis, or clone library analysis (Dionisi et al. 2003; Zeng et al. 2004; Peccia et al. 2006; West et al. 2008; Li 2011).

Many different PCR-based diagnostic techniques have been developed and some techniques have been adopted for studying bioaerosols as shown in Table 2.2, such as end-point PCR, real-time quantitative PCR, reverse transcriptase PCR, terminal restriction fragment length polymorphism, denaturing gradient gel electrophoresis, microarray, sequencing and pyrosequencing (Calderon et al. 2002; Zeng et al. 2004; Metzker 2005; Rinsoz et al. 2008; West et al. 2008; Li et al. 2009; Lee et al. 2010; Li 2011; Langer 2012). Other techniques, included enzyme-linked immunosorbent assay, fluorescent in situ hybridization, flow cytometry with fluorochrome, solid phase cytometry are also proven to be a rapid, useful, and accepted method for evaluation of mixed population including both culturable and non-culturable bioaerosols (Deloge-Abarkan et al. 2007; Rinsoz et al. 2008; Vanhee et al. 2008; Filion et al. 2009; Lee et al. 2010; Wu et al. 2010; Li et al. 2011; Kim et al. 2011).

Some studies have also been conducted to compare the efficiency of the culturing and molecular techniques (Rinsoz et al. 2008; Kim et al. 2011). It was revealed that the abundance and diversity of bioaerosols estimated by the molecular techniques were higher than the culturing methods. In general, the bioaerosols count can be estimated by assuming the average rRNA gene copy number of 4 per bacteria and 200 per fungal or oomycete genome (van Doorn et al. 2007; Lee et al. 2010; Li 2011). The average rRNA gene copy number may not always be accurate, however, as the number per bacterial genome can vary from 1 to 15 (Klappenbach et al. 2001).

In this study, pure cultures of bioaerosols are needed for further analysis for the possible effects (e.g. ventilation) on their dynamic in a chamber experiment. Therefore, the culturing method is applied. In addition, the results obtained from the culturing method can be more easily compared by others and most importantly for the general public who may have limited resources for conducting molecular analysis.

Table 2.2: Selected DNA-based techniques for identification and/or counting of bioaerosols (modified from West et al. 2008).

Diagnostic method	Description	Advantages	Examples
End-point PCR	Enzymic amplification of specific gene targets	Qualitative data on specific gene targets (e.g. universal, species, gene or mutation specific)	Calderon et al. 2002
Quantitative PCR (qPCR)	Enzymic amplification of specific gene targets linked with fluorescent dye or probe	Quantitative data on specific target. Multiplex PCR (multiple targets assessed in one reaction)	Rinsoz et al. 2008
Reverse transcriptase (RT) -PCR	Enzymic conversion of RNA to cDNA for PCR assays	Investigation of gene activity	Li et al. 2009
Terminal restriction fragment length polymorphism (T-RFLP)	Separation of polymorphic terminal fragments after restriction digestion, with an automated sequencer	Comparative community analysis	Lee et al. 2010
Denaturing gradient gel electrophoresis (DGGE)	Separation of PCR products on a denaturing gradient gel	Study changes in population structure or in gene coding	Li 2011
Microarray	Collection of unique DNA probes arranged on a solid substrate (e.g. glass). Each probe has a DNA sequence complementary to the sequence of interest	Sensitive and specific, can process many samples	Langer 2012
Sequencing	Visual representation of specific gene sequences	Population analysis, identification of organisms and investigation of specific genes	Zeng et al. 2004
Pyrosequencing	Sequencing of small specified gene sequences for analysis	SNP gene-mutation analysis, allele frequency, species identification	Metzker 2005

Many different PCR-based diagnostic techniques have been developed since 1980s and some techniques listed this table were those have been used for studying bioaerosols, so it is not intended to be a comprehensive review nor to comment on the advantages and disadvantages of each method West et al. 2008).

Guidelines or standards for indoor bioaerosols level

Table 2.3 shows the recommended assessment pollutants and their corresponding concentration limits defined in standards or guidelines. Overseas regulatory actions related to IAQ are limited, especially in contrast with regulation of outdoor air quality and industrial workplace. Though some guidance has been provided by authorities or organizations, there is a need for a more structured approach for evaluation and control of IAQ. A severe limitation in many countries is the absence of a single governing authority with responsibility for IAQ. The standard and guidelines of other IAQ parameters have been reviewed in other literatures.

Exposure to indoor bioaerosols would raise a number of adverse health concerns, such as acute toxic effects, allergy, cancer, contagious infectious diseases, respiratory symptoms and diseases and sick-building syndromes (Burge 1990; Gots et al. 2003). However, there is still no universal exposure baseline or threshold of indoor airborne fungi exposure for (i) total culturable or countable airborne fungi; (ii) specific culturable or countable airborne fungi (e.g. *Aspergillus fumigatus*); and (iii) assayable fungal metabolites (e.g. mycotoxin, microbial volatile organic compounds) (HKEPD 2003; Health Canada 2004; ACGIH 2007; WHO 2009).

Although guidelines for the ventilation of office buildings are well developed, such as ASHRAE Standard 62.1-2010, it is designed to provide the standards on airflow rates and amount of fresh air supplied but these cannot guarantee that the level of indoor airborne fungi which is acceptable (ASHRAE 2010).

The calculations of indoor-to-outdoor (I/O) ratio of fungi exposure level was a common indicator of potential indoor fungal sources and it would be used to attribute an indoor environment (Gots et al. 2003). Health Canada (1995) suggested an I/O ratio of less than 1 would be considered as ‘acceptable’, but suggestions of the ‘acceptable’ threshold of a ratio consistently more than 2, if the fungal level exceeding 1000 spores m^{-3}, were noted in some cases (Burge 1990).

The major reason for the difficulties in establishing international standards or guidelines is to determine what levels of indoor airborne fungi may pose a threat to human health (Gots et al. 2003). Information on dose-response relationship between indoor airborne fungi and human health is insufficient. And different individuals may have different susceptibility of exposure to airborne fungi (Gots et al. 2003; ACGIH 2007). In addition, since the samples are mixed culture (included both toxic and

non-toxic species), it is difficult to describe only the sample total count.

Furthermore, the airborne fungi level in indoor environment fluctuates greatly depending on time, place, and conditions in the building, as well as on different airborne fungal species. If the indoor airborne fungi levels is higher than outdoors and if the species differ from that detected outdoors, this may indicate mold growth in the building (Gots et al. 2003).

Although no standard numerical guideline exists for assessing whether bacterial or fungal contamination exists in an area, various governmental and private organizations have proposed guidelines on the quantitative limits for airborne bacterial and fungal levels. For example, the measurement can be regarded as one of several ways to detect dampness, as dampness in buildings is generally accepted to be related to human health effects especially for the respiratory system (Bornehag et al. 2001; Eduard 2009).

Most of these guidelines usually include information about fungi, fungi source, building-related illnesses, preventive methods, evaluation methods, control and remediation methods, such as the guideline published by OSHA (2003) on ‘A brief guide to mold in the workplace’, ‘Mold remediation in schools and commercial building’ by USEPA (2001), and most recently, ‘WHO guidelines for indoor air quality: dampness and mould’ (WHO, 2009).

However, the numerical threshold limit value has not been suggested in these guidelines. The recommended exposure limits varied in different guidelines which ranged from 500 colony forming unit (CFU) m^{-3} to 2000 CFU m^{-3} (CEC 1993; Health Canada 1993; ENV 1996; The Brazilian Ministry of Health 1998). These limits are considered as acceptable or unacceptable, where unacceptable indoor airborne fungal level usually requires further examination.

In some of the guidelines, the recommended exposure limit to indoor airborne fungi is defined into different levels (CEC 1993; Health Canada 1995). Among these guidelines, indoor airborne fungal level (i) less than 100 CFU m^{-3} represents a “low” level (CEC 1993); (ii) less than 750 represents an “acceptable” level (CEC 1993; Health Canada 1993; ENV 1996; The Brazilian Ministry of Health 1998) and (iii) larger than 750 CFU m^{-3} represents a “high” level (CEC 1993; Health Canada 1993; ENV 1996; The Brazilian Ministry of Health 1998).

Table 2.3: Available guidelines on indoor bioaerosols in selected countries/cities.

Country / city	Government agency/ Professional organization (Document, Year)	Recommended exposure limit (CFU m^{-3}) [a]		Reference
		Bacteria	Fungi	
Australia	State of knowledge report: Air toxics and indoor air quality in Australia (2001)	–	–	Environment Australia 2001
	AS/NZS 3666.1:2002 Air-handling and water systems of buildings - Microbial control (2002)	–	–	Standards Australia/ Standards New Zealand 2002
	Indoor air quality – A report on health impacts and management options (2000)	Good 0-35 Fair 36-180 Poor>180 (count m^{-2} min^{-1}) (New Zealand Dairy Industry)		Queensland Department of Public Works 2000
Brazil	Act 3523 Indoor air quality(1998)		750	The Brazilian Ministry of Health 1998
Canada	Indoor air quality in office buildings: A technical guide (1993)	–	> 50, need investigations (if one species other than *Alternaria* or *Cladosporium*) ≤ 150, acceptable (if mixed species reflected the outdoor air) ≤ 500, acceptable in the summer (if primarily *Cladosporium* or other tree and leaf fungi)	Health Canada 1993
	Fungal contamination in public buildings: Health effects and investigation methods (2004)	–	–	Health Canada 2004
China	Chinese indoor air quality guidelines GB/T 18883-2002 (2002)	≤2500		Standardization Administration of the PRC 2003
Europe	Indoor air quality and its impact on man Report no. 12: Biological particles in indoor environment (1993)	–	<25, very low <100, low <500, intermediate <2000, high >2000, very high	CEC 1993
Finland	Classification of Indoor Climate 2000; Target Values, Design Guidance and Product Requirements (2001)	–	–	FiSIAQ 2001
Hong Kong	Indoor air quality certification scheme (2003)	≤ 500 (excellent class) ≤ 1000 (good class)	–	HKEPD 2003
Korea	The Act of Indoor Air Quality Management (2004)	≤ 800	–	Ministry of Environment Republic of Korea 2004

Table 2.3: Available guidelines on indoor bioaerosols in selected countries/cities (continued)

Country / city	Government agency/ Professional organization (Document, Year)	Recommended exposure limit (CFU m^{-3}) [a]		Reference
		Bacteria	Fungi	
Singapore	Guidelines for good indoor air quality in office premises 1st ed. (1996)	≤500	≤ 500	EMV 1996
United States	Building air quality: A guide for building owners and facility managers - Appendix C: moisture, mold and mildew (1991)	–	–	USEPA 1991
	Mold remediation in schools and commercial buildings (2001)	–	–	USEPA 2001
	Guidelines on assessment and remediation of fungi in indoor environments (2001)	–	–	The New York City Department of Health and Mental Hygiene 2000
	A brief guide to mold in the workplace (2003)	–	–	OSHA 2003
	Preventing mold-related problems in the indoor workplace (2006)	–	–	OSHA 2006
WHO	WHO guidelines for indoor air quality: dampness and mould	–	–	WHO 2009

[a] '–' represents that no limit is suggested.

Exposure to indoor bioaerosols in different countries/cities

Natural ventilated residential building

The investigation of indoor bioaerosols in residential buildings is more extensive when compared with those in commercial buildings. Table 2.4 summarized some selected studies conducted in residential buildings in different countries. It is revealed that the average indoor airborne bacteria count (ABC) ranged from 40 CFU m^{-3} to 1021 CFU m^{-3} (Jaffal et al. 1997; Pastuzka et al. 2000; Kalogerakis et al. 2005; Lee and Jo 2006), while average indoor airborne fungi count (AFC) ranged from 71 CFU m^{-3} to 20313 CFU m^{-3} (Garrett et al. 1997; Ren et al. 2001; Su et al. 2001; Haegreaves et al. 2003; Basilico et al. 2005). Variations of indoor bioaerosols count among these studies can be explained by different geographic locations, seasonal effects, sampling locations, problems of the building (e.g. presence of visible mold or water damaged) as well as ventilation conditions.

Wu et al. (2000) evaluated the variation of seasonal fungal concentrations in homes located in suburban (N=17) and urban (N=59) areas of southern Taiwan in order to estimate the related health risk. It is reported that the total AFC recorded in homes located in suburban areas were similar to those recorded in urban areas in winter, while it was two times higher than that in summer, especially for the counts of non-sporing fungi and *Cladosporium*. It is suggested that such phenomenon is due to the difference in characteristics between the homes located in urban and suburban areas. For example, most of the homes located in the urban areas are apartment-complex type while those located in suburban areas are single houses with windows at each side of the buildings which affect the air exchange rates (ACH). It is suggested that the effect of the outdoor AFC on indoor AFC is less when compared with those located in suburban areas as lower ACH is usually expected in urban areas. In addition, since the outdoor air temperature in winter of Taiwan is not too cold for windows to be kept shut for the entire season, the indoor fungal profile is greatly dependent on the outdoor. Therefore, the indoor AFC recorded in both urban and suburban homes in winter are quite similar. However, more frequent air exchange presents in suburban homes in summer, so the indoor fungal profile reflects more of the outdoors when compared with those in urban homes. Therefore, more *Cladosporium* and non-sporulating fungi are recorded in suburban homes in

summer. The findings agree with the study conducted in Argentina which also investigated the variations of indoor AFC between urban (N=24) and suburban (N=25) homes (Bascilico et al. 2007). It is reported that the airborne fungal counts in suburban houses are higher than those in urban ones, with significant differences observed for genera *Cladosporium*, *Curvularia*, *Aspergillus*, *Ulocladium* and yeasts ($p<0.05$).

Many researchers investigated the seasonal effects on the indoor bioaerosols exposure. T and RH are two major factors influencing the seasonal effects. Most of the studies recorded a higher AFC in warmer months (like summer) when compared with cooler months (like winter) (Garrett et al. 1997; Pastuszka et al. 2000; Horner et al. 2004; Lee and Jo 2006; Sen and Asan 2009). It may probably due to the different regional locations, sampling methods as well as locations of sampling. For example, the effects of seasonal (winter vs summer, seasonal rain-front period (SRFP) vs no rain-front period (NRFP)) on the indoor bioaerosols exposure were investigated in 40 residential buildings in Korea (Lee and Jo 2006). It is revealed that the indoor bioaerosols concentrations were higher in summer than in winter; and higher in SRFP than in NRFP. Gravitational petri plate method was used for investigating the seasonal variations of the indoor air fungal exposure in 6 residences of Turkey (Sen and Asan 2009). Samples were collected from the living room, bedroom and kitchen every month for a year. Higher AFC were recorded in warmer seasons than cooler seasons. Significant seasonal difference was also observed in 5050 single-family house in USA and the AFC were higher in summer in all sampling locations than winter ($p=0.0496$) (Horner et al. 2004). Bascilico et al. (2007) investigated the seasonal variations of AFC of 49 non-problem houses in Argentina. The average of the indoor AFC was 977 CFU m^{-3}, *Cladosporium* was the most dominant genus with no significant difference among summer and winter. However, significant seasonal effects were observed for genera *Fusarium*, *Curvularia*, *Alternaria*, *Nigrospora*, *Chrysosporium* and *Mucor* ($p<0.05$), the average counts of these genera recorded in summer were higher than that in winter. Pastuszka et al. (2000) also revealed that higher airborne fungi counts were recorded in summer when compared with winter, while there is no seasonal effect on the airborne bacteria counts observed in 43 and 27 apartments with and without mold growth respectively. With similar climate condition as Hong Kong, Su et al. (2001) conducted a year-long survey to examine the seasonal variations of AFC in apartments with asthmatic and non-asthmatic

children in a subtropical region – Taiwan. Duplicate air samples were collected every month in the children's bedroom and outside the entrance of the homes. It is revealed that the average airborne fungal counts recorded in winter for both type of apartments were significantly higher than those in other seasons with the lowest in summer ($p<0.0001$). *Cladosporium*, *Aspergillus*, *Penicillium* and *Alternaria* are the most predominant indoor genera for the total fungal composition. For all samples, seasonal variations of *Cladosporium* and *Alternaria* were observed and *Cladosporium* was the highest in winter and lowest in summer, while *Alternaria* was the highest in spring and lowest in summer. Similar seasonal variations but inconsistent compositions were observed for both types of apartments. Although the seasonal pattern is different, it can be concluded that T and RH have a great influence on the indoor bioaerosols exposure.

Effects of sampling locations on the bioaerosols count inside an apartment are also one of the research focuses. The bioaerosols exposure in bathroom, bedroom, kitchen and living room are always compared. For examples, Lee and Jo (2006) investigated the differences of bioaerosols exposure inside 40 apartments in different areas, including living room, adult and child bedrooms, bathroom, and kitchen room. In summer, it is reported that both ABC and AFC are highest in bathroom, followed by kitchen, bedroom and living room. Haegreaves et al. (2003) conducted a survey of indoor bioaerosols in 14 naturally ventilated houses during late autumn and winter in Australia. Under normal ventilation, it is observed that the airborne fungi count recorded in the living room was the highest followed by bedroom, which were 810 CFU m^{-3} and 692 CFU m^{-3} respectively. And the count recorded in the bathroom and living room with minimum ventilation were lower, they were 499 CFU m^{-3} and 453 CFU m^{-3} respectively. Moreover, it is reported that the AFC is the highest in living room, and followed by kitchen and bedroom in 6 residences in Turkey (Sen and Asan 2009). Exposure to airborne bacteria in a typical 1 bedroom apartment located on the 3rd floor in Greece was investigated by Kalogerakis et al. (2005). Indoor air samples were collected from living room and kitchen using the MAS-100 air sampler. It is reported that the gram-negative airborne bacteria recorded in kitchen was significantly higher when compared with living room and outdoor environments. It may probably because of the poor hygiene condition there, such as presence of old food stuff and unwashed dishes. Based on the above studies, it is indicated that the variations of indoor bioaerosols at different locations indoors may not be consistent

and may be due to other environmental and physical factors. Ren et al. (2001) conducted a large scale study on indoor airborne fungi exposure in 1000 homes in Northeast USA by SAS. It is reported that there was no significant difference in the counts collected in infant bedroom and major living areas. It is observed that the counts were significantly related to the season, T, RH and the presence of cats. In addition, Ren et al. (2001) reported that some home characteristics like presence of pets, mold and mildew formation, year of construction, and use of humidifier may be related to count of each specific fungal genus although it is not consistently related to the number of each genus. It is also reported that the airborne fungi count was not significantly correlated with the $PM_{2.5}$, but a weak and significant correlations were observed between the fungi count and the supermicrometre particle concentrations (i.e. 0.54–19.81 μm) (Hargreaves et al. 2003). On the other hand, Lee and Jo (2006) revealed that there was no difference in bioaerosols exposure among low-floor (1^{st} or 2^{nd} floor) and higher floor (between 10^{th} and 15^{th} floor) in 40 residential buildings.

Exposure to indoor bioaerosols in residential buildings with problems was also well investigated. Presence of visible mold growth and water damage are two major problems encountered in many countries. Haas et al. (2007) also investigated the effects of visible mold on the indoor airborne fungi exposure in 66 apartments in Austria. 29 and 37 apartments without and with visible mold growth respectively were chosen for investigation. For the apartments with visible mold growth, the counts recorded in spring were significantly higher (2 times higher) than those in other seasons, while there was no difference among summer, winter and fall. Moreover, it was revealed that the counts in apartments with visible mold growth were significantly higher than those apartments without visible mold growth. It was observed that the extent of visible mold growth was correlated with both fungi counts and the frequency of occurrence of *Penicillium* and *Aspergillus*. The airborne bacteria counts were similar in both environments, although Nevalainen et al. (1991) reported an elevated level of airborne bacteria in moldy environment. Higher counts of *Penicillium* were reported in moldy environment (relative abundance = 90%) when compared with the controls (3% to 49%). It is reported that *Micrococcus* was the most dominant in all environments followed by *Staphylococcus*, which agrees with the general statement that *Micrococcus* is dominant in the apartments and *Staphylococcus epidermidis* associated with shed skin is the most prominent (Nevalainen 1989, CEC 1993). Pastuazka et al. (2000) suggested that high bacteria

count in moldy environment may only occur in weakly moldy apartments and further investigations are needed. In Pastuazka et al. (2000) study, significantly higher AFC was reported for the moldy building in Poland in both summer and winter, which was at least 3.7 times higher when compared with those controls. However, there was no significant difference in the ABC among moldy and non-moldy environments.

Furthermore, the proper effects of different housing qualities on airborne fungi exposure were investigated in United Arab Emirates by Jaffal et al. (1997). The housing qualities were classified into 3 types: Type 1 (high quality housing), which were spacious, well designed newly built buildings located in the upmarket area; Type 2 (average quality housing), which were the buildings traditionally designed and built by the government for the medium income nationals; and Type 3 (poor quality housing), which were mainly single rooms located in slums. Air samples were collected in the living room and bedroom. The highest airborne bacteria and fungi count were recorded in Type 3 apartments, which were significantly higher than other types ($p<0.045$). It is suggested that higher hygiene condition, lower occupancy density and better ventilation system would lower the indoor bioaerosols level. In all types of apartment, the total indoor bioaerosols counts isolated in living room were higher than that in bedroom. It was reported that more human-related bacteria genera (i.e. *Staphylococci*, *Micrococcus* and gram-negative bacilli) were detected in bedroom rather than in living room in Type 1 apartments.

The ventilation efficiency on the bioaerosols was also investigated in the residential buildings in eastern and southern Taiwan by Su et al. (2006). The ventilation efficiency is expressed by the ventilation rate (air change rate), which is defined as the amount of air circulated per unit time. Su et al. (2006) evaluated the ABC and AFC in 44 natural ventilated apartments to determine the air change per hour (ACH) rate by using the tracer gas (CO_2) concentration decay. It was reported that the ACH rate ranged from 0.19 to 5.4/h with an average of 2.52 h^{-1}. The I/O ratio of bioaerosols was analyzed to evaluate the possible effects due to varying of ACH rate. However, a significantly higher I/O ratios of *A. niger* and *Penicillium* were revealed in the apartments with an ACH rate <2.13 h^{-1} compared to those with higher rate ($p<0.05$). It was observed that the I/O ratios of *Cladosporium* and *Alternaria* also increased (but not significantly) with the increased ACH rate; however, no significant association was observed between the indoor ABC and the ACH rate. It

may be due to airborne bacteria originated from human easily accumulated in the occupied apartments. It was suggested that under improper filtration, the indoor bioaerosols with outdoor origin in natural ventilated apartments may increase with increased ACH rate.

The effects of ventilation rates on human health were also summarized in a review of studies conducted in residential apartments located in Scandinavian countries (Sundell et al. 2011). Despite the lack of direct measurements of indoor bioaerosols levels in these studies, the risk effects being investigated such as asthma, bronchial obstruction, eczema, rhinitis and wheeze are known to be associated with the indoor bioaerosols exposure (WHO 2009). It was suggested that there are significant association between the three allergic conditions (asthma, rhinitis, and eczema) in lower ventilation rates (with average of 0.35 h^{-1}) in a study of 390 houses in Sweden (Bornehag et al. 2005). The risk was associated with the duration or severity of the symptoms rather than with the induction of disease (Bornehag et al. 2005). Another study investigated the first 2 years of life of 4089 children observed that there is significant associated between of a low ventilation rate (<0.5 h^{-1}) and wheeze, however, there was no association between measured ventilation rate and wheeze (Emenius et al. 2004). In addition, Øie et al. (1999) investigated the ventilation conditions in Oslo homes of 172 infants having bronchial obstruction and with 172 controls in a birth cohort of 3754 children. It was observed that there were no direct association between a low ventilation rate (<0.5 h^{-1}) and bronchial obstruction; however, the bronchial obstruction were strongly associated with the enhanced level of indoor air pollutants in homes with low ventilation rate. Although the results obtained from the above studies were not fully consistent, it was suggested that with higher ventilation rate (>0.5 h^{-1}) associated with lower likelihood of symptoms of asthma and allergy from indoor pollutants (Sundell et al. 2011).

Table 2.4: Selected studies on indoor bioaerosols in residential buildings in different countries/cities.

Country / city	N	Air sampler	Location [a]	Indoor bioaerosols Average count (CFU m^{-3}) [b] Bacteria	Fungi	Top three common fungi genera	Reference
Argentina	49	RCS	LM, BE	–	977	*Alternaria, Fusarium, Curvularia* *Penicillium*, yeast	Basilico et al. 2005
Australia	80	Andersen single-stage	LM, BE, KI	–	479 (Sp), 1583 (S)	*Cladosporium*, *Penicillium*, yeast (annual) More *Aspergillus* and *Acremonium* (W)	Garrett et al. 1997
	14	RCS	LR BE BA	–	810 (normal vent.), 453 (min vent.) 692 (normal vent.) 499 (min vent.)	*Cladosporium, Curvularia, Alternaria,*	Haegreaves et al. 2003
Austria	29	Burkard	w/o visible mold growth	–	140(Sp), 420(S), 150(F), 260(W)	*Cladosporium, Penicillium*	Garrett et al. 1997
	37		w visible mold growth		1500 (average), 3000(Sp)	*Penicillium, Aspergillus*	
Greece	1	MAS-100	LR (w people) LR (w/o people) KI	71 40 270	–	–	Kalogerakis et al. 2005
Korea	40	Andersen single-stage	Low-floor High-floor LR Adult BE Child BE BA KI	331 (S), 280 (W) 319 (S), 288 (W) 326 (S), 284(W) 358 (S), 383(W) 341(S), 377(W) 449(S), 465(W) 423(S), 430(W)	456(S), 93 (W) 476(S), 112(W) 503(S), 155(W) 500(S), 176(W) 550(S), 150(W) 450(S), 179(W) 663(S), 576(W)	*Cladosporium, Penicillium, Aspergillus*	Lee and Jo 2006

[a] BE, BA, LR and KI – represented bedroom, bathroom, living room and kitchen respectively.
[b] Sp, S, A and W′ – represented spring, summer, autumn and winter respectively.

Table 2.4: Selected studies on indoor bioaerosols in residential buildings in different countries/cities (continued).

Country / city	N	Air sampler	Location [a]	Indoor bioaerosols			Reference
				Average count (CFU m^{-3}) [b]		Top three common fungi genera	
				Bacteria	Fungi		
Poland	27	Andersen 6-stage	LM (w/o visible mold growth)	1021 (N=24, annual)	225(S), 59(W)	Mainly *Cladosporium*, *Alternaria* and *Aspergillus*	Pastuszka et al. 2000
	43		LM (With visible mold growth)	980 (N=31,annual)	834(S), 256(W)	Mainly *Penicillium*	
Taiwan	12	Burkard	BE (w/o asthmatics)	-	10834 (sp), 5858 (S), 11765 (A), 20313 (W)	*Cladosporium*, *Aspergillus*, *Penicillium*	Su et al. 2001
	23		BE (w asthmatics)		11233 (Sp), 7289 (S), 10727 (A), 20676 (W)	Mainly *Penicillium*	
USA	59	Burkard	BE (Urban)	-	3608 (S), 9099 (W)	*Cladosporium*, *Penicillium*, *Aspergillus*	Wu et al. 2000
	17		BE (Suburban)		7303 (S), 8333 (W)	*Cladosporium*, *Penicillium*, *Aspergillus*	
Turkey	6	Gavitational petri plate method	Total	-	149	*Penicillium*, *Cladosporium*	Sen and Asan 2009
			LM		670		
			K		576		
			BE		544		
USA	945	Burkard	Infant BE	-	1029	Yeast, *Cladosporium*, *Penicillium*	Ren et al. 2001
	942		LM		1038	Similar composition with ↑*Cladosporium*	
	50	SAS	LR	-	189(S), 92(W)	*Cladosporium*, *Penicillium*, *Aspergillus*	Horner et al. 2004
			KI		166(S), 89(W)	Similar composition with ↑*Cladosporium*	
			BE		166(S), 71(W)		
United Arab Emirates	5	MK2	Type 1 building	5417	217	*Aspergillus*, *Trichoderma*, *Chaetomium*	Jaffal et al. 1997
	5		Type 2 building	9871	260	*Aspergillus*, *Penicillium*, *Chaetomium*	
	5		Type 3 building	15179	273	*Aspergillus*, *Alternaria*, *Chaetomium*	

[a] BE, BA, LR and KI – represented bedroom, bathroom, living room and kitchen respectively.
[b] Sp, S, A and W' – represented spring, summer, autumn and winter respectively.

Mechanical ventilated public building

Many commercial buildings are equipped with air conditioning systems in order to maintain good IAQ by controlling the air temperature, humidity, ventilation rate and particulate content. While the monitoring of airborne fungi and bacteria levels are important criteria to determine the biological air quality in the indoor environment. Concentration levels of indoor bioaerosols in different regions of the world recorded in published literatures are summarized in Table 2.5.

Similar to the residential buildings, indoor bioaerosols in mechanical ventilated office buildings varied in different geographic locations. Studies have been conducted in office buildings of different countries and cities, included Australia, United Kingdom, Finland, France, Poland, Taiwan and United States. The average ABC ranged from 87 CFU m^{-3} to 219 CFU m^{-3} while the average AFC ranged from 3 CFU m^{-3} to 661 CFU m^{-3}.

The baseline concentrations of indoor bioaerosols in 100 representative US office buildings were evaluated from 1994 to 1998 in the Building Assessment Survey and Evaluation study. These buildings were located in 37 cities of 25 continental sites in urban (73%), suburban (23%) and rural (4%) areas. In order to study the seasonal effects, the buildings were studied for a 1-week period either in summer (June to September) or winter (December to April) according to a standardized protocol, but it is noted that none of the buildings were visited in both seasons (USEPA 2003). Apart from seasonal effects, the effects of location (indoor vs. outdoor), and collection and analytical method (multi-hole agar vs. slit slide impactor; culture vs. microscopy) on bioaerosols were also evaluated. Similar to those findings reported from most of the studies conducted in residential buildings, it was revealed that both indoor ABC and AFC recorded in summer were significantly higher and the composition is more diverse than in winter.

The indoor airborne fungi level may be different under different ventilation system. Wu et al. (2005) revealed that both ABC and AFC recorded in ventilation system with fan coil unit (FCU) were significantly higher than those with air handling unit (AHU). It was reported that the average ABC recorded in buildings with AHU and FCU were 395 CFU m^{-3} and 715 CFU m^{-3} respectively; while the average AFC were 87 CFU m^{-3} and 661 CFU m^{-3} for buildings with AHU and FCU respectively. Wu et al. (2005) explained such phenomenon was probably due to different mechanical

designs between the AHU and FCU systems, such as the components of a system, placement of air ducts, entry for fresh air intake, and space designated for accommodating return air and air mixing, etc. (Barry et al. 1995; Bearg 1993). In addition, the presence of independent fresh air intake ducts with screen and filter in AHU systems but not in FCU system would lower down the indoor bioaerosols levels.

A large scale study on indoor airborne fungi in the United States from 1996 to 1998 examined 9619 indoor samples in 1717 buildings which can provide an overall picture of the airborne fungi composition (Shelton et al. 2002). It was reported that RA of *Penicillium*, *Cladosporium* and *Aspergillus* were 30.4%, 22.4% and 17.4%, respectively. *Alternaria* and yeast were also detected with RA of 4.1% and 9.8% respectively. The other isolates belonged to *Acremonium*, *Aureobasidium*, *Candida*, *Epicoccum*, *Fusarium*, *Geotrichum*, *Hyalodendron*, *Rhinocladiella*, *Rhodotorula*, *Stachybotrys*, *Trichoderma*, *Tritirachium*, non-sporulating and unidentified fungi. This study also compared the airborne fungal measurement results due to different sampling reasons which included employee health complaints, visible fungal growth, water damage and part of a proactive IAQ program. Although association between the high AFC and hypersensitivity pneumonitis was reported, no association was observed between reported health complaints and the presence of any common airborne fungal genera or potentially toxigenic fungus. Although variations were observed in the composition of outdoor air samples, in general, the outdoor composition can be reflected by the indoor one (Shelton et al. 2002). Kemp et al. (2003) collected the samples at different locations included outdoor air before and after the ventilation systems and offices from a typical building in Australia. It is reported that the fungal composition varied at different sampling locations while the RA of *Penicillium*, *Cladosporium* and *Aspergillus* were 34.3%, 21.8% and 7.8% respectively (Kemp et al. 2003). The other isolates belonged to *Aureobasdium*, *Botrytis*, *Fusarium*, *Phoma*, *Rhizopus*, *Sporobolomyces* and *Ulocladium*. Wu et al. (2005) collected 1051 indoor air samples from 5 buildings in subtropical region (Taiwan). The RA of *Cladosporium*, yeast, *Aspergillus* and *Penicillium* were 16.7%, 14.6%, 9.4% and 7.7%, respectively. The relatively high RA of yeast may be due to the presence of occupants as a significant correlation was observed between the occupant density and yeast concentration. The other isolates belonged to *Curvularia*, *Fusarium*, *Paecelomycetes*, *Zygomycetes* and no-sporulating fungi.

Furthermore, the review of indoor airborne fungi written by Gots et al. (2003) revealed that the indoor AFC measured in office buildings without associated health complaints were sometimes with much higher levels than that measured in buildings with complaints of nonspecific health symptoms. It was suggested that reported levels vary within a geographic location and among geographic locations (Gots et al. 2003).

In addition, Kemp et al. (2003) evaluated the influences of the ventilation system on indoor fungi by measuring the AFC in all accessible components in the system and the chambers between the indoor and outdoor air. It was observed that reductions in the concentrations and composition of fungi outdoors and sequentially throughout ventilation systems were found. The ventilation systems acted as a source of fungi are well maintained.

Kembel et al. (2012) also investigated the effects of source of ventilation air, airflow rates, RH and T on indoor airborne bacteria in health-care facilities with both mechanically and window ventilated (i.e. outdoor air was supplied from window and removed through a return duct, bathroom exhaust and the window) rooms. It is observed that the airborne bacteria composition in indoors is less diverse than the outdoor. The airborne bacteria composition recorded in the mechanically ventilated rooms were distinctive with that recorded in outdoor, while the composition recorded in window ventilated room was in intermediate between the mechanically ventilated rooms and the outdoor air. It was reported that the abundance of potentially pathogenic airborne bacteria in both mechanically and window ventilated rooms was negatively correlated with airflow rates, and the abundance was lower in the rooms with higher airflow rate. However, there was no significant impact of the ventilation method on the potential pathogen load indoor as the RA of the potential pathogen was higher indoors than outdoors.

Based on the literature review on studies (N=12) investigating the relationship between the prevalence of sick building syndromes (SBS) and ventilation rates with a range of 2 l s^{-1} to 60 l s^{-1} per person, it was revealed that there were associated between the SBS in air-conditioned offices and the ventilation rates (Sundell et al. 2011), although the results are not fully consistent. It was suggested that the syndromes would be reduced under higher ventilation rate (up to about 25 l s^{-1} per person). It was also observed that there were increased prevalence of indicators of inflammation, rates of communicable respiratory infections, frequency of asthma

symptoms and rates of short-term sick leave in the building environments with lower ventilation rates. Further studies are needed to confirm the nature of that relationship in order to establish the rational ventilation standards.

Table 2.5: Selected studies on indoor bioaerosols in public buildings in different countries/cities.

Country / city	N	Sampler	Location	Indoor bioaerosols		Common fungal genera	Reference
				Average Count (CFU m^{-3}) [a]			
				Bacteria	Fungi		
Australia	1	Andersen 6-stage	Non-problem	–	265	*Cladosporium, Penicillium,* Yeast, non-sporulating isolates	Kemp et al. 2003
United Kingdom	15		Mould-damaged	–	301	-	Harrison et al. 1992
Finland	56	Andersen 6-stage	Non-problem	62	3	*Aspergillus versicolor, Cladosporium, Penicillium,* Yeast, non-sporulating isolates	Salonen et al. 2007
	46		Mould-damaged	122	20		
France	1	Andersen single-stage	Non-problem	171	17	*Aspergillus, Penicillium, Cladosporium*	Parat et al. 1997
Poland	15	Andersen 6-stage	Non-problem	–	245 (S), 49(W)		Pastuszka et al. 2000
Taiwan	5	Burkard	Non-problem (AHU)	395	87	*Aspergillus, Cladosporium, Penicillium,* Yeast, non-sporulating isolates	Wu et al. 2005
	7		Non-problem (FCU)	715	661		
	37	Burkard	Non-problem	219	154	–	Tseng et al. 2011
United States (BASE study)	100	Single-stage, one-slit slide impactor	Problem and non-problem	–	130 (S), 60 (W)	*Cladosporium, Penicillium,* non-sporulating isolates	Tsai et al. 2007
	100	Single-stage, One-slit slide impactor	Problem and non-problem	116 (S), 87 (W)	–	Unknown and gram-positive cocci	Tsai and Macher 2005

[a] '–' represents no information is available.

Review of indoor bioaerosols assessment in Hong Kong

Natural ventilated residential building

The studies of indoor bioaerosols in residential buildings in Hong Kong are much scare when compared with those conducted in mechanical ventilated public buildings. Only very few information of the indoor airborne fungi in residential buildings in Hong Kong is available (Wong 1997; Lee et al. 1999; Lee 2002). Wong (1997) conducted a survey on indoor airborne fungi in 8 air-conditioned residential apartments. A total of 14 samples were collected using Andersen six-stage air sampler and RCS, it was reported that the mean airborne fungi count were 543 CFU m^{-3} and 728 CFU m^{-3} respectively. *Cladosporium herbarum*, *Penicillium citrinum* and *Aspergillus versicolor* were the most frequent species in these sampling sites. Furthermore, Wong (1997) also investigated the difference of airborne fungi in the apartment of allergic rhinitis patients and controls. Samples were collected from 35 allergic rhinitis patients and 47 sex- and age- matched controls. It was revealed that the airborne fungal composition in the patient's apartments were significantly different when compared with the control. The three most common fungi recorded in the patient's apartments were *Cladosporium cladosporioides* (occurrence frequency=97%), *C. sphaerospermum* (49%) and *Penicillium citrinum* (37%); while in the controls' apartments were *C. cladosporioides* (81%), *C. sphaerospermum* (66%) and *P. citrinum* (51%).

Furthermore, the indoor airborne bacteria counts were monitored in different locations included kitchen, bathroom and living room in six residential buildings with building age of 2 to 30 years locating in different regions of Hong Kong and investigated by Lee et al. (1999). It was reported that the airborne bacteria counts ranged from 231 CFU m^{-3} to 840 CFU m^{-3}, and the average was 525 CFU m^{-3}. The airborne bacteria counts were higher in old building (over 15 years) when compared with the new building. Moreover, different airborne bacteria counts were recorded in different locations inside an apartment. The airborne bacteria count recorded in the kitchen was the highest, followed by toilet, living room and bedroom, the counts were 1320 CFU m^{-3}, 950 CFU m^{-3}, 820 CFU m^{-3}, 750 CFU m^{-3} respectively. It was suggested that the indoor airborne bacteria count in an apartment was affected by

several parameters, included the age of building, frequency of cleaning, the rate of ventilation, humidity and temperature.

Lee et al. (2002b) conducted another IAQ investigation in 6 residential apartments with building age of 3 to 15 years, the airborne bacteria counts were recorded in living room and kitchen. The airborne bacteria counts varied with different apartments, which ranged from 800 CFU $m^{-3}$to 1100 CFU m^{-3} for living room and 560 CFU $m^{-3}$to 1310 CFU m^{-3} for kitchen respectively. The average count recorded in kitchen was at least 1.3 times higher when compared with the living room. Once again, it was reported that the airborne bacteria count were related to frequency of cleaning and rate of ventilation. Furthermore, reasonably correlations were found between the average count and the occupant load in both areas. However, no significant correlations were reported between the average count and the T, RH and age of building. The sample size of the study may affect the accuracy of the correlation.

Mechanical ventilated public building

Unlike the other IAQ pollutants, the assessment of airborne bacteria and fungi are limited. Table 2.6 summarized the available database of the airborne bacterial and fungal assessment conducted in 480 and 53 air-conditioned offices respectively. These studies were conducted from 1996 to 2003. In order to compare with the findings obtained in the present study, these previous investigations are denoted as 'Database A'. Only those databases with detailed sampling information (e.g. location of sampling, sampling method and time) are chosen for comparisons. The significantly fewer airborne fungal assessments were conducted which may probably due to the AFC is not mandatory in the current IAQ certification scheme (HKEPD 2003). All these offices were typical and installed with a centralized MVAC system. Multiple samples were collected from each sampling site using the Andersen six-stage impactor (ASI), Burkard single-stage impactor (BSI) and RCS. It was reported that the ABC ranged from 41 to 2912 CFU m^{-3} with an arithmetic mean (AM) of 597 (arithmetic standard deviation (ASD)=523) CFU m^{-3} and geometric mean (GM) of 449 (geometric standard deviation (GSD)=2.2) CFU m^{-3}, while the AFC ranged from 0 CFU m^{-3} to 3852 CFU m^{-3} with an AM of 147(240) CFU m^{-3} and GM of 73 (3.1) CFU m^{-3} (HKEPD 1997; Wong 1997; Law et al. 2001; Chao et al. 2001; Lee 2002; Lee et al. 2002a; Chan et al. 2003; Chow et al. 2005; Leung et al.

2005; Wong et al. 2006b).

The first extensive airborne bacteria and fungi assessment for Hong Kong offices was conducted at the first IAQ study carried out by an appointed independent consultant in 1996 and published in 1997 (HKEPD 1997). Detailed monitoring and laboratory analysis of a number of offices and public places in Hong Kong, which included both smoking and non-smoking areas, was conducted between March and October 1996. The selected samples consisted of 40 typical offices in both private and government-owned buildings and a number of other public utility premises equipped with MVAC system and building age ranged from 3 to 35 years. All these offices were typical and installed with a centralized MVAC system. The ABC recorded in these offices ranged from 56 CFU m^{-3} to 2782 CFU m^{-3} with an AM of 739 (ASD=541) CFU m^{-3} and GM of 570 (GSD=2.2) CFU m^{-3}, while the AFC ranged from 15 CFU m^{-3} to 1413 CFU m^{-3} with an AM of 187 (ASD=382) CFU m^{-3} and GM of 108 (GSD=2.9) CFU m^{-3} (HKEPD 1997).

During 1998 to 2003, a regional cross-sectional measurement of airborne bacterial concentration in 422 air-conditioned offices was conducted (Wong et al. 2006b). The sample size is large enough to show the overall picture of airborne bacterial and other IAQ pollutant levels in local offices. The samples covered a range of open-plan offices and conference rooms to individual small offices in all regions for office development. Their floor areas ranged from 10 m^2 to 300 m^2. In this study, the ABC was the only bioaerosols parameter measured and ranged from 41 CFU m^{-3} to 2304 CFU m^{-3}, with an AM of 580 (392) CFU m^{-3} and GM of 447 (GSD=2.2) CFU m^{-3} (Wong et al. 2006b).

Except for the above studies, the airborne bacterial and fungal assessments were conducted in a small scale (<10 offices) (Wong, 1997; Law et al. 2001; Lee 2002; Chan et al. 2003; Chow et al. 2005; Leung et al. 2005). Lee et al. (2002a) compared the ABC and other 4 IAQ pollutants in different indoor environments (i.e. offices, residential, classroom, shopping mall and restaurant). The offices (N=10) were located in Hong Kong commercial districts with heavy traffic and floor areas ranged from 18 m^2 to 135 m^2. It is found that the ABC is related to the occupancy density and the ABC in the office was the lowest when compared with other indoor environments due to lower occupancy density. The ABC reported ranged from 181 CFU m^{-3} to 819 CFU m^{-3} with an AM of 478 CFU m^{-3}.

Daily profiles of ABC and AFC were investigated by several authors (Wong 1997; Chao et al. 2001; Law et al. 2001). Wong compared the differences of the AFC variations between a weekday (Tuesday) and a public holiday (Sunday) (Wong 1997). Samples were collected every 2 hours from 07:00 to 19:30 by using an A6I. For the weekdays, the AFC increased sharply from 11 CFU m^{-3} to 512 CFU m^{-3} as the MVAC system turned on and then decreased to a relatively steady level after the system has been operated for 2 hours. In the weekend, the AFC kept below 160 CFU m^{-3} and no sharp peak was observed.

Law et al. (2001) conducted a longer-period (1 week) study by measuring the indoor airborne fungi and bacteria in two individual air-conditioned offices. Air samples were collected once every hour between 07:00 and 09:00, and once every 2 hours between 09:00 and 19:00 by using an A6I. Similar to Wong (1997), the AFC increased right after the start of the MVAC system and then decreased within 2 hours from the system in-operation, such observations were also recorded for the ABC. However, in another office, the ABC and AFC fluctuated widely throughout the day, probably due to large variations of human activity levels caused by a lot of transient movement of come-and-go visitors. Chao et al. (2001) also recorded higher ABC in the morning in one of the office (total N=3) during a day of measurements.

The peak bioaerosols levels in daily profiles were probably due to amplification of bioaerosols airborne fungi during shut down period of the MVAC system at night (Wong 1997; Chao et al. 2001; Law et al. 2001; Chan et al. 2003; Chow et al. 2005). The highest ABC (2912 CFU m^{-3}) and AFC (3852 CFU m^{-3}) were recorded during the shutdown period of the MVAC system, 6 to 12 times higher than those recorded in office hours (Law et al. 2001). Chow et al. (2005) investigated the microbial contamination with air samples at three different locations within the MVAC system, i.e. in the air mixing chamber, beyond the cooling coil and at diffuser outlets, and corresponding indoor and outdoor environments with an RCS. The investigations were conducted in three different modes of system operation – system-on, system-off during weekdays and system-on in a Monday morning (after the system was switched off for more than 24 hours). It was reported that, during the system-off period, the AFC was 3 to 14 times higher than those measured in the other two periods. It was suggested, for an air-conditioned office in hot and humid climates, the relatively higher air temperature and relative humidity as well as the stagnant air flow favored the bioaerosols amplification inside the MVAC system.

Seasonal variations of indoor airborne fungi bi-daily measurements in two typical offices were made with an RCS (Chan et al. 2003). Higher AFC levels (2 to 6 times) were recorded in autumn than that in winter and the results from a Taiwan study were similar with the AFC in hot season (summer) approximately 20 times higher than those in cold season (winter). It was suggested that relatively high temperature and relative humidity in warmer months favor the growth of airborne fungi (Li and Kuo 1994).

The commonly found indoor airborne fungal genera in Hong Kong air-conditioned offices were *Aspergillus, Cladosporium* and *Penicillium,* which were similar to some other Asian cities (HKEPD 1997; Wong 1997; Li and Kuo 1994; Wu et al. 2005; Lee and Jo 2006). This can be explained by the climate of this city, where the outdoor daily minimum and maximum air temperatures were 6°C and 35°C respectively, and the daily mean relative humidity ranged from 30% to 97% respectively (HKO 2011). Indoor air condition of offices with an air-conditioning system operating was at an average air temperature from 13°C to 28°C and at a relative humidity from 30% to 90% respectively (Wong et al. 2006b). It was noted that the air-conditioning system would be operated part of the day. Wong (1997) conducted a physiological study on some isolated common airborne fungi. It was shown that the optimum temperature and water activity range for the growth, germination and sporulation of these fungi fell within that of the climate condition of Hong Kong.

Other air-conditioning spaces

The indoor bioaerosols in other air-conditioned public places were also investigated, but the sampling size was lower than the air-conditioned offices. These public places include cinemas, health care facility, indoor gymnasium, lecture hall, library building, light industrial premises, pubs and karaokes, restaurants, shopping malls, and waiting hall (HKEPD 1997; Chao et al. 2001).

For the public places, different time periods were targeted. For example, restaurants were studied at peak hours during lunch (12:00 to 14:00) and dinner (19:00 to 21:00), pubs and karaokes were examined during happy hours, and cinemas were monitored over the entire duration of a movie. To capture the most crowded period, shopping malls were surveyed from 12:00 to 20:00 on Sundays. It was noted that smoking was not restricted in the surveyed restaurants but some of them had designated smoking areas. A total of 5 sampling points were chosen at each premise (HKEPD 1997).

Although the results obtained in the previous studies provided some information on the abundance and dominant species, there are some limitations in these studies Therefore, there are several reasons for developing a regional cross-sectional database of indoor bioaerosols: (1) the inability of the available data of the airborne fungi in apartments and air-conditioned offices to represent the overall picture of the indoor bioaerosols of Hong Kong, a samples size with at least 67 is needed in order to reach 90% confidence interval; (2) the inconsistent results reported in previous studies with different sampling methods (i.e. equipment and agar media) of the bioaerosols samples with inconsistent results (HKEPD 1997; Wong 1997; Law et al. 2001; Chao et al. 2001; Lee 2002; Lee et al. 2002a; Chan et al. 2003; Chow et al. 2005; Leung et al. 2005); (3) the unavailability of information of some important environmental parameters (e.g. ventilation in air-conditioned offices), which affect the abundance of bioaerosols; and (4) the limited amount of information on the composition of indoor airborne fungi. Therefore, in order to provide more information for exposure and control strategies against the indoor bioaerosols, additional surveys were conducted in this study.

Table 2.6: Indoor bioaerosols in residential and commercial building of Hong Kong.

No. [a]	No. of sites (N)	Airborne bacteria count (CFU m^{-3}) [b]			Airborne fungal count (CFU m^{-3}) [b]			Reference
		Range	AM (ASD)	GM (GSD)	Range	AM (ASD)	GM (GSD)	
				Residential building				
1	8		–			543 (Andersen 6-stage) 728 (RCS)	–	Wong 1997
2	6	231-840	525(208)	486(1.6)		–		Lee et al. 1999
3	6	800-1310	877 (388)	816(1.5)		–		Lee et al. 2002
				Commercial office building				
1	40	56-2782	739(541)	570(2.2)	15-1413	187(271)	108(2.9)	HKEPD 1997
2	1		–		22-1322	131(121)	94(2.5)	Wong 1997
3	422	41-2304	580(392)	447(2.2)		–		Wong et al. 2006
4	2	64-2912	472(475)	326(2.3)	0-3852	330(710)	100(4.8)	Law et al. 2001
5	3	267-629	448(181)	–		–		Chao et al. 2001
6	10	181-819	478	–		–		Lee et al. 2002a
7	5		–		4-64	22(25)	14(3.1)	Lee 2002
8	2		–		1-20	9(8)	7(2.56)	Chan et al. 2003
9	1	228-370	299(100)	290(1.4)	10-34	22(17)	18(2.4)	Chow et al. 2005
10	2	128-798	463(474)	320(3.6)	34-72	47(23)	44(1.6)	Leung et al. 2005

[a] The sampling sites are either centrally or individually air-conditioned.
[b] '–' represents no information is available.

Table 2.6: Indoor bioaerosols in residential and commercial building of Hong Kong (Continued).

No.	No. of sites (N)	Airborne bacteria count (CFU m^{-3})		Airborne fungi count (CFU m^{-3}) [a]		Reference
		Range	**AM (ASD)**	Range	AM (ASD)	
Cinema	5	69-856	430 (280)	6-44	26	HKEPD 1997
Hospital	3	226-564	402 (169)	-		Chao et al. 2001
Lecture hall	3	237-424	311 (99)	-		Chao et al. 2001
Library	4	283-726	477 (215)	-		Chao et al. 2001
Restaurant	20	125-2275	1003 (508)	6-200	77	HKEPD 1997
Restaurant	3	112-544	310 (218)	-		Chao et al. 2001
Shopping Mall	8	465-4891	2140 (1736)	77-1161	377	HKEPD 1997
Stadium	3	116-315	198 (104)	-		Chao et al. 2001
Waiting hall	3	234-657	502 (233)	-		Chao et al. 2001
Workshop	3	184-761	560 (326)	-		Chao et al. 2001

[a] '–' represents no information is available.

Study on dynamic of indoor bioaerosols

Dynamic of bioaerosols in indoor environments

It is well known that outdoor bioaerosols are one of the important sources of bioaerosols indoors. It can be transported indoors by many means, such as attachment on occupant's clothing, through natural ventilations or mechanical ventilation, etc. (Cox and Wathes 1995; WHO 2009). Considering the physical properties of bioaerosols particles, same as the other non-biological airborne particles, same physical laws can be applied to the bioaerosols particles as all aerosol particles have a commonality – aerodynamic behavior (Cox 1995). However, the biological properties of bioaerosols also play a role in determining their dynamics in air.

Like other non-biological aerosols, size, shape and density are three major parameters characterizing the behavior in a space (e.g. sources, composition, dynamic behavior, fates, and effects) (Hinds 1999; Lai 2002; Nazaroff 2004; Bouilly et al. 2005).

The size is conventionally referred to particle diameter which is indicated by the unit micrometer (μm) (Hinds 1999). Bioaerosols comprised with different sizes, the aerodynamic diameter of bioaerosols ranged from 0.01 μm to 100 μm, and the diameter of common bacterial cells and fungal spores ranged from 0.3 μm to 11 μm (Cox and Wathes 1995; Samson et al. 2002). Pastuzka et al. (2000) stated that both infectious and non-infectious diseases are not only due to the biological and chemical characteristic of the bioaerosols, but also related to the concentration of inhaled compound and the location of their deposition in the respiratory tract of human. The bioaerosols size is therefore a crucial factor for assessing the human exposure while the deposition location in respiratory tract is determined by the aerodynamic diameter (Reponen et al. 2001). Bioaerosols with smaller size would increase the risk of entry into the respiratory tract and induce a prolonged exposure period. Most of the bioaerosols are slightly hygroscopic, so the aerodynamic diameter would be increased when entering the moist respiratory tract (Lacey and Dutkiewicz 1994).

For those bioaerosols cells or spores with diameter less than 1 μm, for examples,

virus and some bacterial species, the motion or displacement is described as 'Brownian motion', where the intensity increases with T and decreases with the particle size.

The motion can be expressed by the Einstein equation (Cox 1995) as follows

$$\overline{X} = 5X10^{-6}\sqrt{\sqrt{(t/r)}} \quad \text{... (Eq. 2.1)}$$

where $\overline{X}$ is the root mean square particle displacement, t is time (s) and r is the radius of particle (cm)

However, most commonly isolated bacteria and fungi are with diameter larger than 1 µm, therefore the diffusion of these bacterial cells and fungal spores due to Brownian motion is less than gravitational settling. Once the bioaerosol particles become airborne in the still air, according to Stokes Law, it falls due to the gravity and the falling velocity depends on its mass. When the drag or viscous frictional force equals to the gravitational force, the particle attains its terminal velocity (v) which is described as follows (Cox 1995):

$$v = \frac{\rho d^2 g C_c}{18\eta}, \text{ for } d > 1 \text{ µm amd Re } < 1.0 \quad \text{... (Eq. 2.2)}$$

where ρ is the particle density (g cm^{-3}), d is the particle diameter (cm), g is the gravitational acceleration (cm s^{-2}), η is the air viscosity (g cm^{-1}) and C_c is the Cunningham slip correction.

Shape also influences the behavior of aerosols and it is always assumed that the shape of particles is spherical when developing the theory of aerosols properties. Since bioaerosols are in different shapes, for example, the shape of bacterial cells and fungal spores ranged from spherical, oval, rod, coli, clusters, chain, etc. Therefore, correction factors and equivalent diameters are applied to these irregular particles when applying the theory of properties of spherical particles (Hinds 1999).

Density of bioaerosols is still not fully understood. Hinds (1999) points out that since the bacteria cells are mostly comprised of water, therefore depending on the degree of hydration, the density can be ranged from 1000 kg m^{-3} to 1500 kg m^{-3}, which is 1 g cm^{-3} to 1.5 g cm^{-3}.

Apart from particle properties, other factors included the dynamics of both aerosols

and bioaerosols airflow pattern, ventilation rates, geometry configurations, locations and direction of supply and exhaust diffuser, internal partitions, thermal buoyancy due to the heat generated by occupants and/ or equipment, etc. (Hinds 1999; Lai 2002; Lai 2005). Investigation on the dynamic of bioaerosols in indoor spaces, such as dispersion and deposition, is essential in assessing bioaerosols exposure and preventing airborne infection. In addition, studies show that airborne transmission of infectious agents in an indoor space is related to ventilation airflow patterns, therefore the effects of ventilation on bioaerosols dispersion and deposition are focused in this study (Lai 2002; Nazaroff 2004; Zhao et al. 2005; Li et al. 2007; Wan and Chao 2007; Gao and Niu 2007).

Experimental investigation on the dynamic of indoor bioaerosols

Many experiments on investigating the deposition of aerosols were conducted in a chamber (see review by Lai 2002). Some of the studies are summarized in Table 2.7. And most of the studies have been conducted on indoor particle deposition from turbulent airflow. Lai (2002) summarized the area-averaged deposition velocities for room-sized chamber (Figure 2.1). Six major factors influence the particle deposition rate significantly, which include electrostatic field effect, surface roughness effect, turbulent intensity, thermophoresis effect, turbophoresis and spatial distribution. It is impossible to fulfill all these requirements in one experiment. CFD seems to be one of the best solutions to study the indoor particle deposition process. A drift-flux model for particle distribution and deposition in indoor environments was applied for investigation on spatial and temporal particle concentration in enclosures even the well-mixed assumption cannot hold for coarse particles (Lai and Cheng 2007). It is revealed that the deposition velocity of aerosol particles onto a smooth surface decreased when the particle size increased from 0.9 μm to 3 μm, and then increased to saturation when the size increased from 3 μm to 7 μm (Lai 2002; Lai and Nazaroff 2005).

In addition, the surface roughness of the experimental chamber can be smooth or rough while it can be further divided into microscale roughness, with average roughness heights much less than a millimeter (Abadie et al. 2001), and macroscale roughness, with average roughness heights larger than a millimeter (Lai et al. 2002). It is observed that the deposition velocity of aerosol onto a rough surface is higher than a smooth surface.

Furthermore, mixing fan was always used to ensure that there is complete mixing in the chamber since the well-mixed assumption (aerosols are uniformly distributed in the enclosure) is widely adopted in many former IAQ studies (Lai 2002). With the well-mixed assumption, one can simplify the governing equations, ordinary differential producing system and algebraic equations in the CFD model.

Table 2.7: Previous studies on deposition of airborne particles (modified from Lai 2002).

Particle size range (μm)	Enclosure dimensions (m) and surface/volume ratio (m^{-1})	Mixing method	Surface type	Measuring instrument	Reference
0.006-2	2.6 l, cylinrical, S/V=47	A mechanical stirrer, zero and various speed	Smooth surface	Optical particle counter	Okuyama et al. (1986)
0.019-0.21	230 l, spherical, S/V=7.89	Natural convection	Smooth surface	Condensation nucleus counter	Van Dingenen et al. (1989)
0.06-1.5	4.56x3.38x2.37, S/V=1.87	Four mixing fans, zero and various speed	Unfurnished test house	Optical particle counter, condensation nucleus counter, differential mobillity particle sizer	Xu et al. (1994)
0.7, 2.5,4.5 and 5.4	2x2x2, S/V=3	A mixing fan	Smooth surface	Neutron activation analysis	Byrne et al. (1995)
0.015-2.0	0.75x0.75x1.8, S/V=6.4	Continuous flow, 0, 8, 1.7 and 2.4 ACH	Smooth surface	Diffusion scintillation cell	Nomura et al. (1997)
0.7, 1 and 5	0.6x0.6x0.6, S/V=10	A mixing fan	Surface covered with various textures	Optical particle counter	Abadie et al. (2001)
0.7, 2.5, 4.5 and 5.4	2x2x2, S/V=3	Three mixing fans	Three-dimensional roughness elements	Neutron activation analysis	Lai et al. (2001)
0.5-10	2.2x2.7x2.4, S/V=2.48	Four mixing fans, zero and various speed	Bare, carpeted and furnished	Aerodynamic particle sizer	Thatcher et al. (2002)
0.9-9	1.22x1.22x1.22, S/V=11	A mixing fan	Sandpapers with different grades of roughness glass	fluorometer	Lai and Nazaroff (2005)

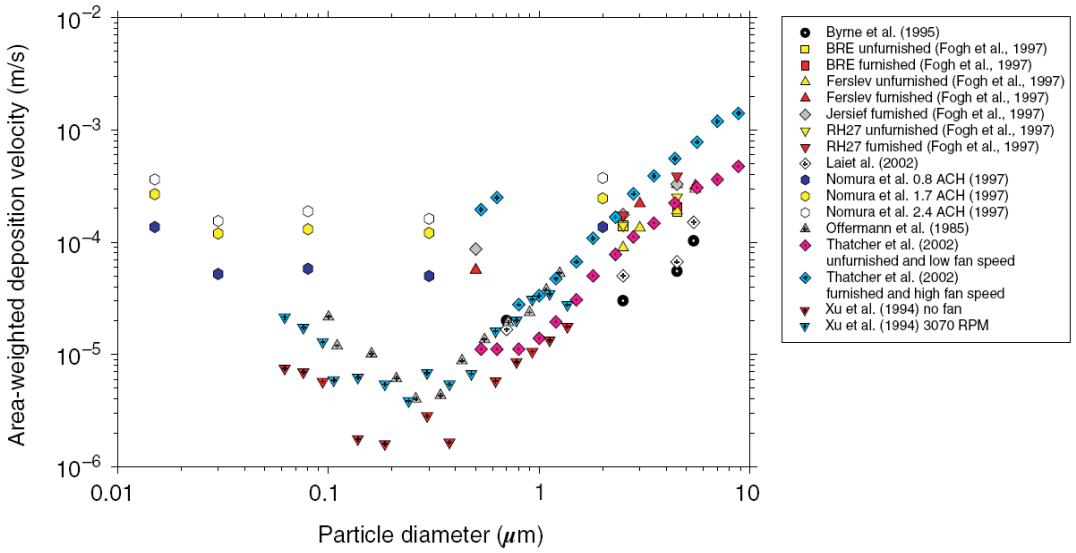


Figure 2.1: Area-averaged deposition velocities for room-sized chamber (adopted from Lai 2002).

However, unlike the other aerosols, very few studies focused on investigating the dynamics of indoor bioaerosols only (Reck et al. 2002; Sze To et al. 2008; Kanaani et al. 2008a). Many studies focused on assessing the mechanism of bioaerosols deposition in the airways only, the deposition of indoor bioaerosols is still being unknown. Although deposition of bioaerosols on the respiratory tract can induce adverse health effects or those onto interior surfaces of buildings can cause soiling problem and lead to damage, deposition can be a positive phenomenon as deposited particles cannot be inhaled unless resuspended. Deposition onto surfaces is an important fate for bioaerosols in indoor space, which reduces the concentration in air. Reck et al. (2002) investigated the deposition of spoilage fungi (*Alternaria*, *Cladosporium* and *Penicillium*) onto a petri dish, a surface and on a warm box-shaped object placed in a food-processing environment. Kanaani et al. (2008a) investigated the deposition rates of airborne fungi (*Aspergillus niger* and *Penicillium* sp.) in a chamber installed with ceiling-mounted air diffusers operating at a ventilation rate up to 2.5 h^{-1} and reported that the deposition rates of the test fungal spores and other aerosols of comparable size were similar, especially at very low ventilation rates. Their results also showed increasing deposition rates with increasing ventilation rates. Effects of different ventilation design and rates on airborne bioaerosols concentration were reported while results of several studies on

the bioaerosols deposition also revealed such influences (Wu et al. 2005; Sze To et al. 2008; Kanaani et al. 2008a). Sze To et al. (2008) investigated the spatial distribution patterns of bacteriophage in an experimental ward with a ceiling-mixed type ventilation system operated at a ventilation rate of 11.6 h^{-1} and showed that the bacteriophage transmission was related to the flow pattern.

Although the above studies gave us an insight into the deposition of bioaerosols indoors, the deposition pattern as well as the dispersion under a specific type of air distribution system over a wide range of ventilation rates have never been detailed. The location and air supply direction of an air inlet dictate airflow patterns as well as velocity fluctuations and thus have significant effects on the diffusion performance (Fanger et al. 1988; Chow and Wong 1994, 1998a). According to a survey study on typical air diffusion systems for air-conditioned and mechanically ventilated offices in Hong Kong, 76% of the air inlet devices mounted in or near the ceiling discharged air horizontally while the rest projected air vertically down (Chow and Wong 1998b). The ranges of air temperature, relative humidity and air speed recorded at the air inlets were from 15 °C to 27.6 °C, 48 % to 82% and 0.15 ms^{-1} to 3.05 ms^{-1} respectively. Except for a few extreme cases (i.e. small offices in which problems of providing low ventilation rate were raised), the ventilation rates of the surveyed offices ranged between 2 h^{-1} and 40 h^{-1}.

In order to enrich the knowledge in the field of bioaerosols dynamic, a chamber is developed in this study to investigate the dispersion and deposition pattern of the several commonly isolated airborne bacteria and fungi under different ventilation rates and mixing conditions (Chapter 5).

Chapter 3 Indoor Bioaerosols in Residential Buildings

Survey of indoor bioaerosols in residential buildings of Hong Kong

Introduction

As mentioned in Chapter 2, the information on indoor bioaerosols in residential buildings are very rare. In Wong's (1997) study, although samples were collected from 82 residential sites, details of other IAQ parameters are not known. This part of study aims (1) to develop an indoor bioaerosols database in typical residential buildings; (2) to evaluate interactions between different areas in typical apartments; (3) to propose the relative index for exposure of indoor bioaerosols; and (4) to investigate the influence of indoor bioaerosols and other IAQ parameters on patients with COPD.

A total of 103 typical apartments of high-rise residential buildings were sampled in two assessments in Hong Kong from 2007 to 2011. The assessments were conducted by using the same sampling protocol. These sites included public rental and private housing with age ranged from 5 to 48 years. The apartments were located on the 1st to 25th floor and the floor areas of apartments ranged from 18.5 m^2 to 92.9 m^2 with an average of 45.5 m^2. In general, the residential buildings in Hong Kong are based on standardized architectural designs with considerable variations depending on different marketing demands. According to the Hong Kong Property Review 2012 (by the Rating and Valuation Department), a residential apartment is defined as independent dwellings with separate cooking facilities and bathroom (and/or lavatory), and are categorized into five classes according to the floor areas – Class A (saleable area <40 m^2), Class B (40 to 69.9 m^2), Class C (70 to 99.9 m^2), Class D (100 to 159.9 m^2) and Class E (>160 m^2). Based on this classification, 92.5% of apartments in private and public residential buildings belong to Class A to C, with Class B contributing to 48.8%. As the floor area of investigated apartments covered 92.5% of all classes in Hong Kong, the sampled apartments were regarded as typical

apartments in Hong Kong.

Hong Kong is geographically divided into 18 districts and the sampled apartments covered all these areas (Figure 3.1), which included Central and Western, Eastern, Island, Kowloon City, Kwai Tsing, Kwun Tong, North, Sai Kung, Sha Tin, Sham Shui Po, Southern, Tai Po, Tsuen Wan, Tuen Mun, Wan Chai, Wong Tai Sin, Yau Tsim Mong, and Yuen Long districts. The apartments located at both suburban (N=29) and urban areas (N=74).

Site description

The personal interview method was developed based on some earlier residential survey studies done in Hong Kong (Wong 2003; Tu 2005; Mui et al. 2007). Air samples were collected in the center of the living room and corresponding outdoor air intake of all investigated apartments in both warm and cold seasons in Hong Kong (July 2007 to April 2011). The indoor bioaerosols in other areas (i.e. kitchen and bedroom) were also assessed in the 50 apartments.

During the interview, information of the occupant and the tenement, including occupant load patterns, time budget for activities, usage patterns of various home appliances and home cleaning practice, was surveyed. For each apartment, the furniture used, window locations and sizes, and potential indoor air pollutant sources (e.g. pets, plants, moldy wall surfaces, places under renovation, etc) were recorded. Surroundings of the apartment were also observed to set down the nearby major pollution sources such as vehicle traffic routes, construction sites, noticeable building exhaust, and vegetation.

Site measurement

In this study, culturable airborne bacteria and fungi samples were collected by using RCS. The commercially purchased agar strips coated with total count tryptic soy agar (Agar TC, Biotest) and MEA (supplemented with Rose Bengal) (Agar YM, Biotest) were used to collect airborne bacteria and fungi respectively. At each sampling site, 500 L air sample was collected at 1 m above the floor level. After sampling, the agar strips were aseptically removed from the air sampler and restored to the original packing and sealed. All the strips were transported back to the laboratory at 4°C on the same day of sampling. The agar strips were then incubated at 30°C for 2 days for bacteria and 25°C for 7 days for fungi. The ABC Φ_B and AFC

Φ_F on the strips were recorded and expressed into CFU m^{-3},

$$\Phi_{B/F} = \frac{No.\ of\ colonies\ on\ the\ agar\ strip\ (CFU)}{Volume\ of\ air\ collected\ (m^3)} \quad \ldots \text{(Eq. 3.1)}$$

The colonies were isolated and cultivated for identification using Nutrient agar (NA) for bacteria and 2% MEA for fungi. The isolated bacteria were identified by a series of biochemical tests including Gram's stain, catalase, oxidase test, etc. The isolated fungi were identified by the macromorphological and micromorphological characteristics. The unidentified bacterial isolates were grouped into gram-positive and gram-negative bacteria. While the unidentified fungal isolates were grouped into sporulating and non-sporulating fungi (failed to sporulate after 2 weeks incubation).

Other measurement equipment details can be found in an earlier study (Wong et al. 2006b). All samples were collected at 1 m above ground and at least 1 m away from any obstruction. Apart from the indoor bioaerosols, IAQ measurements also made both inside and outside the apartment. A number of environmental parameters: airborne particulates from 0.3 to >10.0 μm and RSP, T, RH, CO_2, CO, and TVOC were monitored. The sampling interval was set to 1 minute throughout the site survey period. The airborne particulates (SP) were denoted as $SP_{0.3}$, $SP_{0.5}$, SP_1, SP_2, SP_5 and SP_{10} and enumerated using a particle counter (Fluke 983) with size detection ranges of 0.3-0.5 μm, 0.5-1 μm, 1-2 μm, 2-5 μm, 5-10 μm and >10 μm respectively. Most of the residential sites (97%) in this study are with natural ventilation.

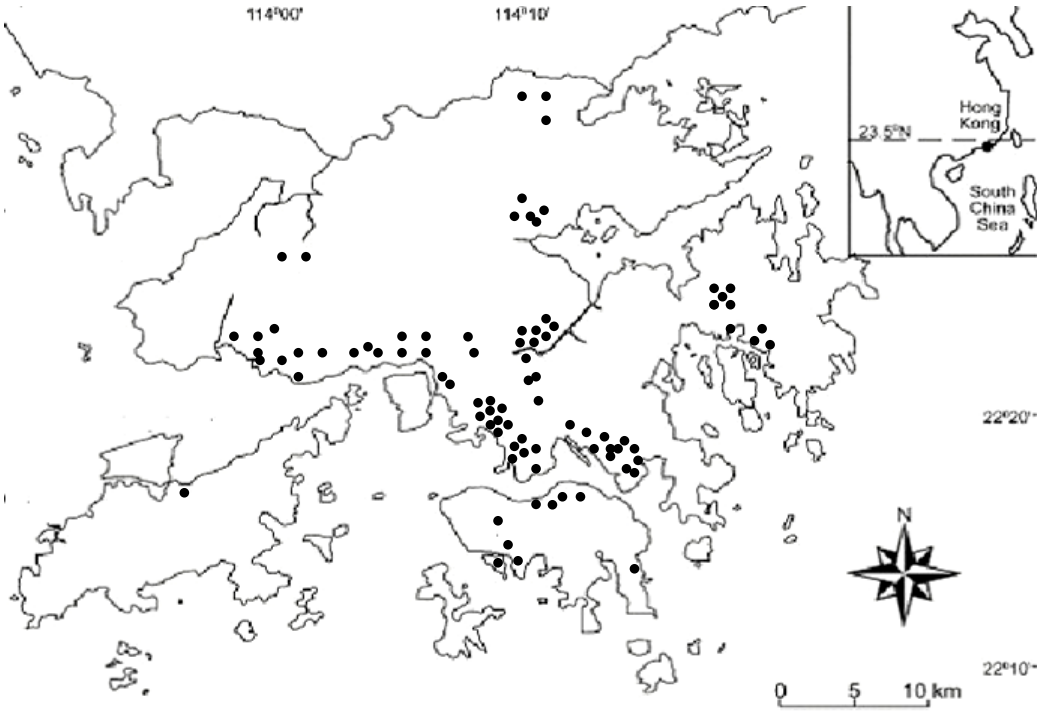


Figure 3.1: Map of Hong Kong showing the sampling locations of indoor bioaerosols in residential buildings

Regional cross-sectional database for indoor bioaerosols in residential buildings of Hong Kong

Environmental condition

In general, the apartments have an average T 27±3 °C in summer and 22±4 °C in winter. The average RH was 64±13 % in summer and 65±15 % in winter. The range of RH recorded were 30% to 80% for summer and 30% to 55% for winter. Seasonal variation was observed for the indoor air pollutants and bioaerosols. For the indoor air pollutants, except CO and TVOC, the average levels were lower in summer than in winter. Indoor sources of CO include gas and oil appliances, tobacco smoke, joss sticks burning and infiltration. This study reported that the number of apartments used town gas, liquefied petroleum gas, electricity and kerosene as cooking fuel was 47 (75%), 12 (19%), 3 (5%) and 1 (2%) respectively. This study also reported that occupants in 16 apartments (25%) would burn joss sticks. In addition, a survey study

reported that 95% households in Hong Kong would cook at home (Wong and Mui 2004; Mui et al. 2007). Indoor CO ranged from 0 μg m^{-3} to 6190 μg m^{-3} in summer and 0 μg m^{-3} to 4318 μg m^{-3} in winter. The average CO level was higher in summer (2317±1011 μg m^{-3}) when compared with winter (2249±656 μg m^{-3}), however, the measured levels were within the ASTER (≤48000 μg m^{-3} for 1-hr average). The φ of CO was 0.99 in summer and 0.97 in winter, and the R was 0.15 in summer and 0.74 (significant, $p< 0.01$) in winter.

The indoor sources of TVOC include the combustion by-products, cooking, emission from building materials, furnishings, varnishes and solvents, and other building contents (Jia et al. 2008; Guo et al. 2009). The indoor TVOC level reported in this study ranged from 0 μg m^{-3} to 951 μg m^{-3} in summer and 26 μg m^{-3} to 1424 μg m^{-3}. The average indoor TVOC in summer was higher than winter, which was 95±161 μg m^{-3} and 78±189 μg m^{-3}, respectively. The average TVOC level recorded in this study was compared with average TVOC level (sum of 15 VOCs) obtained from a cross-countries and regions project (China, Hong Kong, Taiwan, Korea and Japan) conducted in 2002 (Guo et al. 2009). It was reported that the average TVOC level obtained in this study was higher than the measured in 100 homes in Hong Kong and Taiwan, which were 46.1±8.8 μg m^{-3} and 35±3 μg m^{-3}, respectively, while was significantly lower than the average TVOC level (sum of 15 VOCs) measured in China (N=94 homes), Korea (N=96) and Japan (N=97), with average of 186±15 μg m^{-3}, 180±21 μg m^{-3} and 188±31 μg m^{-3}, respectively ($p<0.00001$) (Guo et al. 2009). Although the average outdoor TVOC level was higher in summer (34±20 μg m^{-3}) than in winter (40±14 μg m^{-3}), the decreased of TVOC level in winter may due to different occupants activity at home as well as the higher indoor temperature in summer (5°C) may increase emissions of TVOC from indoor sources (Jia et al. 2008). The lower TVOC levels in winter were also reported in some countries, such as in Danish and southeast United States (Wolkoff et al. 1999; Jai et al. 2008). The φ of TVOC was 3.08 in summer and 1.69 in winter, which further indicated the possible indoor source and the R was 0.22 and 0.56 (significant, $p<0.01$).

The indoor CO_2 is regarded as a surrogate indicator of general IAQ and mainly generated by the occupants and cooking activities (Mui and Wong 2007a). The indoor CO_2 ranged from 320 ppm to 1320 ppm in summer and 336 ppm to 2262 ppm in winter. There is no significant difference of average CO_2 obtained between these seasons. The average CO_2 was 519±269 ppm in summer and 520±273 ppm in winter.

The measured indoor CO_2 level was lower than that previously reported from a case study conducted in Hong Kong (average was 611±95 ppm) (Lee et al. 2002b). The φ of CO_2 was 1.48 in summer and 1.42 in winter and the R was 0.30 in summer (significant, $p<0.05$) and 0.14 in winter.

The indoor sources of RSP and airborne particulates ($SP_{0.3}$ to SP_{10}) include combustion appliances, tobacco cigarettes, cooking, cleaning and use of consumer products. The indoor RSP ranged from 12 μg m^{-3} to 560 μg m^{-3} in summer and 25 μg m^{-3} to 289 μg m^{-3} in winter. The average RSP was lower in summer (101±87 μg m^{-3}) than in winter (112±57 μg m^{-3}). However, the average level was higher when compared with those in the previous studies in Hong Kong (average RSP was 78.8±25.9 μg m^{-3}) (Tung et al. 1999). The $SP_{0.3}$, $SP_{0.5}$, SP_1, SP_2, SP_5 and SP_{10} increased significantly from 118040±69897 L^{-3} to 172395±43830 L^{-3}, 20953±22603 L^{-3} to 39821±31522 L^{-3}, 1685±1765 L^{-3} to3804±5874 L^{-3}, 785±599 L^{-3}, 1454±923 L^{-3}, 51±50 L^{-3} to 97±163 L^{-3} and 6±7 L^{-3} to 8±7 L^{-3} in summer to winter, respectively.

Regarding the assessment conducted in summer, φ of IAQ parameters ranged from 0.65 to 3.08. For parameters ABC, CO_2, TVOC and SP_{10} having $\varphi>1$, indicated indoor levels of the surveyed residential apartments would source from outdoor.

Table 3.1: 13 measured parameters of high-rise residential apartments in Hong Kong.

Parameters(unit)	Summer (N=63)				Winter (N=88)			
	Indoor AM(ASD)	Outdoor AM(ASD)	I/O ratio	I/O correlation	Indoor AM (ASD)	Outdoor AM (ASD)	I/O ratio	I/O correlation
Thermal comfort								
T (ºC)	27 (3)	29 (3)	0.95	0.62[b]	22 (4)	22 (4)	1.00	0.82[b]
RH (%)	64 (13)	63 (12)	1.03	0.68[b]	65 (15)	58 (18)	1.09	0.82[b]
Air pollutant [a]								
CO (μg m^{-3})	2317 (1011)	2517 (1093)	0.99	0.15	2249 (656)	2311 (674)	0.97	0.74[b]
CO_2 (ppm)	519 (269)	351 (29)	1.48	0.30[c]	520 (273)	367 (27)	1.42	0.14
TVOC (μg m^{-3})	95 (161)	34 (20)	3.08	0.22	78 (189)	40 (14)	1.69	0.56[b]
RSP (μg m^{-3})	101 (87)	112 (90)	0.96	0.95[b]	112 (57)	112 (64)	1.06	0.89[b]
$SP_{0.3}$ (L^{-3})	118040 (69897)	138039 (67770)	0.86	0.83[b]	172395 (43830)	169197 (39781)	1.04	0.90[b]
$SP_{0.5}$ (L^{-3})	20953 (22603)	25376 (24150)	0.82	0.95[b]	39821 (31522)	36964 (26322)	1.08	0.89[b]
SP_1 (L^{-3})	1685 (1765)	2173 (2030)	0.76	0.95[b]	3804 (5874)	3217 (2371)	1.01	0.87[b]
SP_2 (L^{-3})	785 (599)	1114 (669)	0.71	0.80[b]	1454 (923)	1549 (948)	0.95	0.85[b]
SP_5 (L^{-3})	51 (50)	81 (60)	0.65	0.86[b]	97 (163)	97 (77)	0.87	0.81[b]
SP_{10} (L^{-3})	6 (7)	8 (9)	1.01	0.88[b]	8 (7)	9 (9)	1.27	0.65[b]
Bioaerosols								
ABC (CFU m^{-3})	430 (176)	66 (40)	7.86	0.02	272 (126)	216 (121)	1.61	0.21[b]
AFC (CFU m^{-3})	93 (62)	124 (178)	0.96	0.39[b]	133 (109)	145 (133)	1.20	0.25

[a]IAQ parameters only recorded in 57 apartments in winter.
[b]Correlation is significant at the 0.01 level (2-tailed).
[c]Correlation is significant at the 0.05 level (2-tailed).

Indoor bioaerosols level

The indoor airborne bacteria and fungi level recorded in living room of typical apartment in Hong Kong were approximated by a geometric distribution in this study ($p>0.05$, Chi-square test). A total of 63 and 88 apartments were investigated in summer and winter respectively. All the air samples were collected at the center of the living room and it was revealed that both airborne bacteria recorded in summer were significantly higher when compared with winter, and the mean airborne bacteria level recorded in summer and winter were 430±176 CFU m^{-3} and 272±126 CFU m^{-3}, respectively. However, the mean airborne fungi level recorded in summer were significantly lower when compared with that in winter, which were 93±62 CFU m^{-3} and 133±109 CFU m^{-3}, respectively. Both indoor AFC and ABC recorded in this study were significantly lower than that reported in previously studies in Hong Kong as well as with similar climates in Taiwan (Wong 1997; Lee et al. 1999, 2002b; Wu et al. 2000; Su et al. 2001). The reported concentration in this study was also relatively lower when compared with those in other countries (Jaffal et al. 1997; Garrett et al. 1997; Pastuzka et al. 2000; Ren et al. 2001; Haegreaves et al. 2003; Kalogerakis et al. 2005; Basilico et al. 2005; Lee and Jo 2006).

Air samples for investigating bacterial concentration were collected in living room and outdoor only. According to Basilico et al. (2007), the bacterial concentration was the highest in living room when compared with other two rooms, bedroom and kitchen; hence, bacterial concentration was measured in the living room only. Therefore, this study investigated the indoor airborne fungi level in different locations of the apartment. Indoor bioaerosols in 50 apartments were approximated by a geometric distribution in this study ($p>0.05$, Chi-square test). The airborne bacteria and fungi were detected in all of the indoor air samples. There were 2 apartments with visible mold growth and 5 apartments with pets. The overall GM of AFC and ABC recorded in these apartments were 135±1.9 CFU m^{-3} and 299±1.6 CFU m^{-3}, respectively. It was revealed that the highest AFC was recorded in the kitchen, followed by living room and bedroom. Similar observations were observed in Lee and Jo (2006) study, which was found that higher indoor bioaerosols concentrations were recorded in kitchen. The overall GM of AFC recorded in the kitchens was 137±2.0 CFU m^{-3}. It was reported that the relatively high indoor airborne fungi recorded in the kitchen might probably due to the different

environmental conditions, hygiene conditions as well as the activities (Lehtonen et al. 1993; Kalogerakis et al. 2005; Lee and Jo 2006). During periods of handling food, such as washing the vegetables as well as other food preparation, would increase the indoor AFC (Lehtonen et al. 1993; Lee and Jo 2006).

On the other hand, the overall average indoor AFC recorded in the living room was higher than the bedroom. The overall GM of AFC recorded in the living room and bedroom were 134±2 CFU m^{-3} and 125±2 CFU m^{-3}, respectively. Hargreaves et al. (2003) and Buttner and Stetzenbach (1993) also reported that the average AFC recorded in the living was higher than in bedroom although another study reported that there was no significant difference among these two areas (Ren et al. 2001). In the present study, it is believed that the difference in the AFC between the living room and the bedroom is probably due to different level of human activities. Since more settled fungal spores would be resuspended due to the air movements caused by human (Buttner and Stetzenbach 1993), and also the presence of more stuffs in the living rooms would also increase the AFC, such as plant, newspaper, food, pet, etc. Moreover, it is interesting that the overall average AFC recorded in the apartments with pets (N=5) was 110 CFU m^{-3}, which was higher than the other apartments without pets. Similar findings were also reported by Ren et al. (2001), the AFC was positively correlated with the presence of pets.

The seasonal differences on the distribution of the indoor bioaerosols inside an apartment were shown in Table 3.2. It was reported that the overall average of indoor AFC recorded in spring was significantly higher than that in winter ($p<0.05$). While the overall average of ABC recorded in spring was slightly lower than that in winter. It was similar to other studies which reported that the indoor bioaerosols levels were higher in warmer months than cooler months (Garrett et al. 1997; Pastuszka et al. 2000; Horner et al. 2004; Lee and Jo 2006; Sen and Asan 2009). It is probably due to difference in the environmental conditions, especially the T and RH. The average T recorded in spring (24.9°C) was higher than that in winter (20.2°C), while the average RH recorded in spring (71.1%) was also higher than that in winter (65.0%). Therefore, the higher T and RH in spring supported more indoor fungal growth. In addition, it is observed that the outdoor AFC recorded in spring was significantly higher than that in winter. The GM recorded in spring and winter were 154±1.7 CFU m^{-3} and 113±2.1 CFU m^{-3}, respectively. Since all the sampling locations were naturally ventilated, therefore the windows were always opened for increasing the air

change rates, thus the indoor AFC was also increased.

Table 3.2: Indoor bioaerosols level at different locations of the apartment.

Site	Winter (N=25)			Spring (N=25)		
	Range	AM (ASD)	GM (GSD)	Range	AM (ASD)	GM(GSD)
Airborne fungi						
Living room	18 – 398	143 (96)	114 (2.1)	40 – 494	188 (117)	157 (1.9)
Bedroom	16 – 390	136 (101)	105 (2.1)	58 – 400	169 (93)	147 (1.7)
Kitchen	16 – 478	156 (128)	118 (2.2)	66 – 458	190 (115)	161 (1.8)
Outdoor	14 – 402	138 (86)	113 (2.1)	72 – 470	179 (108)	154 (1.7)
Airborne bacteria						
Living room	112 – 618	328 (137)	299 (1.6)	104 – 678	322 (142)	294 (1.6)
Outdoor	14 – 402	280 (133)	235 (2.0)	64 – 456	246 (112)	219 (1.7)

Indoor airborne fungal composition

The composition of the indoor airborne fungi recorded in apartments is presented in Table 3.3. A total of 3343 and 4596 fungi isolates belonging to 12 and 13 fungal genera were identified in the winter and spring samples respectively. In general, *Cladosporium* was the most dominant fungal genera recorded in both indoor and outdoor environments during both seasons, followed by *Penicillium*, *Rhizopus* and *Aspergillus*. *Cladosporium* was detected in (i.e. OF) 96.0% and 94.7% of samples collected in the indoor environments during winter and spring, respectively; while detected in 100% and 92% of samples collected in the outdoor environments during winter and spring, respectively. This fungal genus contributed to (i.e. RA) 63.8% and 72.2% of total AFC recorded in indoor environment during winter and spring, respectively; and contributed to 64.2% and 76.7% of total AFC recorded in outdoor environments during winter and spring, respectively. *Cladosporium* was reported as dominant genus in other countries as well, such as Australia, Austria, Korea, Poland, Taiwan, Turkey and USA (Garrett et al. 1997; Pastuzka et al. 2000; Ren et al. 2001; Su et al. 2001; Horner et al. 2004; Lee and Jo 2006; Sen and Asan 2009).

The other commonly isolated fungal genera included, *Aspergillus*, *Penicillium* and *Rhizopus*, these fungal genera were detected in 26.7% to 48.0% of the indoors samples collected in winter and 12.0% to 82.7% of samples collected in spring, respectively; while these genera were detected in 16.0% to 92.0% of the outdoor samples collected in winter and 8.0% to 92.0% of samples collected in spring, respectively. *Aspergillus* and *Penicillium* are also regarded as dominant fungal

genera in the indoor collected from the residential buildings. The other fungal genera which detected in 9.1% and 12.3% of indoor samples collected in winter and spring, which contributed to 0.8% and 0.7% of total AFC, respectively. These fungal genera recorded in winter samples included *Acremonium*, *Alternaria*, *Aureobasidium*, *Chrysonilia*, *Fusarium*, *Geomyces*, *Stachybotrys*, *Trichoderma*, *Ulocladium*, *Wallemia* and Yeast; while *Botrytis*, *Curvularia*, *Memniniella* and *Scopulariopsis* were only detected in the spring samples and no *Geomyces* and *Wallemia* were detected.

Table 3.3: Profile of airborne fungi in apartments and outdoor environment of Hong Kong.

Fungal genus/ species	Indoor (N=25)				Outdoor (N=25)				I/O ratio	RIFE
	Distribution (%)		Count (CFU m^{-3})		Distribution (%)		Count (CFU m^{-3})		AM	
	OF	RA	Range	AM	OF	RA	Range	AM		
Winter										
Total	100	100	17 – 417	145	100	100	14 – 402	138	1.1	1.0
Aspergillus	26.7	1.4	0 – 14	2	16.0	0.3	0 – 4	0.4	4.7	7.8
Cladosporium	96.0	63.8	2 – 436	85	100	64.2	6 – 190	76.7	1.1	1.0
Penicillium	93.3	21.0	0 – 182	28	92.0	20.9	0 – 52	25.0	1.1	1.0
Rhizopus	48.0	3.5	0 – 24	5	56.0	2.7	0 – 14	3.3	1.4	1.1
Others	9.1	0.8	0 – 24	1	9.5	0.9	0 – 28	1	0.6	0.9
Spring										
Total	100	100	56 – 407	183	100	100	72 – 470	183	1.1	1.0
Aspergillus	12.0	0.2	0 – 4	<1	8.0	0.1	0 – 4	0.2	1.2	3.0
Cladosporium	94.7	72.2	0 – 406	133	92.0	76.7	22 – 448	136.2	1.0	1.0
Penicillium	82.7	16.6	0 – 338	30	88.0	11.7	0 – 70	20.7	1.5	1.3
Rhizopus	46.7	2.36	0 – 38	4	52.0	1.9	0 – 14	3.4	1.3	1.1
Others	12.3	0.7	0 – 28	1	12.0	0.8	0 – 36	1	0.4	0.9

When comparing the indoor fungal composition recorded at different locations in winter, it is revealed that the higher concentration of *Cladosporium* and *Rhizopus* were recorded in the kitchen, while the highest concentration of *Aspergillus* and *Penicillium* were recorded in bedroom and living room, respectively. Except for *Cladosporium* and *Aspergillus*, the highest concentration of *Penicillium* and *Rhizopus* were recorded in other locations when compared with the winter samples. The highest concentration of *Penicillium* and *Rhizopus* were recorded in bedroom and living room, respectively.

Purpose of Relative Index for Exposure of Indoor Bioaerosols

In order to study the relative risk of the indoor bioaerosols, this study proposed an index which can be regarded as a quantitative measure of the influence due to bioaerosols exposure risk in an indoor environment. In an indoor bioaerosols assessment, the I/O ratio of bioaerosols level is a common indicator of potential indoor bioaerosols sources and it has been used to attribute an indoor environment (Gots et al. 2003). The I/O ratio φ^* of a bioaerosol species or genus is determined by the bioaerosol level Φ_{in} (CFU m^{-3}), Φ_{ou} (CFU m^{-3}) of indoor and outdoor air samples in the same sampling time period, respectively.

$$\varphi^* = \frac{\Phi_{in}}{\Phi_{ou}} \quad \text{... (Eq. 3.2)}$$

This study reveals that the I/O ratio φ of bacteria in typical apartments of Hong Kong ranged from 0.3 to 5.7 with mean φ of 1.6±0.9. The ABC recorded in 68% of the apartments were higher than that of outdoor, the indoor concentrations recorded in these apartments were approximately 1.2 times greater than the outdoor levels. The reported mean I/O ratio φ of bacteria in Hong Kong was lower when compared with some of the other regions.

For the airborne fungi, the indoor AFCs recorded in 42% to 54% of samples collected in the living room, bedroom and kitchen were higher than that of the outdoor. The average I/O ratios recorded in kitchen, living room and bedroom were 1.1±0.6, 1.1±0.4 and 1.0±0.3, respectively. Since the I/O ratio was greater than 1, which indicated the indoor AFCs in some offices were higher than the outdoor ones. It was reported that the I/O ratio was probably affected by the environmental

conditions in both indoors and outdoors, such as air temperature, relative humidity, fluctuations in wind speed and turbulence in outdoors as well as the occupants activities (Kemp et al. 2003; Tsai and Macher 2005; Araujo et al. 2008).

For airborne bacteria, therefore $\varphi \geq 1$ was always reported in the literature since the major source indoors is from human. However, for airborne fungi, $\varphi \leq 1$ would be considered as 'acceptable' (Health Canada 2004), but suggestions of the 'acceptable' threshold of a ratio consistently more than two, with a fungi level exceeding 1000 spores m^{-3} has also been suggested as an 'acceptable' threshold in some cases (Burge 1990). This illustrates that it might be difficult to establish a universal exposure baseline or threshold for indoor airborne fungal exposure in indoor environments.

In detailed assessments of indoor environment with collective samples, the exposure risk of a bacterial/fungal species or genus would be described by the occurrence frequency and relative abundance. The occurrence frequency α_i of a bacterium/fungus is the percentage that the samples with the bacterium/fungus Φ_i presented in the total samples; and the relative abundance β_i is the total counts of the bacterium/fungus Φ_i as an percentage of the total ABC/AFC in all samples. When the species is present in a space, this index assumes that the occurrence frequency and the relative abundance are independent parameters, and a high value of either parameter will indicate a high exposure risk to the ABC/AFC concerned. Followed the hazard matrix concept, an indicative rating for exposure risk analysis can be expressed by the product of these two independent risk parameters (USDD 1993).

In order to quantify the influence on the bioaerosols exposure risk of an indoor environment relative to the outdoor environment, the indicative rating is 'normalized' by the outdoor value and the relative index of bacteria/fungi exposure (RIBE/RIFE) ϖ_i^* is proposed below,

$$\varpi_i^* = \alpha_i^* \beta_i^* \quad \text{... (Eq. 3.3)}$$

where the subscript i represents a bacterial/fungal species or genus, α_i^* is the occurrence ratio and β_i^* is the abundance ratio. The α_i^* and β_i^* measure the relative exposure risk of the bacterial/fungus regarding the number of samples and the total ABC/AFC in all collected samples that correspond to the outdoor are given below,

$$\alpha_i^* = \frac{\alpha_{i,in}}{\alpha_{i,ou}} \quad \text{... (Eq. 3.4)}$$

where $\alpha_{i,in}$ and $\alpha_{i,ou}$ are the occurrence frequency of the bacterium/fungus i in the indoor and outdoor samples, respectively,

$$\beta_i^* = \frac{\beta_{i,in}}{\beta_{i,ou}} \quad \text{... (Eq. 3.5)}$$

where $\beta_{i,in}$ and $\beta_{i,ou}$ are the relative abundance of the bacterium/fungus i in the total ABC/AFC of the indoor and outdoor samples, respectively.

When regarding the occurrence frequency of bacterium/ fungus i, ratios of $\alpha_i^*=1/\alpha_i^*$ >1 represent the indoor environment associated with an equal/ higher exposure as in outdoor environment, respectively. On the other hand, when regarding the relative abundance of bacterium/ fungus i, $\beta_i^*=1/\ \beta_i^*>1$ represent the indoor environment associated with an equal/ higher exposure as in outdoor environment, respectively.

The RIBE/RIFE index ϖ_i^* is used to express the relative overall exposure risk associated with an indoor environment compared with the outdoor. A RIBE/RIFE index of '1' indicates an indoor exposure risk is equal to that of the outdoor, and an index >1 indicates a higher exposure risk in the indoor environment as compared to the outdoor.

In order to evaluate the fungi exposure risk of occupants, this study has examined the feasibility of the RIFE index ϖ_i^*, through investigations of airborne fungi levels, the I/O ratios and compositions recorded in the assessments of this study (shown in Table 3.3). The RIFE can be regarded as a quantitative measure of the influence due to the fungal exposure risk in an indoor environment. By using this index, the evaluation of an assessment of indoor bioaerosols could be improved with an indication of the relative overall exposure risk associated with an indoor environment compared with the outdoor. It could also provide a useful reference for the assessment of the relative fungal exposure risk in indoor environments in addition to the I/O ratio which only compared the abundance.

As shown in Table 3.3, the RIFE of the dominant fungal genera ranged from 0.9 to 7.8 in samples collected in winter, while ranged from 0.9 to 3.0 in samples collected

in spring. The RIFE of all dominant fungal genera were equal or higher than 1. It is observed that the RIFE of *Cladosporium* and *Rhizopus* were the same in the samples collected from winter and spring. While the RIFE of *Aspergillus* recorded in the winter samples was higher than that in spring and RIFE of *Penicillium* recorded in the winter was lower than that in spring. Therefore, in general, the exposure risk of these domain fungal genera in indoor environment was higher than that of outdoors, and the risk was higher in winter than in spring.

In winter, *Cladosporium* and *Penicillium* were the dominant indoor fungi in the apartments, and their average I/O ratios were the same ($\varphi^* = 1.1$). This might not give a clear indication of indoor sources. It was also reported that the RIFE ϖ^* of *Cladosporium* and *Penicillium* were also the same (1.0), which indicated an equal relative indoor exposure risk as compared with that of the outdoors. While the RIFE ϖ^* of *Aspergillus* were 7.8 which indicated a higher relative indoor exposure risk as compared with that of the outdoors. In other words, occupants exposed to more *Aspergillus* indoors. *Aspergillus* can induce allergic diseases or syndromes, infectious diseases like Aspergillosis, and the genus produces a wide range of mycotoxins, including aflatoxin B1, ochratoxin A, and sterigmatocystin (Kurup et al. 2002; Jarvis and Miller 2005). For *Rhizopus*, the average I/O ratio was 1.4, which indicated possible presence of indoor sources in some offices for these fungi. However, careful examination revealed that although the average relative abundance of *Rhizopus* recorded in indoor (3.5%) was higher than the outdoor (2.7%), *Rhizopus* was found in more samples outdoors than indoors. The RIFE of *Rhizopus* was 1.1, so that the relative indoor exposure risk was a little bit higher as compared with that of the outdoors. Similar RIFE of dominant fungal genera were observed in spring, except for *Aspergillus* and *Penicillium*.

Case study: The influence of IAQ on patient with chronic obstructive pulmonary disease (COPD)

COPD is one of the leading causes of death, which is the fifth leading cause of death in Hong Kong. The relationship between urban air pollution and its short-term health effects on patients suffering from COPD is confirmed. Despite the finding that urban air pollution (mainly the particulate matter) is associated with increased mortality and hospital admission rates in patients with COPD (Ko et al. 2007; Sunyer 2001), an understanding of the impact of indoor air pollution upon quality of life (QOL) for patients with COPD is still lacking.

In a long-term study of the relationship between five major air pollutants (i.e. SO_2, RSP, NO_2, CO, and O_3) and hospital admissions for COPD in a tropical city (Kaohsiung, Taiwan), statistically significant positive results were found in all pollutants with only one exception – SO_2 on warm days (≥25°C) (Lee et al. 2007). Similarly in Hong Kong, multivariate analysis showed that SO_2, NO_2, and O_3 had a greater effect on COPD admissions in the cold season (December to March) than in the warm season (Ko et al. 2007). These findings provide evidence that higher levels of ambient pollutants increase the risk of hospital admission for COPD during winter season in tropical and subtropical cities.

Moreover, QOL was demonstrated strongly related to the number of yearly and past exacerbations in patients with COPD, although there was no relation between hospital admission and exacerbation frequency because not all of the exacerbations required hospital admission (Donaldson et al. 2002; Ko et al. 2007; Seemungal et al., 1998). Through a cross-sectional survey, this study investigates such impact in terms of the scores of the (Chinese) chronic respiratory questionnaire (CCRQ) and the measurements of IAQ, lung function and Moser's activities of daily living (ADL). Using Yule's Q statistic with a cutoff $|Q|>0.7$ to identify the strong relationships between environmental parameters and CRQ sub-scores. As the CRQ developed by Guyatt et al. (1987) is one of the most prevalent health-related quality of life (HRQOL) instruments for pulmonary rehabilitation programme (PRP) (Lacasse et al. 2002) and has advantages over some of the other outcome variables or QOL questionnaires which are more responsive to the effect of pulmonary rehabilitation (Singh et al. 2001; de Torres et al. 2002), it is the preferred QOL assessment tool, and

CCRQ was employed in this study (Chan et al. 2006).

Target participants

In a cross-sectional study, data was collected from patient interviews via home visits. Forty-one patients with COPD were recruited by convenience sampling, a method which is most useful for pilot testing. Invitations, together with the study objectives and survey details, were sent to five selected self-help groups for people with COPD. Prior to commencement of the study, which was carried out in accordance with the principles of the Declaration of Helsinki, all participants provided written informed consent. Ethical approval was also sought from The Hong Kong Polytechnic University (Reference: HSEAR20070308001). Each participating patient was interviewed twice through two seasonal surveys – the first (Measurement A) was conducted in a summer while the second (Measurement B) was conducted in the winter of the same year, 6 months apart. Participant dropout did not occur between the surveys. Each interview lasted for about 3 h. A target-oriented questionnaire was employed to assess the influence of IAQ parameters on patient QOL. Patients with other lung diseases including active tuberculosis, lung cancer, and cardiac complications such as ischemic heart disease were excluded.

Chronic Respiratory Questionnaire (CRQ)

Reproducible and sensitive to change, this questionnaire is an established measure of health status for patients with COPD in four dimensions, namely dyspnoea, fatigue, emotion, and mastery (Guyatt et al. 1987; Siafakas et al. 1995). Via a list of validated questions, patient QOL can be assessed on a 7-point Likert-type scale ranging from 1 for ‘maximum impairment’ to 7 for ‘no impairment.’ In this study, a Chinese version of the questionnaire (Appendices I) was administered as a structured interview performed by a registered occupational therapist.

Lung function tests

Lung function values including mainly the forced expiratory volume in one-second (FEV1) of two standard deviations below the predicted score, which is a diagnostic test for COPD, and the ratio of it to forced vital capacity (FEV1/FVC), and peak expiratory flow (PEF; for suspected asthma) were chosen for this study because they are the most common figures showing airflow limitation and provide useful

quantitative criteria of health status for patients with COPD (Sunyer 2001). Previous literature has shown that a small respiratory infection will lead to a decline in FEV1 (Fletcher and Peto 1977). Furthermore, arterial oxygen saturation (SaO_2) values during specified indoor activities (i.e., at rest SaO_2,rest; after walking on level ground for 2 min SaO_2,indoor; after sitting and standing repeatedly for 2 minutes SaO_2,sit) were measured. SaO_2 measurement is an initial assessment tool for moderate to severe COPD (van Dijk et al. 2004) (Appendices II).

Moser's Activities of Daily Living (ADL) class

A classification system of functions developed in an attempt to classify patients with COPD according to their functional pulmonary disability into five levels: level 1 indicates patients with no substantial restriction of instrumental activities of daily living tasks and level 5 indicates those who are confined to bed or chair most of the day (Moser et al. 1980). It has been used quite commonly with the COPD Disability Scale established by the American Thoracic Society in most of the pulmonary rehabilitation programs in Hong Kong. In this study, the therapist rated the patient activities by asking all of the patients to grade their respective actual ADL performances over a 2-week period immediately preceding the interview.

Under the assumptions that the paired differences were independent and identically normally distributed, paired t-test was performed to test the null hypothesis of no difference between Measurements A and B. Shapiro-Wilk's test was also applied to test the normality at a significance level of 0.01.

Under the null hypothesis of zero correlation, regression line can be tested using Equation (3.5), a t-distribution with N−2 degrees of freedom, where R is the sample correlation coefficient and N is the total number of data pairs for the regression line,

$$t_{distribution} = \frac{R\sqrt{N-2}}{\sqrt{1-R^2}} \qquad \text{(Eq. 3.6)}$$

The characteristics of the 41 COPD patients surveyed are shown in Table 3.5. With a mean age of 69.3 (18 women and 23 men; aged from 40 to 89), this patient group had a mean ADL score of 1.98±0.85. The number of patients observed in the ADL scale levels 1, 2, 3, 4, and 5 was 14, 15, 11, 1, and 0, respectively. The mean of the forced expiratory volume (FEV) was 45±24% while that of PEF was 50±27%. As the mean of lung function impairment in terms of FEV1/FVC was 61%±20%, most of

the surveyed patients were having moderate COPD. The relatively high % of variation may due to different functional pulmonary disability of the patient (average was 1.98). All patients stayed home at least 16 hr per day, with an average daily indoor time of 21±2.6 hr.

Table 3.4: Characteristics of 41 patients with COPD[a].

Patient characteristics	Summer	Winter
	Basic information	
Age	69.3 (11.9) 73*	
Gender: M/F	23/18	
Daily indoor time (hr)	21.0 (2.6) 21.5*	
Moser's ADL class	1.98 (0.85) 2*	
	Lung Function	
FEV1 (%)	44 (24) 38*	46 (24) 48*
FEV1/FVC (%)	62 (21) 61*	60 (19) 58*
PEF (%)	48 (28) 39*	52 (27) 46*
SaO2,rest (%)	96 (2) 96*	96 (2) 97*
SaO2,indoor (%)	92 (5) 94*	91 (5) 93*
SaO2,sit (%)	93 (4) 94*	93 (4) 94*
	CRQ sub-scores	
Dyspnoea	5.16 (1.46)	5.41 (1.12)
Fatigue	4.08 (1.21)	4.46 (1.07)
Emotion	5.37 (1.25)	5.41 (1.16)
Mastery	5.67 (1.18)	5.62 (1.03)

[a] Values shown: average; standard deviation in brackets; median with an asterisk.

8 of the 41 patients were on oxygen therapy. The mean levels for $SaO_{2,rest}$, $SaO_{2,indoor}$ and $SaO_{2,sit}$ were 96±2%, 92±4% and 93±4%, respectively. No significant differences between the collective averages were found in the two measurements ($p \geq 0.1$, paired t-test). The average CRQ sub-scores for the patients were 5.27, 4.26, 5.39 and 5.65 regarding dyspnoea, fatigue, emotion and mastery respectively. There were no significant differences detected between the collective results ($p \geq 0.1$, paired t-test) in the measurements conducted in summer and winter. All lung function indicators and CRQ sub-scores were assumed normally distributed ($p \geq 0.01$,

Shapiro-Wilk's test); except for the FEV1/FVC and PEF scores measured in winter ($p \geq 0.01$, Shapiro-Wilk's test).

Environmental condition

Table 3.6 shows the environmental characteristics obtained in the patient apartments and the corresponding outdoor environments. PM_{10} mass concentrations did not indicate any seasonal variation ($p \geq 0.3$, paired t-test). Likewise, there were no significant differences between other indoor and outdoor readings when comparing samples collected in both seasons ($p > 0.05$, paired t-test), except for: indoor and outdoor temperatures ($p < 0.001$, paired t-test); indoor RH ($p < 0.05$, paired t-test); indoor particles in the size range 0.5–5 μm ($p \leq 0.05$, paired t-test); and outdoor *Penicillium* sp. ($p < 0.0005$, paired t-test). The IAQ index, which is the average fractional dose within the 8-h exposure limits of indoor PM_{10}, CO_2 and TVOC in the workplace and a screening indicator for unsatisfactory IAQ (Hui et al. 2008), also suggested insignificant seasonal variation ($p > 0.05$, paired t-test).

Table 3.5: Environmental characteristics (at patient's apartments).

Parameter	Summer [a]		Winter [a]	
	Indoor AM (ASD)	Outdoor AM (ASD)	Indoor AM (ASD)	Outdoor AM (ASD)
PM_{10} (μgm^{-3})	99.6 (64)	116 (70.2)	105 (56)	101 (62.6)
CO_2 (ppm)	517 (302)	352 (26.5)	523 (326)	360 (28.9)
CO (μgm^{-3})	3124 (5155)	2664 (1279)	2259 (752)	2330 (763)
T (°C)	26.8 (2.9)	28.3 (3.7)	23.2 (3.1)	23.5 (4.2)
RH (%)	58 (12)	59 (12)	66 (13)	64 (16)
TVOC (μgm^{-3})	107 (170)	36.7 (13.5)	93 (238)	41.6 (14.6)
SP0.3 (L^{-1})	130006 (72590)	144308 (67159)	161075 (47373)	15733 (42943)
SP0.5 (L^{-1})	23218 (23864)	27969 (25646)	39227 (34180)	35441 (26923)
SP1 (L^{-1})	1949 (2007)	2527 (2512)	4146 (7203)	3300 (2607)
SP2 (L^{-1})	893 (659)	1243 (734)	1482 (958)	1614 (995)
SP5 (L^{-1})	64.2 (58.1)	97.0 (66.3)	102 (199)	92.0 (70.4)
SP10 (L^{-1})	7.67 (7.89)	10.4 (10.0)	7.85 (7.98)	8.49 (7.99)
AFC (CFU L^{-1})	95.4 (67.4)	151 (182)	120 (111)	151 (183)
Aspergillus (CFU L^{-1})	12.4 (17.0)	12.5 (13.3)	18.7 (22.9)	10.5 (13.7)
Cladosporium (CFU L^{-1})	49.3 (55.6)	106 (191)	55.4 (52.6)	66.4 (101)
Penicillium (CFU L^{-1})	11.6 (16.0)	8.46 (12.2)	18.1 (22.9)	24.4 (22.6)
IAQI	0.42 (0.20)	–	0.42 (0.28)	–

[a] '–' represents no data is collected.

The corresponding data of Air Pollution Index (API) and its six contributing air pollutants, viz. SO_2, PM_{10}, NO, NO_2, O_3 and CO, gauged at Hong Kong Observatory stations are shown for reference (Table 3.7). API is calculated by taking the maximum of subindices of scale extending from 0 to 500 among all the parameters measured to indicate the overall pollution level: a subindex level of 100 corresponds to no adverse acute health effects to human while a level of 500 corresponds to significant harm to human health (Yau and Pun 2008). From the station data, the exposure levels of SO_2, CO and O_3 were significantly different between the two seasons ($p \leq 0.01$, paired t-test). As more than half of the station CO concentrations were noted below detection limits, CO exposure level was not used in the QOL evaluation.

Table 3.6: Environmental characteristics (At Hong Kong observatory stations).

Parameter	Summer	Winter
	AM (ASD)	AM (ASD)
API	47.6 (17.7)	47.0 (16.8)
(Station) SO_2 (μgm^{-3})	24.5 (19.1)	19.4 (18.6)
(Station) PM_{10} (μgm^{-3})	68.9 (38.1)	58.7 (33.4)
(Station) NO (μgm^{-3})	119 (68.2)	146 (86.2)
(Station) NO_2 (μgm^{-3})	62.7 (22.7)	70.5 (29.4)
(Station) O_3 (μgm^{-3})	58.4 (40.3)	36.7 (30.8)
(Station) CO (μgm^{-3})	1144 (227)	781 (507)

Although indoor $PM_{2.5}$ was not a monitoring parameter in this study, its particle counts were measured for comparison. By assuming that average particle density is the same for all particle sizes (Chao and Wong 2002), mass concentrations for particles that fell within the size range of 2.5–10 μm were approximated from the measured particle counts. For there were no significant differences detected between the weighted-average densities of particle size ranges <2.5 μm and 2.5–10 μm ($P \geq 0.2$, t-test), the assumption should be applicable. This study revealed that under the assumption, the weight contribution of larger particles SP_2 and SP_5 (i.e., 2–10 μm) was 70–80% while that of fine particles $SP_{0.3}$ (i.e., 0.3–0.5 μm) was only 4–8%.

A number of studies reported that outdoor particle mass concentrations of particulate matter PM_{10} and $PM_{2.5}$ had influences on COPD admission rate (Ko et al. 2007). If patients with COPD spend long time indoors, then I/O pollutant correlations will be important in a residential environment. Based on the air pollutant particle counts measured from the surveyed apartments in this study, there were significant I/O correlations ($R \geq 0.74$, $P < 0.0001$, t-test). Except for $SP_{0.3}$, correlations were significant among particle counts of different sizes both outdoors ($R \geq 0.5$, $P \leq 0.0001$, t-test) and indoors ($R \geq 0.6$, $P \leq 0.0001$, t-test). PM_{10} mass concentrations correlated with particle counts for all sizes ($R \geq 0.3$, $P \leq 0.05$, t-test) except SP_5. As it was noted that there would be some correlations between indoor PM_{10} level and SP_5 ($P = 0.097$, t-test), PM_{10} concentration could be a valid surrogate indicator for monitoring environmental quality in the surveyed apartments if fine particles were a concern. The relationship between outdoor ϕ_1 and indoor ϕ_2 particle concentrations

can be expressed by Equation (3.7), where i = 1–7 are the parameters for PM_{10}, $SP_{0.3}$, $SP_{0.5}$, SP_1, SP_2, SP_5, and SP_{10}, respectively, C_1 is the regression constant and ε is the zero mean error term approximated by a normal distribution with a standard error C_2,

$$\phi_{2,i} = C_{1,i}\phi_{1,i} + \varepsilon(C_{2,i}) \quad \text{(Eq. 3.7)}$$

The constants C_1 and C_2 for Equation (3.6) are exhibited in Table 3.8. Indoor particle concentrations were found generally lower than the outdoor levels by 67 % to 99.8%. This percentage indicated that the outdoor–indoor penetration was closer to unity for finer particles. A significant correlation was reported between the particle size and the I/O particle count ratio ($R = -0.868$, $p < 0.05$, t-test). Moreover, the average I/O ratio of PM_{10} (i.e., $C_1 = 0.9085$) was within the range of PM10 I/O ratios (0.88–1.04) resulted from an earlier measurement for Hong Kong apartments (Chao and Wong 2002).

Table 3.7: Constants for Equation (3.6).

Pollutants	PM_{10}	$SP_{0.3}$	$SP_{0.5}$	SP_1	SP_2	SP_5	SP_{10}
Constants	i = 1	2	3	4	5	6	7
C1	0.9085	0.9977	0.9015	0.8272	0.8135	0.7338	0.6710
C2	0.0252	0.017	0.0319	0.0304	0.0346	0.0356	0.0462

Effect of the environmental factors on health of COPD patients

This study assumed that a change of the environmental exposure level in a patient's apartment would associate with a change in the patient's CRQ sub-scores. To further analyze the data on an individual basis, 2 × 2 contingency tables were employed to compute for: concordant positive (CP) and concordant negative (CN) – the number of increment and decrement cases, respectively, in which both the environmental parametric value and CRQ sub-score increase; discordant positive (DP) – the number of cases in which the environmental parametric value increases while the CRQ sub-score decreases; and discordant negative (DN) – the number of cases in which both the environmental parametric value and CRQ sub-score decrease. A total of 21 × 4 = 84 cases were considered, i.e., 21 environmental parameters (including 14 indoor parameters, viz. PM_{10}, CO_2, CO, T, RH, TVOC, $SP_{0.3}$, $SP_{0.5}$, SP_1, SP_2, SP_5,

SP_{10}, AFC, IAQI; and 7 outdoor parameters, viz. API, SO_2, PM_{10}, NO, NO_2, O_3, CO) times 4 CRQ sub-scores (for dyspnoea, fatigue, emotion, and mastery). Association between a CRQ sub-score and an environmental parameter for each of the 84 cases can be measured by Yule's Q statistic given by Equation (3.8) below; where cases of $Q < 0.5$, $0.75 > Q \geq 0.5$, and $Q \geq 0.75$ suggest weak, moderate, and strong relationships, respectively (Knoke et al. 2002; Mui et al. 2009b).

$$Q = \frac{CP\ x\ CN - DP\ x\ DN}{CP\ x\ CN + DP\ x\ DN} \qquad \text{(Eq. 3.8)}$$

Table 3.8 presents 23 cases (out of 84) of moderate to strong correlations based on a cutoff $|Q|>0.7$ regarding the four CRQ sub-scores. A negative Q value indicates that a degraded environment attributed to an increased pollutant level will lead to a drop in the CRQ sub-score. It was noted that three parameters namely AFC, T, and RH had positive Q values; a result of Hong Kong winter weather – lower temperature and lower RH. Reportedly, COPD admission rate during the winter in Hong Kong is higher (Ko et al. 2007). It was also noted that in the same range of environmental conditions, increased indoor airborne fungi counts were related to a warmer and more humid environment.

Table 3.8: Influence of air quality on QOL in patients with COPD.

Parameter	Max. change	Q-statistics	Unit increment δ	Likelihood ratio L_r	Proportion	$\theta_{0.5}$	$\theta_{0.8}$
Dyspnoea							
AFC	252 (CFU L^{-1})	0.71	27.2	2.7	9.27	0.9	1.6
Fatigue							
$SP_{0.5}$	91287 (L^{-1})	−0.73	−56627	1.9	−1.61	0.7	3.8
SP_2	3483 (L^{-1})	−0.75	−788	1.8	−4.42	0.6	2.4
SP_5	294 (L^{-1})	−0.73	−36.7	1.9	−8.01	0.4	0.6
Mastery							
(Station) PM_{10}	145 (μgm^{-3})	−0.72	−417	3.9	−0.35	2.0	4.0
(Station) NO_2	90 (μgm^{-3})	−0.71	−217	3.5	−0.41	5.0	8.0
Emotion							
PM_{10}	222 (μgm^{-3})	−0.89	−506	6.7	−0.44	2.5	4.6
CO	3960 (μgm^{-3})	−0.86	−2756	6.8	−1.44	2.1	10
T	13.6 (°C)	0.96	67.5	5.8	0.20	2.3	3.3
RH	41 (%)	0.82	145	5.7	0.28	2.1	4.5
$SP_{0.3}$	197032 (L^{-1})	−0.80	−891418	4.2	−0.22	2.5	6.0
$SP_{0.5}$	91287 (L^{-1})	−0.98	−278640	14	−0.33	2.3	3.3
SP_1	6164 (L^{-1})	−0.99	−19697	16	−0.31	2.4	3.5
SP_2	3483 (L^{-1})	−0.81	−6514	3.1	−0.53	2.1	2.7
SP_5	294 (L^{-1})	−0.91	−473	6.4	−0.62	2.0	3.8
SP_{10}	30 (L^{-1})	−0.96	−48.7	12	−0.61	3.2	4.0
AFC	252 (CFU L^{-1})	0.89	221	8.3	1.14	2.1	5.3
(Station) SO_2	28 (μgm^{-3})	−0.76	−16.7	4.3	−1.70	1.7	3.8
(Station) PM_{10}	145 (μgm^{-3})	−0.89	−220	7.5	−0.66	3.6	4.8
(Station) NO	139 (μgm^{-3})	−0.87	−421	6.0	−0.33	7.0	7.0
(Station) NO_2	90 (μgm^{-3})	−0.75	−173	3.4	−0.52	3.6	6.7
(Station) API	57 (−)	−0.89	−141	7.6	−0.40	2.1	3.4
IAQI	1.31 (−)	−0.77	–1.24	4.2	−1.06	2.8	6.7

From the table, the CRQ emotion domain score and most (17 of 21) environmental parameters were sufficiently correlated. In other words, patient emotion was the most sensitive indicator for tracing environmental changes.

On the basis that an environmental change is a suggestion of possible QOL degradation, the likelihood ratios L_r (of the selected environmental parameters as shown in Table 3.8) were determined for the positive indications of the CRQ sub-score decrement and are expressed by,

$$L_r = \begin{cases} \dfrac{P_s}{1-P_s}; Q > 0 \\ \dfrac{1-P_f}{P_s}; Q < 0 \end{cases} ; P_s = \frac{CP}{CP+DN} \; ; P_f = \frac{CN}{CN+DP} \qquad \text{(Eq. 3.9)}$$

P_s and P_f, the sensitivity and specificity indicators according to the changes of an environmental parameter, refer to the ability of an indication to identify an environment that does and does not have a degraded QOL, respectively.

Alternatively, L_r can be determined from all patient cases N_p by counting the number of correctly identified patients who are suffering with the degraded environment as indicated by the monitored environmental parameter, with $N_{p,0}$ symbolizing those incorrectly identified patient cases,

$$L_r = \frac{N_P - N_{p,0}}{N_{p,0}} \qquad \text{(Eq. 3.10)}$$

As the likelihood ratios for the CRQ emotion domain score were generally larger than 3, with some larger than 10, this study revealed that at least 75% of the surveyed patients (i.e., 3:1) would suffer emotionally in a degraded environment. For the CRQ mastery domain score, the likelihood ratios with respect to the station PM_{10} and NO_2 values were about four and that suggested poor outdoor air quality would affect patient activity. Comparatively, the influence of air quality on dyspnoea and fatigue was less significant.

The corresponding maximum changes of environmental exposure levels are also shown in Table 3.8. The average unit increment δ_{ij} in terms of the environmental parameter ϕ_i and the unit change of corresponding CRQ sub-score ϕ_j is,

$$\delta_{ij} = \frac{1}{N_p} \sum_{k=1}^{N_p} \left(\frac{\phi_{i,2} - \phi_{i,1}}{\phi_{j,2} - \phi_{j,1}} \right)_k \qquad \text{(Eq. 3.11)}$$

Proportion is a hypothetical ratio of the maximum change to the average unit increment δ for indicating the sensitivity of an environmental parameter to the CRQ

sub-score. As the proportion values displayed in Table 3.8 were evaluated via linear extrapolation without examining a threshold value, they did not indicate any maximum change in the CRQ sub-scores surveyed.

To evaluate the use of δ_{ij}, goodness-of-fit was examined by applying the odds ratio θ as given by Equation (3.12) below, where $N_{p,1}$ is the number of correctly indicated patient cases with the predicted CRQ sub-score ϕ_p lying within the chosen acceptable error limits ϕ^* when compared with the observed CRQ sub-score ϕ_o, while $N_{p,2}$ is the number of correctly indicated patient cases with ϕ_p lying outside ϕ^*. It should be noted that $N_{p,0}$ is the number of all incorrectly indicated patient cases (in which patients with an increased CRQ sub-score were found in a degraded environment and vice versa) and thus is excluded from the equation.

$$\theta = \frac{N_{p,1}}{N_{p,2}}; \begin{cases} N_{p,1} : \left|\phi_o - \phi_p\right| \le \phi^* \\ N_{p,2} : \left|\phi_o - \phi_p\right| > \phi^* \end{cases}; N_p = N_{p,0} + N_{p,1} + N_{p,2} \qquad \text{(Eq. 3.12)}$$

The odds ratios $\theta_{0.5}$ and $\theta_{0.8}$ determined for two chosen error limits $\phi^* = 0.5$ and 0.8, respectively, to show the prediction sensitivity is exhibited in Table 3.8.

As the results of $\theta_{0.5}$ for the CRQ dyspnoea and fatigue domain scores were low (<1), the predictions did not fit the survey data well and that was consistent with the likelihood ratio test. With respect to the CRQ emotion domain score, the values of $\theta_{0.5}$ ranged from 1.7 to 7 for the station parameters: 7 for NO; 3.6 for both PM_{10} and NO_2; and 2.1 for API. The differences revealed that the overall API level is not adequate for emotion evaluation. Furthermore, the odds ratios were found higher for finer particles. It was reported that the concentration level of both fine and coarse particles had a significant impact on patient emotion (i.e., $\theta_{0.5} > 2$). In the size range below 10 μm, more patients would be emotionally affected by high concentrations of fine particles. IAQI, as an indicator which addresses basic IAQ issues including dilution, filtration, and emission control, showed a good correlation with patient response. As $\theta_{0.5}$ for IAQI was slightly higher than $\theta_{0.5}$ for PM_{10} (i.e., 2.8 vs. 2.5), the other two contributors of IAQI, viz. TVOC and CO_2, might have some indications for patient QOL.

This study revealed that no significant differences were found between the assessment results in the two periods regarding lung function measurements and CRQ scores. There were no significant differences between indoor and outdoor

environmental parametric levels ($p > 0.05$, paired t-test), except for ($p \leq 0.05$, paired t-test): indoor and outdoor temperatures; indoor RH; indoor particles in the size range 0.5–5 μm; and outdoor *Penicillium* sp. For the data recorded from the regional environmental monitoring stations, the exposure levels of carbon monoxide (CO), SO_2 and O_3 showed significant seasonal variations ($P \leq 0.01$, paired t-test).

With environmental conditions of studied apartments shown in Table 3.5, it was indicated that the IAQ index significantly correlated with its contributors CO_2, PM_{10}, and TVOC ($p \leq 0.0001$, t-test). Correlations were significant among particle counts of different sizes both indoors and outdoors, except for particle size 0.3 μm to 0.5 μm. If fine particles are a concern, then PM_{10} mass concentration can be a surrogate indicator for monitoring environmental quality in the surveyed apartments. Moreover, the patients with COPD surveyed were found staying predominantly at home. Using Yule's Q statistic with a cutoff $|Q|>0.7$ to identify the strong relationships between environmental parameters and CRQ sub-scores, this study revealed that patient emotion was strongly associated with indoor environmental parameters although the evidence of a causal relationship between them necessitated further research.

Conclusions

This study investigated the indoor airborne bacteria and fungi level as well as other environmental parameters in 103 typical apartments in residential buildings of Hong Kong. The average indoor airborne bacteria and fungi level recorded in summer were 430 CFU m^{-3} and 93 CFU m^{-3} respectively; while the average indoor airborne bacteria and fungi level recorded in winter were 272 CFU m^{-3} and 133 CFU m^{-3} respectively. Investigation of indoor airborne fungi at different locations (i.e. living room, bedroom and kitchen) within the same apartment revealed that the highest concentration was recorded in the kitchen, followed by living room and bedroom. In order to study the relative risk of the indoor bioaerosols, this study proposed a 'relative index for exposure of indoor bioaerosols' which can be regarded as a quantitative measure of the influence due to bioaerosols exposure risk in an indoor environment. And the indoor airborne fungi composition was used as an example to illustrate the use of this proposed index. Furthermore, the impact of some common air pollutants including the indoor bioaerosols upon the QOL in patients with COPD was investigated.

Chapter 4 Indoor Bioaerosols in Commercial Office Buildings

Introduction

As reviewed in Chapter 2, currently, there is no universal standard on the number and type of parameters in the IAQ assessment guideline. The HKEPD IAQ certification scheme covered commonly assessed parameters (N=12) with relatively high exposure limit level. Despite the relatively large number of epidemiological, clinical and toxicological studies related to indoor bioaerosols exposure conducted, the importance of assessing indoor bioaerosols in IAQ investigations has not been well demonstrated. Moreover, the indoor airborne bacteria are the only assessed bioaerosols parameter in most of the existing guidelines/schemes. In order to prove the importance of indoor bioaerosols, the importance of the indoor airborne bacteria and fungi in an IAQ assessment are evaluated.

Hong Kong is taken as a typical example to study such importance. Firstly, based on the data reported by the previous studies (Database A), the importance of assessing indoor bioaerosols in IAQ investigation, Bayesian assessment of acceptable bioaerosols levels and thermal environmental interference were reviewed. Secondly, the regional cross-sectional database (Database B) was constructed to further enrich the database.

Most of the commercial buildings in Hong Kong are equipped with MVAC systems which help maintain good IAQ through adequate ventilation with filtration and provide thermal comfort. A multiple chiller plant is usually designed for supplying chilled water to the airside equipment, which is located in different floors or zones. Depending on different airside designs, it can be divided into variable air volume (VAV), constant air volume (CAV) and FCU systems. VAV systems are now the most prominent airside system designs for commercial buildings of Hong Kong, which was introduced in 1970′s, while the indoor temperature control, VAV static pressure control, AHU supply air temperature control, outdoor ventilation flow control are some examples of typical local controls in VAV (Wang and Jin 2000; Mui 2002).

Due to outdoor conditions and indoor loads, the optimal settings of these set points can be changed accordingly.

Importance of Assessing Indoor Bioaerosols in IAQ Investigation

Assessments of bioaerosols are important in IAQ investigations, however, the contributions of unsatisfactory IAQ due to the airborne bacteria and fungi in air-conditioned offices are unknown. Except for the airborne fungi, the criteria of other IAQ parameters have been set in the form of regulations or guidelines in Hong Kong as well as other countries and cities (Health Canada 1987; ENV 1996; Environment Australia 2001; WHO 2005). As mentioned in Chapter 2, according to HKEPD IAQ certification scheme, the IAQ of the air-conditioned offices can be classified into 'Good' and 'Excellent' levels based on the exposure limits of 12 listed IAQ parameters.

The acceptability of IAQ of an indoor environment can be judged by referring to some suggested exposure limits of the selected assessment parameters for the minimum IAQ provision. Therefore, an indoor environment is considered to have 'unsatisfactory IAQ' when any one of the specified independent parameters 'i' of measured concentration Φ_i exceeding the exposure limit $\Phi_{i,e}$, i.e. $\Phi_i > \Phi_{i,e}$; while is considered to have 'satisfactory IAQ' when $\Phi_i \leq \Phi_{i,e}$ (Wong et al. 2006a).

In order to assess the importance of indoor bioaerosols, especially the AFC, indoor bioaerosols levels recorded in Database A (Table 4.1) are taken as a typical example to demonstrate the contribution of unsatisfactory IAQ by comparing the unsatisfactory rates with the 12 currently audit parameters of IAQ certification scheme. Together with the reported patterns of some air pollutants from previous studies in Hong Kong (HKEPD 1997; Wong 1997; Law et al. 2001; Chao et al. 2001; Lee 2002; Lee et al. 2002a; Chan et al. 2003; Chow et al. 2005; Leung et al. 2005; Wong et al. 2006b), the possible IAQ patterns in air-conditioned offices were mapped by Monte Carlo simulations (Binder 2002).

The average values of listed 12 assessment parameters measured in the previous studies with the exposure limits for an acceptable IAQ in 'Good' Class are shown in Table 4.1 and detailed description of the bioaerosols assessment has been presented previously in Chapter 2 (Table 2.5) (HKEPD 2003). As mentioned in Chapter 2, since the reference value of AFC varies widely, so that an exposure limit of 200 CFU

m^{-3} is suggested and which is determined based on the recommended fungal level considered as 'low' and 'acceptable' and the average fungal levels recorded in the non-problem/non-complaint buildings (N=150) .

The unsatisfactory rate $\hat{p}$, regarding the exposure limits of IAQ labels 'Good' (HKEPD 2003) is determined by

$$\hat{p}_i = 1 - \int_{-\infty}^{\Phi_i^*} G(\Phi_i) d\Phi_i \quad \text{… (Eq. 4.1)}$$

where G is the distribution function of the assessment parameter i approximated by a distribution function with a mean and a standard deviation, Φ^* is the set criterion of unsatisfactory environment having $\Phi_i > \Phi_i^*$ (Wong et al. 2006b).

As shown in Table 4.1 and Figure 4.1, the unsatisfactory rate $\hat{p}$ of airborne bacteria and fungi were 15.3 % and 18.7% respectively. Except for the TVOC, the $\hat{p}$ of other IAQ parameters were 13.2% or below.

An Express Assessment Protocol (EAP) was then developed to monitor IAQ problems of air-conditioned offices in Hong Kong by assessing some representative contributors to unacceptable IAQ prior to any detailed assessment for benchmark purposes (HKEPD 1997, 2003; Chao et al. 2001; Hui et al. 2006). Using the EAP, the independent IAQ assessment parameters i in a total number of parameters *n* can be ranked in an assessment order according to their respective unsatisfactory rates $\hat{p}$ of the assessment parameters, from the most one to the least one, such that the dominant contributors Φ to an unsatisfactory IAQ,

$$\Phi = \Phi_i \; ; \; i = 1 \ldots n; \;\; \hat{p}_1 > \hat{p}_2 > \ldots > \hat{p}_{n-1} > \hat{p}_n \quad \text{…(Eq. 4.2)}$$

Table 4.1: **Common indoor air pollutant levels of air-conditioned offices of Hong Kong (Database A).**

Parameter (Unit)	Distribution	Exposure limit (HKEPD 2003)	AM (ASD)	GM (GSD)	Observed unsatisfactory rate	Expected unsatisfactory rate $\hat{p}$ (%)	Rank for contribution of unsatisfactory IAQ
Bioaerosols parameter							
ABC (CFU m^{-3})	Geometric	<1000	597(523)	449(2.2)	15	15.3	3
AFC (CFU m^{-3})	Geometric	200[a]	147(240)	73(3.1)	17	18.7	2
Thermal comfort and IAQ parameters							
T (°C)	Normal	<25.5	22.0(1.9)	21.9(1.1)	2	3.2	8
RH (%)	Normal	<70	59.4(8.8)	58.7(1.2)	12	11.3	5
V ($m\ s^{-1}$)	Normal	<0.3	0.08(0.07)	0.10(1.8)	2	0.2	11
CO_2 (ppm)	Geometric	<1000	689.7(190.4)	666.1(1.3)	6	6.0	6
CO (ug m^{-3})	Geometric	<10000	992.9(381.7)	922.0(1.5)	<0.2	<0.1	13
HCHO (ug m^{-3})	Geometric	<100	53.1(63.0)	33.5(2.7)	8	13.2	4
NO_2 (ug m^{-3})	Geometric	<150	27.6(15.7)	23.9(1.7)	<0.2	<0.1	12
O_3 (ug m^{-3})	Geometric	<120	48.3(43.1)	36.0(2.2)	5	6.0	7
Rn (Bq m^{-3})	Geometric	<200	53.3(46.4)	40.3(2.1)	0.2	1.6	9
RSP (ug m^{-3})	Geometric	<180	33.5(24.1)	27.0(2.0)	<0.2	0.3	10
TVOC (ug m^{-3})	Geometric	<600	433.4(472.9)	296.5(2.4)	16	20.7	1

[a] Suggested value based on the recommended and measured levels of available guidelines and literature (CEC 1993; ENV 1996; Health Canada 1993; Burge et al. 2000; Gots et al. 2003; Salonen et al. 2007).

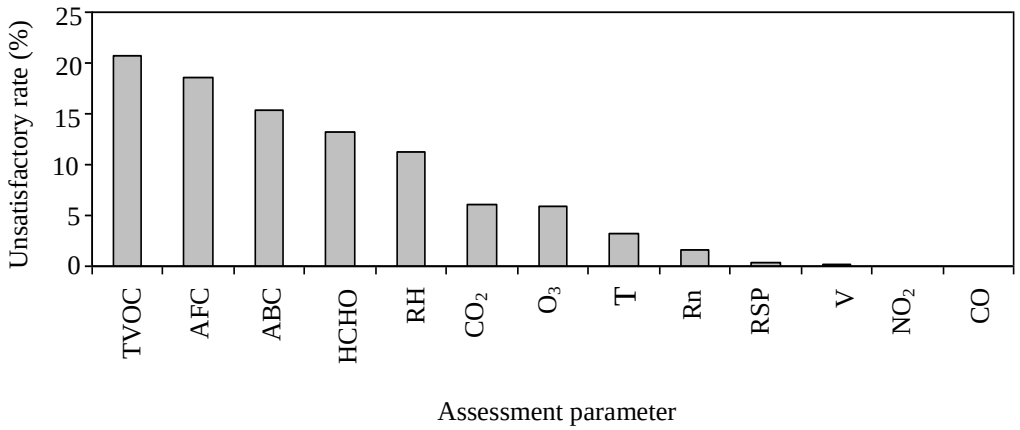


Figure 4.1: Expected unsatisfactory rates of environmental parameters in air-conditioned offices of Hong Kong (Database A).

A new ranking was reported when considering the AFC as one of the parameter in the assessment protocol when compared with Hui et al. study (2006). TVOC was reported as the top ranked contributors among IAQ parameters and the average concentration in Hong Kong air-conditioned offices was 444.4 μg m^{-3}, with the highest observed and expected unsatisfactory rates of 16% and 21% respectively. Indoor TVOC would closely relate to the emission from building materials, furnishings and other building contents (Wolkoff 1999; Luo and Niu 2006). Indeed, exposure to TVOC is well known to induce adverse health effects such as sick building symptoms, acute and chronic health effects (WHO 1987).

It was not surprising that the two bioaerosols parameters (AFC and ABC) were found as the second and third top contributors for a region of hot and humid climates, which properly favored the bioaerosols growth (Wong 1997; Chan 2006; HKO 1997–2011). The observed and expected unsatisfactory rates for AFC were 17% and 18.7% respectively while for ABC were 15% and 15.3% respectively. For other IAQ parameters, the observed and expected unsatisfactory rates were 13.2% or below. Figure 4.1 shows the expected IAQ unsatisfactory cases as a percentage of the total offices in Hong Kong and the contribution of the unsatisfactory due to each assessment parameter. According to the expected unsatisfactory rates, the top ranked 3 contributors were TVOC, AFC and ABC.

Bayesian assessment of acceptable indoor airborne bacteria level

Indoor airborne bacteria level is usually selected as a reference to identify the cleanliness of a MVAC system. An epistemic approach for assessing acceptance of air-conditioned spaces against bioaerosols is proposed. Since the information of airborne fungi level in Database A is limited, airborne bacteria level is used as an example to illustrate this assessing method.

Most commercial buildings are equipped with MVAC system which controls the T, RH and particulate content in order to maintain IAQ by means of filtration, humidification, dilution and cooling or warming of the outdoor air (Wu et al. 2005). However, without proper design and maintenance, the MVAC systems can act as potential amplification sites for indoor airborne bacteria and induce serious indoor IAQ problems. Water spray humidifiers containing stagnant water, filters packed with organic dust, cooling coils covered with condensation, condensate pans being undrained, and any excessively humid interior would provide a favorable condition with moisture and plenty of nutrients for growth of bacteria (Chow et al. 2005). The MVAC systems can act as paths for spreading the hazards from the locus of contamination to occupants in the vicinity of the building. The ABC assessed in an indoor environment could be a good indicator of the cleanliness and performance of the HVAC system. Besides, inadequate ventilation rate would associate with an increased exposure level to airborne bacteria (Lee et al. 2002a).

Therefore, several surveillance systems have issued to monitor the indoor airborne bacteria level (ACGIH 1989; HKEPD 2003). Assessments of airborne bacteria in different environments including offices, schools, residential homes and underground public concourses have also been reported (Jaffal et al. 1997; Parat et al. 1997; HKEPD 1997; Chao et al. 2001; Law et al. 2001; Lee et al. 2002a; Lee et al. 2002b; Zhu et al. 2003; Seino et al. 2005; Kalogerakis et al. 2005). Determining the representative indoor bacteria level is not a simple task as indoor bacteria level is affected by certain indoor environmental factors including seasonal and daily variations due to RH, T, air pressure, ACH as well as human activities (Parat et al. 1997; Law et al. 2001; Lee et al. 2002a; Wu et al. 2005). Accurate and informative sampling methods are very important in the evaluation of bacterial exposure in indoor environment.

Questions still remained for the confidence level and standard error in an airborne

bacteria assessment. It was shown that an insufficient number of samples and assessment results with unknown confidence intervals might contribute to the failure of finding significant associations between microbial concentrations and personal health (Straja et al. 1996; Nelson et al. 1995). Long-term and comprehensive measurements of the airborne bacteria levels are necessary for regional surveillance, but a rapid estimation of the space failure rate using epistemic assessment could be useful for screening unrecognized problematic indoor environments so that timely decisions on mitigation actions typical of HVAC systems can be made (Wong et al. 2006a; Hui et al. 2007a; Mui et al. 2008). In an epistemic assessment, prior knowledge of the possible unsatisfactory rate of a space due to excessive airborne bacteria level is required. This unsatisfactory rate, taken as the fraction of spaces of the same kind in a region having an average bacteria level above certain actionable bacteria levels, can be determined by intensive measurements over the region. Hong Kong is a hot, humid, densely populated, and characterized by high-rise building environment, which provides a favorable environment for indoor airborne microbial growth (Law et al. 2001; Lee et al. 2002a).

This part of study proposes a statistical model for the prediction of pre-assessed unsatisfactory failure rate of air-conditioned public spaces over the local region. The model was based on the distribution function of ABC under certain indoor environmental conditions and approximated by the expected bacteria levels and standard errors of the correlations obtained from the databases. To demonstrate its applicability to data reproducibility and provisions of confidence intervals, the developed model was used to estimate the possible unsatisfactory rates against certain bacteria levels in two Hong Kong offices. This model would be useful to policymakers for estimating the possible unsatisfactory rate of offices in a region against certain bacteria levels and making timely decision on any microbiological pollutant problems from limited samples, while avoiding the inappropriate level of reliance on the results.

In the occupied period of an IAQ assessment, an indoor environment having an average ABC higher than a certain set limit would be considered as ‘unsatisfactory’.

A test average level Φ_θ, with a set threshold value Φ^* over certain exposure time, was used to assess the occupant acceptance of the environment. A negative outcome ($\theta = –$, or $\Phi_\theta \leq \Phi^*$) would indicate a space of a ‘satisfactory’ airborne bacteria level,

and a positive outcome (θ = +, or $\Phi_\theta > \Phi^*$) would indicate a space of an 'unsatisfactory' airborne bacteria level. If the space is 'unsatisfactory' (event A) and the outcome is positive (event B), then the probability of a positive test given an 'unsatisfactory' environment is P(B|A). Since the tests are subject to uncertainties, a test might produce a false positive given a 'satisfactory' environment, i.e. $P(B|\overline{A})$. Hence, given a positive test P(B), the probability of having an 'unsatisfactory' environment P(A|B)can be determined by a conditional probability as follows, where P(A) is the 'prior' probability of A before the test is conducted (Wong et al. 2006a; Hui et al. 2007a),

$$P(A|B) = \frac{P(A)P(B|A)}{P(B)} \quad \text{... (Eq. 4.3)}$$

ABC was shown to have a significant correlation with T and RH of an air-conditioned indoor environment (Wong et al. 2006b; Mui et al. 2008). For an epistemic assessment of an air-conditioned workplace without any prior assessment figures, assessment results of offices over the same region would be taken as the 'prior' knowledge (Wong et al. 2006a; Wong et al. 2006b; Hui et al. 2007a). This study proposes that the pre-assessed unsatisfactory rate of an office $P(A)\big|_{\infty}^{\Phi^*}$, i.e. the probability of an office giving an average airborne bacteria level Φ above the set threshold limit Φ^*, could be determined from an airborne bacteria distribution function $\tilde{\Phi}_{T,\varphi}$ under certain indoor environmental conditions (T and RH) and approximated by two estimators, μ_Φ ($CFUm^{-3}$) the expected bacterial levels and σ_Φ the standard error of the correlations, determined from the measurement results of typical air-conditioned spaces.

$$P(A)\big|^{\Phi^*} = 1 - \int_{-\infty}^{\Phi^*} \tilde{\Phi}_{T,\varphi}\, d\Phi \;\; ; \;\; \tilde{\Phi}_{T,\varphi} = \tilde{\Phi}(\mu_\Phi, \sigma_\Phi) \quad \text{... (Eq. 4.4)}$$

Particularly, for typical air-conditioned spaces in the subtropics, μ_Φ was proportional to T and RH. Taking σ_Φ as the standard error of the correlation μ_Φ, with a normal distribution for the residuals ($\Phi_i - \mu_\Phi$) of the correlation from i measurements, the

distribution function $\tilde{\Phi}$ can be approximated by,

$$\tilde{\Phi}_{T,RH} = \tilde{\Phi}(\mu_\Phi, \sigma_\Phi) = \frac{e^{-(\Phi-\mu_\Phi)^2/2\sigma_\Phi^2}}{\sigma_\Phi\sqrt{2\pi}};\ \ \mu_\Phi = G(T, RH) \qquad \text{... (Eq. 4.5)}$$

As the result accuracy of an airborne bacteria assessment is closely related to the test value Φ_θ obtained from samples collected in a relatively 'short-term' measurement, indoor airborne bacteria levels was transient and the possible sampled airborne bacteria levels was described by certain distribution function $\tilde{\Phi}_\theta$ (Law et al. 2001). Using the criterion Φ^* of an acceptance from the sample result θ, the probability P (B|A) was approximated by the following, where μ_θ and σ_θ are the mean and standard deviation of sampled airborne bacteria levels in an air-conditioned space,

$$P(B \mid A) = 1 - \int_{-\infty}^{\Phi^*} \tilde{\Phi}_\theta \, d\Phi_\theta\ ;\ \ \tilde{\Phi}_\theta = \tilde{\Phi}(\mu_\theta, \sigma_\theta) \qquad \text{... (Eq. 4.6)}$$

For a sampling scheme at a measurement time period, the uncertainty ratio ς is a '*per-unit*' measure of the possible error of the assessed bacteria levels (Mui et al. 2008),

$$\varsigma = \frac{\sigma_\theta}{\mu_\theta} \qquad \text{... (Eq. 4.7)}$$

For evaluating the environmental risk of ABC in workplaces, criteria of acceptable concentrations have been proposed (see Chapter 2). In Hong Kong, the HKEPD certification scheme adopts the 8-hour averages of 500 and 1000 $CFUm^{-3}$ as the action levels of airborne bacteria for 'Excellent' and 'Good' classes respectively (HKEPD 2003). The rationale behind the 8-hour measurement period is that the levels of indoor air contaminants may fluctuate during office hours. However, implementation of a continuous measurement of airborne bacteria may not be practical. As a 1/2-hour or 1-hour sampling collected more air samples than required for the counting purpose, this study adopted a sampling strategy of collecting 5 to 10 minute samples only.

Field measurement

The measurement results of airborne bacteria level in Database A were used to develop the statistical model and demonstrate its applications (data presented in Table 2.5, 2.6, and 4.4). These studies are denoted as A1 (HKEPD 1997), A2 (Chao et al. 2001), A3 (Wong et al. 2006a) and A4 (Law et al. 2001). The measurement results used in these studies covered a wide range of indoor thermal environments: air temperature 13-28°C and relative humidity 29-88% (Mui and Wong 2007b).

Table 4.2: Airborne bacteria levels in some air-conditioned spaces.

Premises	No. of sites N	T (°C)		RH (%)	
		Range	AM (ASD)	Range	AM (ASD)
HKEPD 1997 (A1)					
Cinema	5	21.2-25.0	23.4 (1.6)	54-60	58 (2.5)
Office	40	20.9-24.6	22.3 (0.8)	49-72	60 (5.0)
Restaurant	20	18.8-27.2	23.6 (2.4)	52-73	63 (5.9)
Shopping Mall	8	21.9-25.5	23.5 (1.2)	56-67	61 (4.0)
Chao et al. 2001 (A2)					
Hospital	3	22.3-24.1	23.3 (0.9)	35-43	41 (4.6)
Library	4	21.3-23.0	22.2 (0.9)	52-67	57 (7.1)
Lecture hall	3	18.5-22.4	20.1 (2.1)	54-67	62 (7.1)
Office	3	19.6-22.6	21.2 (1.5)	44-46	45 (1.1)
Restaurant	3	18.0-19.2	18.5 (0.6)	60-79	69 (9.5)
Stadium	3	15.9-21.0	19.1 (2.8)	54-69	61 (7.3)
Waiting hall	3	18.1-23.8	21.1 (2.9)	42-55	48 (6.5)
Workshop	3	19.6-20.2	19.8 (0.3)	54-60	56 (3.4)
Wong et al. 2006a (A3)					
Office	422	13.4-27.8	22.0 (2.0)	29-88	59 (9.0)
Law et al. 2001 (A4)					
Office	2	20.2-22.1	21.1 (1.3)	63-67	65 (2.8)

Figure 4.2 presents the ABC of all the assessed spaces as a function of T (15 °C to 25 °C) and RH (40% to 70%). The results show that indoor airborne bacteria levels of typical air-conditioned spaces in Hong Kong are proportional to the T and RH being maintained. The average bacteria count μ_Φ ($CFUm^{-3}$) could be correlated with the environmental conditions using a correlation coefficient R=0.7029 ($p \leq 0.01$) as shown below, ε is the standard error assumed to be normally distributed,

$$\mu_{\Phi} = 5.8 \times 10^{-12} T^{7.1} RH^{2.5}; \varepsilon = 356 \quad \text{... (Eq. 4.8)}$$

For the objective of A1 was to measure IAQ during 'peak' hours, the surveyed averages of the public places were expectedly higher than those of the offices in general, as illustrated in Figure 4.2.

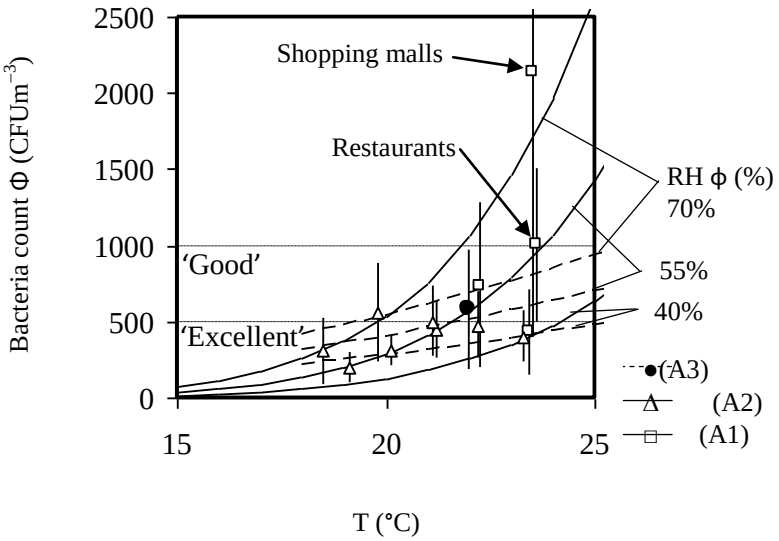


Figure 4.2: Airborne bacteria count in air-conditioned spaces of Hong Kong.

Figure 4.3 shows the longer-term measurements of airborne bacteria levels made in A4. The time averages, GM and GSD of the airborne bacteria levels for the offices 1 and 2 when the air-conditioning system was ON (office hours) and OFF (non-office hours) are summarized in Table 4.3. It is observed that 1 and 2 had significantly different thermal environments in terms of air temperature and relative humidity when the air-conditioning system was on ($P < 0.001$), but not when the system was off ($P > 0.05$). This could be explained by the fact that different offices have different functions.

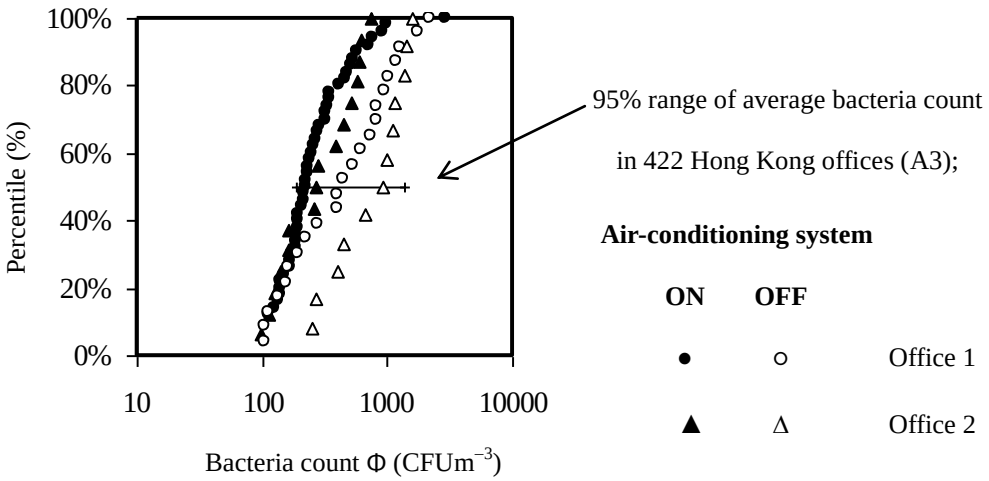


Figure 4.3: Airborne bacteria count in air-conditioned offices 1 and 2 (A4).

On the contrary, there was no significant difference between the average bacteria levels found in 1 and 2 when the air-conditioning system was on ($p > 0.5$). When the system was off, some (but not significant) differences were reported ($p < 0.06$). Probably, offices in the same region were typical and had similar environmental conditions. The system in both offices would effectively remove contaminants generated by the occupants. The average bacteria levels measured in these two offices fell within the average bacteria level range of A3, as shown in Figure 4.3.

Table 4.3: Indoor air conditions of A4 for offices 1 and 2.

Office	**1**		**2**	
MVAC system	**ON**	**OFF**	**ON**	**OFF**
N	50	23	16	12
T [a](^{o}C)	22.1 (1.5)	23.2 (1.3)	20.2 (1.4)	22.3 (1.4)
RH [a] (%)	66.5 (4.7)	67.9 (3.6)	62.9 (2.3)	66.2 (6.2)
ABC [b](CFU m^{-3})	249 (2.1)	429 (2.6)	280 (2.0)	742 (1.9)

[a] The readings are normally distributed and AM (ASD) are shown.

[b] The readings are normally distributed and GM (GSD) are shown.

The operation of the HVAC system might have significant influence on the average bacteria levels in an office. This study showed that significantly different average

bacteria levels were found in the same office due to the ON-OFF operation of the air-conditioning system ($p \leq 0.03$ for office 1, and $p \leq 0.001$ for office 2). The high airborne bacteria counts recorded during the main HVAC system off period would reduce the effect of dilution. The increased air temperature and the condensation on the air ducts and building contents in the measured ranges would favour the growth of bacteria (Chow et al. 2005; Mui et al. 2008).

Illustration example

Typical thermal environmental conditions in Hong Kong offices, i.e. T = 22.5 ℃ to 25.5 ℃ and RH = 50% to 70%, were used to demonstrate the application of the proposed model (HKEPD 2003; Mui and Wong 2007b). Figure 4.4 illustrates the sample airborne bacteria levels required for the 'satisfactory' level of 500 $CFUm^{-3}$ within arbitrary allowable probabilities of 'false acceptance' at 5% and 10%. These tested levels were determined by Equation (4.3) based on the prior knowledge gained from Equation (4.7). For an office environment of higher T or RH, i.e. with a higher risk of unsatisfactory IAQ, a lower test value was required to fulfill the IAQ acceptance at certain confidence level. Taking an uncertainty ratio 0.13 with a 10% probability of 'false acceptance' at T = 22.5℃ and 25.5℃ as an example, the maximum allowable sample ABC would be 250 $CFUm^{-3}$ and 140 $CFUm^{-3}$ for a RH of 50% (Figure 4.4a), or 140 $CFUm^{-3}$and 40 $CFUm^{-3}$ for a RH of 70% (Figure 4.4b), respectively.

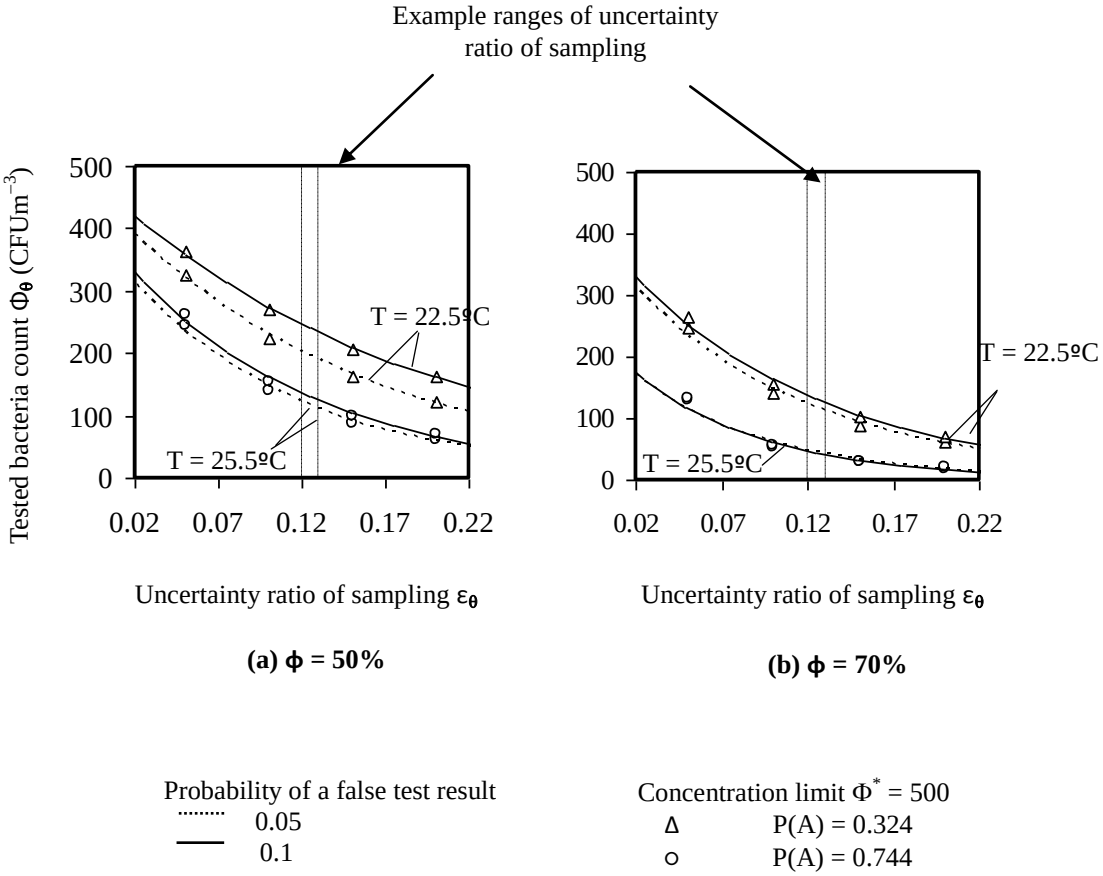


Figure 4.4: Maximum test values Φ_θ for acceptable indoor airborne bacteria count Φ^*.

It was reported that for an office with a 'stable' airborne bacteria level, i.e. with a very small uncertainty ratio, the maximum allowable test value would be close to the set limit. Any assessment with test values exceeding the levels illustrated above needs further detailed measurements in order to confirm an acceptable environment.

It was suggested that the prior knowledge of unsatisfactory IAQ due to an excessive airborne bacteria level could be correlated with the thermal environmental conditions in the test office. The model parameters were developed from reported databases of some air-conditioned spaces in the subtropics with airborne bacteria levels ranging from 41 CFU m^{-3} to 2304 CFU m^{-3}, air temperature from 13.4 ^oC to 27.8 ^oC and relative humidity from 29 % to 88%. For an office environment having a higher risk of unsatisfactory IAQ (e.g. high T or high RH), a lower test value of the sample airborne bacteria level was required to meet the IAQ acceptance at certain confidence level. The proposed model should be useful to policymakers for making a

fast response to the microbiological pollutant problem with the best information available, while avoiding the inappropriate level of reliance on the results. This study also serves as a source of reference for developing an epistemic IAQ assessment tool regarding an IAQ parameter.

Thermal environmental interference with indoor bioaerosols level

The survival of indoor airborne bacteria and fungi depends strongly on the environmental conditions (e.g. T and RH). Positive correlation has been observed between the dampness and the proliferation of indoor fungi, and epidemiological studies revealed that the risk of respiratory symptoms and infections, and exacerbation of asthma is higher for those people stayed in damp or mouldy buildings (Dales et al. 1997; Górny 2004; WHO 2009).

It is also well established that the growth of indoor fungi can be restricted by reducing the RH (Adan 1994; Cox and Wathes 1995; Rowan et al. 1999; WHO 2009). A surface RH of 62% to 65% is found to be the ultimate lower surface RH for the fungal germination; however, experimental results revealed that common building and finishing materials can be free of fungal growth if the surface RH is maintained at < 80% (Adan 1994). It is also recommended that the surface RH should be maintained at <75% in order to limit the fungal growth in buildings, as the range of minimum RH allowing the fungal growth which, depending on the substrate, is from 75% to 95% (Viitanen and Ritschkoff 1991; Rowan et al. 1999; WHO 2009). In addition, Johansson et al. (2005) found that the critical relative humidity (maximum long-term RH allowed for non-growth) was 75% to 90% for clean materials and 75% to 80% for contaminated or soiled materials.

Apart from the moisture content of building materials, the T and RH of air may also have both positive and negative influences on bioaerosols concentration. In general, common indoor T is not a limiting factor for growth of both bacteria and fungi, as most of them grow at 10°C to 35 °C. Tang (2009) reviewed the experimental results on the survival of airborne bacteria of different species, and suggested that their survival rate decreased when the T increased to or above 24°C and when RH increased from intermediate (50% to 70%) to high (70% to 90%). While there are relatively few experiments were conducted on the airborne fungi survival under varying T and RH, most of the data regarding the relationship have been obtained

from field study only (Tang 2009).

Many field studies have reported the correlation between bioaerosols concentration and T and RH. Generally, T and RH had a positive effect on total ABC and AFC in both indoor and outdoor environments (Wu et al. 2000; Chan et al. 2006; Aydogdu et al. 2010; Erkara et al. 2008; Rajasekar and Balasubramanian 2011; Abdel Hameed et al. 2012). For example, *Aspergillus*, *Alternaria* and *Cladosporium* were reported to be positively correlated with the T and RH (Quintero et al. 2010; Abdel Hameed et al. 2012), AFC recorded in summer were higher than winter (Wu et al. 2000). The regression coefficient (r^2) between indoor ABC and AFC with RH was found to be as high as 0.9 (Orosaa and Oliveira 2011). Furthermore, Liao et al. (2004) also reported a positive relationship between the AFC and the RH, and purposed a model to estimate the indoor source concentrations of bioaerosols, provided that the actual measured fungus-specific I/O ratios are available by incorporating the effects of RH.

Therefore, investigation of the relationship between the airborne bacterial and fungal levels and thermal environmental parameters in air-conditioned offices is very important. However, questions about the level of confidence in an airborne bacteria and fungi assessment remain. Assessment results with limited samples may be deficient in representing personal exposures and insufficient number of samples and assessment results with unknown confidence intervals may even contribute to the failure of concluding significant associations between microbial concentrations and personal health. Although long-term and comprehensive measurements of bacteria and fungi levels can be a good approach for monitoring regional indoor air pollution levels, a rapid estimate of the office failure rate may be more applicable to a timely decision on the mitigation actions of the MVAC system (Mui et al. 2008, unsatisfactory airborne bacteria level). Therefore, instead of recording a continuous profile, the average of repeated sample values of airborne bacteria and fungi levels can be taken within an assessment period.

In this study, mathematical expressions are proposed for the estimates of airborne bacteria and fungi levels correlated with the parameters measured, which is useful in detection of asymptotic microbiological pollutant problems by a quick estimate of the possible unsatisfactory rate of offices over a region against certain bacteria and fungi levels from a few samples, while avoiding an inappropriate level of reliance on the results.

Results of assessment A4 in Database A is chosen for investigation. The measured T, RH, ABC and AFC of the two offices (1 and 2) during office hours (when the main MVAC system was operating) and non-office hours (when the main system was shut down) are summarized in Table 4.4. The T measured in the office hours was between 19°C and 24°C and the RH was between 55% and 80%. The results were not significantly different from the thermal environment of offices in Hong Kong where the T was between 19.5°C and 29.1°C and the RH was between 42% and 72%.

Table 4.4: Common indoor air pollutant levels of an unoccupied air-conditioned office (A4 in Database A).

Office	**Office 1**		**Office 2**	
	Office hours	**Non-office hours**	**Office hours**	**Non-office hours**
Operation of MVAC system	On	Off	On	Off
Number of samples	50	23	16	12
Thermal parameter, AM(ASD)				
T (°C)	22.1(1.5)	23.2(1.3)	20.2(1.4)	22.3(1.4)
RH(%)	66.5(4.7)	67.9(3.6)	62.9(2.3)	66.2(6.2)
Bioaerosols, GM(GSD)				
ABC (CFU m^{-3})	249(2.1)	429(2.6)	280(2.0)	742(1.9)
AFC (CFU m^{-3})	42(5.4)	301(6.2)	52(3.1)	222(4.8)

It was reported that a small air-conditioning unit was operated during non-office hours to maintain acceptable RH so that no significant difference in average relative humidity between office and non-office hours was reported ($p \geq 0.77$). Nevertheless, the average T recorded during the non-office hours was significantly higher ($p \geq 0.001$).

The airborne bacteria levels were 249 CFU m^{-3} and 280 CFU m^{-3} and the fungi levels were 42 CFU m^{-3} and 52 CFU m^{-3} for offices 1 and 2 in office hours respectively; and for the non-office hours, the ABC were 429 CFU m^{-3} and 742 CFU m^{-3} and the AFC were 301 CFU m^{-3} and 222 CFU m^{-3} for offices 1 and 2 respectively. The ABC and AFC can be approximated by a geometric distribution

(p≥0.05) with the percentiles of the measured values as shown in Figure 4.5 and the GM and GSD as summarized in Table 4.4.

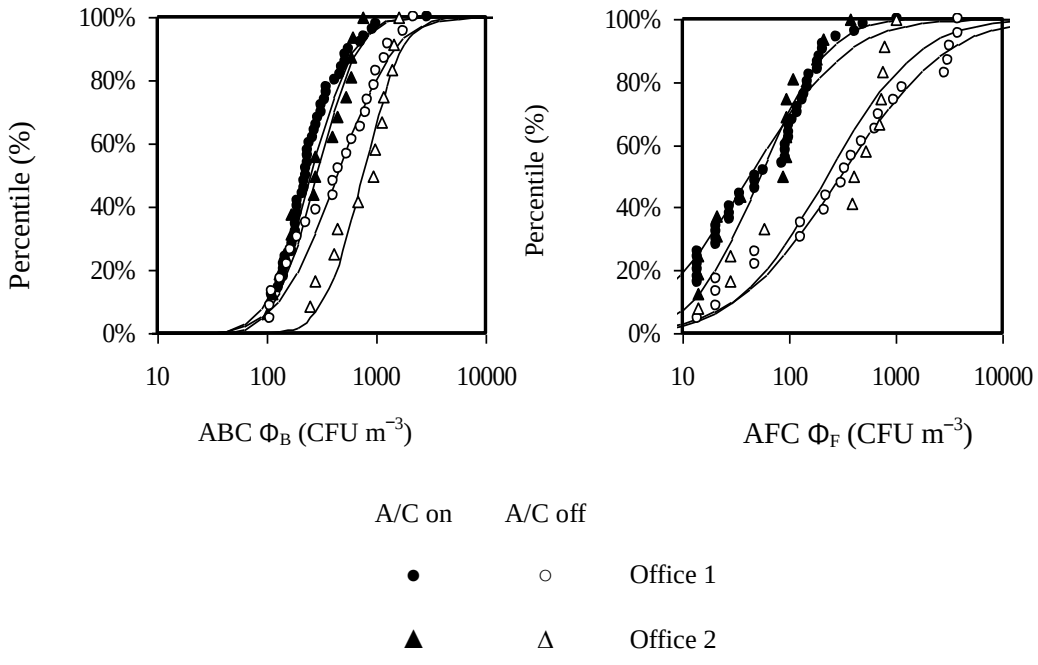


Figure 4.5: Airborne bacterial and fungal levels in two air-conditioned offices.

This study showed that the operation of the MVAC system in offices could have significant influence on both indoor airborne bacteria and fungi levels. Table 4.5 summarizes the t-test p-values for the measurements from offices 1 and 2. Small case studies (e.g. unoccupied office 1 and 2) were chosen when proposed the mathematical expression for the estimation of airborne bacteria and fungi levels correlated with the RH and T. It was designed to minimize the effects of other factors (e.g. different ventilation rates, design, human activities, etc.), and to improve the accuracy of the equation (Eq. 4.9 and 4.10).

There were parallel observations in some air-conditioned environments where T and RH were reported to have influence on the ABC. From the results, the ABC and AFC between offices 1 and 2 were comparable (p>0.05) when the main MVAC system was either on (office hours) or off (non-office hours). For each office by itself (i.e. 1 or 2), however, both of the ABC and AFC were significantly higher when the main system was off (p<0.03). It is believed that while the main MVAC system was not in

operation, air temperature increased and water vapors condensed onto the indoor building materials as well as inside the system; these favored indoor microbial growth (Bluyssen et al. 2003).

Table 4.5: Statistical analysis of airborne bacterial and fungal levels in two air-conditioned offices with various MVAC system operation modes.

Office designation, operation of MVAC system		t-test p-value	
		ABC	AFC
Office 1, ON	Office 2, ON	>0.05	>0.5
Office 2, OFF	Office 2, OFF	>0.05	>0.6
Office 1, ON	Office 1, OFF	<0.001	<0.001
Office 2, ON	Office 2, OFF	<0.03	<0.02

It is observed that both the ABC Φ_B (CFU m^{-3}) and AFC Φ_F (CFU m^{-3}) of the two air-conditioned offices are correlated with ($p < 0.0001$) the T (ºC) and RH (%) in the measured ranges 19ºC ≤ T ≤ 25ºC and 50% ≤ RH ≤ 80%.

$$\Phi_B = 1.9 \times 10^{-7} T^{4.47} RH^{1.85} \quad \ldots \text{(Eq. 4.9)}$$

$$\Phi_F = 3.3 \times 10^{-22} T^{6.01} RH^{8.71} \quad \ldots \text{(Eq. 4.10)}$$

For the above correlations, the standard errors of airborne bacteria and fungi levels were ε_B = 438 CFU m^{-3} and ε_F = 683 CFU m^{-3} respectively. The measured levels Φ_B and Φ_F, plotted together with the predicted levels against indoor T 19°C to 26°C and RH 45% to 85%, are shown in Figure 4.6.

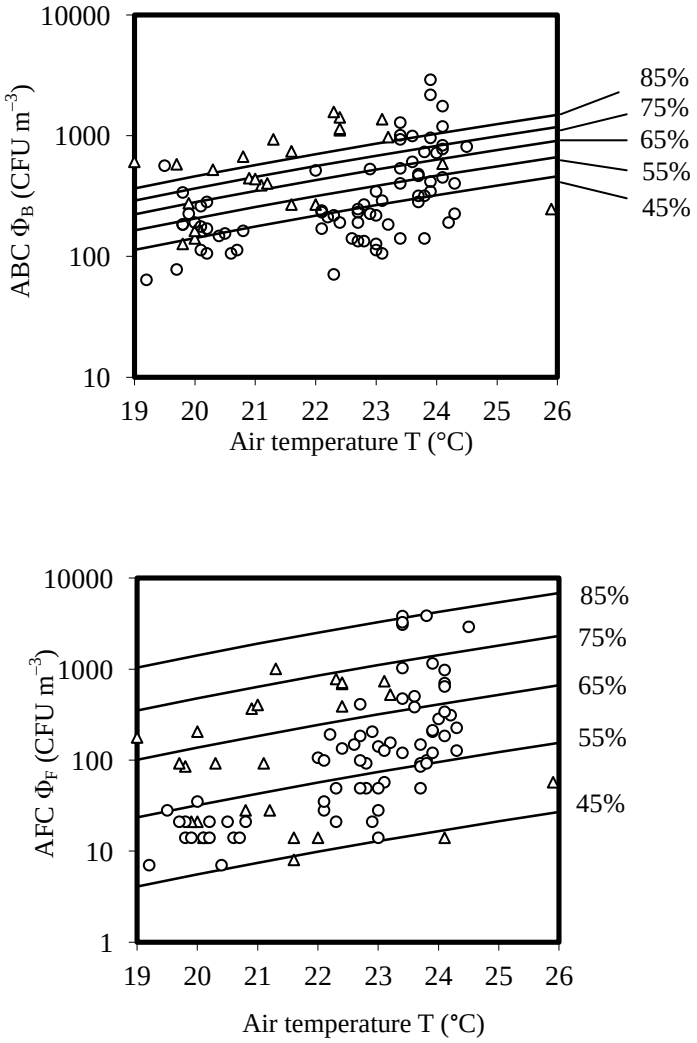


Figure 4.6: Correlations for the airborne bacterial and fungal levels in two air-conditioned offices.

They are comparable with the measurements found earlier in some other non-domestic air-conditioned spaces as illustrated in the figure (Wong et al. 2006b; Hui et al. 2007b; Mui et al. 2008). As expected, an office under higher air temperature and relative humidity within the measured ranges will give higher bacteria and fungi levels.

Figure 4.6 also presents the numbers recommended for an 'excellent' office environment: thermal environmental conditions in which 20 ºC ≤ T ≤ 25.5 ºC and 40% ≤ RH ≤ 70% (HKEPD 2003); maximum airborne bacteria level = 500 CFU m^{-3} and maximum fungi level = 200 CFU m^{-3} (ACGIH 1989; HKEPD 2003).

To attain the excellent airborne bacteria and fungi levels at 60% RH, for instance, the air temperatures should be 23.5ºC and 23.9ºC respectively. The results show that some thermally excellent air-conditioned spaces will have expected bacteria and fungi levels beyond the advised limits. For both offices 1 and 2, correlations with their airborne bacteria and fungi levels are observed and shown in Figure 4.7 ($p < 0.0005$).

$$\Phi_F = 0.18\Phi_B^{1.09} \quad ; 70 \le \Phi_B \le 2900 \qquad \ldots \text{(Eq. 4.11)}$$

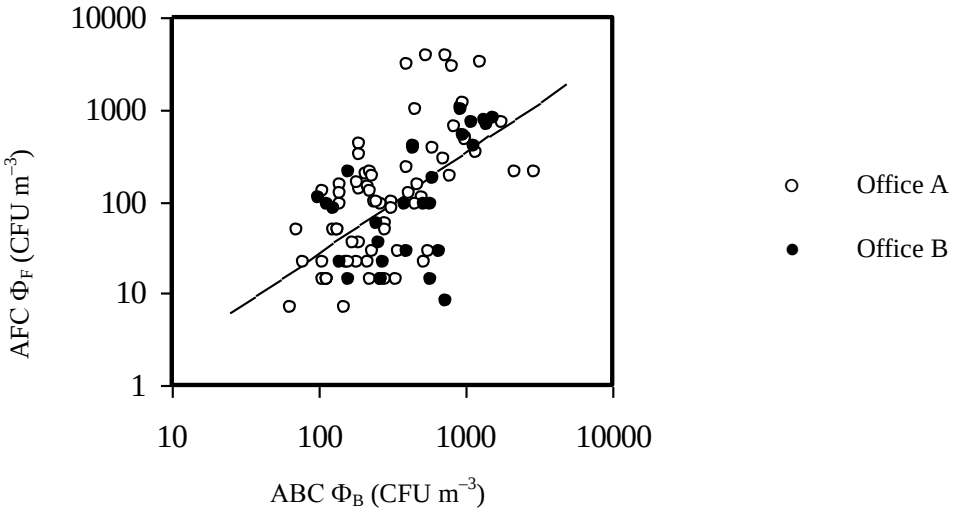


Figure 4.7: Correlations between the airborne bacterial and fungal levels ($p < 0.0005$).

The above mathematical expressions can be used for a rapid estimation of the expected airborne bacteria and fungi levels under certain thermal environmental conditions. These expressions were proven practical tools for epistemic IAQ assessment of some air-conditioned offices in the same region (Hui et al. 2006). And indoor thermal parameters can be selected as reference to identify the performance of the indoor environment and estimate the failure rates due to excessive airborne bacteria and fungi levels.

Regional Cross-sectional Database of Indoor Bioaerosols

Based on the analysis of data obtained from Database A, it is revealed that the assessment of airborne fungi levels in indoor environment is an important issue and points out that further investigations for the airborne fungi in the IAQ audits is indeed. Therefore, there are several reasons for developing a regional cross-sectional database of indoor bioaerosols: (1) the available data of the airborne fungi in air-conditioned offices (N=53) are not enough to represent the overall picture of the indoor bioaerosols of Hong Kong, a samples size with at least 67 is needed in order to reach 90% confidence interval; (2) different sampling methods (i.e. equipment and agar media) of the bioaerosols samples have been used in the previous studies, therefore the results are not consistent (HKEPD 1997; Wong 1997; Law et al. 2001; Chao et al. 2001; Lee 2002; Lee et al. 2002a; Chan et al. 2003; Chow et al. 2005; Leung et al. 2005); (3) the information of some important environmental parameters, (e.g. ventilation) which affect the abundance of bioaerosols, are not available; and (4) limit information on the composition of indoor airborne fungi. Therefore, in order to provide more information for exposure and control strategies against the indoor bioaerosols, the additional surveys are conducted in this study (Table 4.6).

Table 4.6: Summary of new surveys of indoor airborne bacteria and fungi in Hong Kong (Database B).

Assessment	N	Location	Other IAQ parameters (HKEPD 2003)	Purpose
B1	157	Offices in high-rise commercial buildings located at different regions	11	To study the overall picture of indoor bioaerosols in different regions of Hong Kong
B2	82	Offices in a Grade A commercial building	11	To investigate the indoor bioaerosols profile in Grade A building with excellent IAQ

Air sampling schedule and site description

500 L air samples of bioaerosols are collected from each sampling sites and the procedure is the same as the residential apartments which was mentioned in Chapter 2. Apart from indoor bioaerosols, the other indoor air pollutants were monitored during the sampling period in order to investigate the possible effects of these IAQ parameters on the bioaerosols profile. The equipments used for monitoring are listed in Table 4.3, and were calibrated before site measurements (Chao et al. 2001). This equipment can be grouped as real-time monitoring and passive sampling followed by laboratory analysis. The real-time monitors which provide instant information of the IAQ parameters' variations were used for monitoring T, RH, V, CO_2, CO, RSP, O_3, TVOC and Rn and the readings were logged at 5 min interval. While the passive samplers which provide information of the total exposure within the sampling period were used for collecting HCHO and NO_2, and then the concentrations were determined by using the High-performance liquid chromatography and Ion chromatography, respectively.

For the IAQ measurement in air-conditioned offices (Assessment B1&2), it was made on an 8-hr basis within normal working hour (i.e. 09:00 to 17:00) (HKEPD 2003). During the sampling period, the air-conditioning system was operated under normal conditions. Surrogate measurement of the IAQ parameters was adopted for these two assessments, which is an intermittent measurement strategy based on the average of 30 min monitoring at 4 time-slots (i.e. 2 in the morning and 2 in the afternoon). The outdoor air measurement was also made, which was close proximity to the fresh air-intakes of the sampling sites in order to study the indoor-outdoor relationship and 2 outdoor monitoring (i.e. morning and afternoon) (HKEPD 2003).

Table 4.7: List of equipment for IAQ monitoring.

Parameter	Working principle	Range	Accuracy	Resolution
Real time monitor				
CO_2	Non-dispersive infrared	0–5000 ppm	±3% reading or 50 ppm	1 ppm
CO	Electrochemical oxidation devices	0–500 ppm	± 3% reading or 3 ppm	0.1 ppm
O_3	Heated-metal oxide semiconductor sensor	0–5 ppm	±0.5 ppm	0.01ppm
RH	Thin-film capacitive	5–95 %	± 3%	0.1 %
Rn	Solid state alpha detector	0.1–999 pCi l^{-1}	±20%	
RSP	Light scattering	0.001–100 mg m^{-3}	NA	1% of reading or 0.001 mg m^{-3}
$SP_{0.3\text{-}10\ \mu m}$		0.3, 0.5, 1.0, 2.0, 5.0 and 10.0 µm	Efficiency: 50% (0.3µm); 100% (>0.45µm)	
T	Thermistor	0–50 °C	± 0.6°C	0.1 °C
TVOC	Photoionization detection method	0–2000ppm	±20 ppb or 10% of reading	1 ppb (0–9999 ppb);0.1 ppm (10.0–99.9 ppm);1 ppm (100–2000ppm)
V	Hot-wire anemometer	0–20 m s^{-1}	±0.03 m s^{-1}	0.01 m s^{-1}
Passive sampler				
HCHO	Analyzed by High-performance liquid chromatography	5ppb –5 ppm	±25%	200 ppb (15 min); 5 ppb (8 hr); 2 ppb (24 hr)
NO_2	Analyzed by ion chromatography	0.4–8 ppm	±30%	2 ppm (15 min); 0.1 ppm (8 hr)

Assessment B1: Indoor bioaerosols in air-conditioned offices located at different regions

157 offices in 26 typical office buildings were randomly selected in Hong Kong in 2007. These buildings are located at 11 different districts of Hong Kong (Figure 4.8). All of these buildings are equipped with MVAC system and the sampled offices are located at G/F to 38/F. Air samples were collected at 1 m above the floor at the center of each sampling sites. Airborne bacteria and fungi and the 11 HKEPD listed IAQ parameters (i.e. T, RH, V, CO_2, CO, RSP, NO_2, O_3, HCHO, TVOC and Rn) were measured at each sampling site.

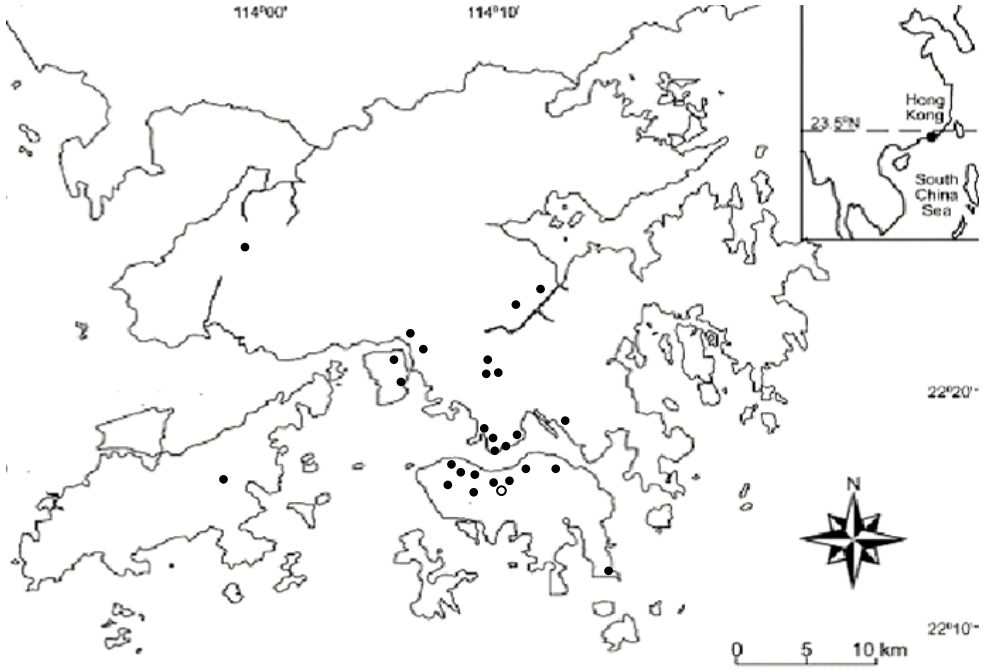


Figure 4.8: Location of the sampled air-conditioned offices in Hong Kong (●Assessment B1, ○ Assessment B2).

Assessment B2: Indoor bioaerosols in air-conditioned offices with excellent IAQ

82 in-used air-conditioned offices were randomly selected in a 54-floor in-use Grade A typical air-conditioned commercial building in Hong Kong during September to December 2006. This building is located at the major commercial center and built in early 1970s (Figure 4.8). The sampled offices were randomly selected in the building which is located from 1/F to 53/F. Each office floor is served by a MVAC system composed of 4 air handling units (AHUs), which supply 20% fresh air and 80% re-circulated air mix. Fresh (outdoor) air is supplied to each AHU from a centralized primary air handling plant located on a mechanical floor. The property owner targeted to maintain a good IAQ, by better design and frequently maintenance of the MVAC system. The systems are maintained every 3 months, by replacing the air filters, and cleaning the systems and air ducts. Therefore, it is expected that the IAQ of the offices in this Grade A building should be better when compared with the offices randomly sampled in this region. As same as the Assessment B1, the indoor airborne bioaerosols together with 11 IAQ parameters were monitored.

Regional cross-sectional of environmental conditions and indoor bioaerosols

Table 4.8 summarized the indoor air pollutant levels in the 157 air-conditioned offices of Hong Kong. The AM, ASD, GM and GSD of 3 thermal comfort parameters and the 8 common indoor air pollutants levels are presented. Based on the environmental condition data, the IAQ of the commercial buildings can be classified into 'excellent' and 'good' class according to the HKEPD IAQ certification scheme. The thermal comfort parameters, i.e. T, RH and V, of the surveyed offices were approximated by normal distribution ($p>0.05$, Chi-square test). The T, RH and V recorded in these locations in office hours ranged from 20.3°C to 29.1°C, 45% to 72% and 0.01 m s^{-1} to 0.41 m s^{-1} respectively and the AM were 23.4 (ASD=1.3) °C, 59 (ASD=6) % and 0.10 (ASD=0.06) m s^{-1} respectively. The 8-hr exposure levels of other 8 IAQ parameters were geometrically distributed ($p>0.05$, Chi-square test). The CO_2 ranged from 345 ppm to 993 ppm, with a GM of 572 (GSD=1.3) ppm; CO ranged from 230μg m^{-3} to 2734 μg m^{-3}, with a GM of 400 (GSD=1.7) μg m^{-3}; HCHO ranged from 8 μg m^{-3} to 63 μg m^{-3}, with a GM of 26 (GSD=1.7) μg m^{-3}; NO_2 ranged from 20 μg m^{-3} to 138 μg m^{-3}, with a GM of 63 (GSD=1.6) μg m^{-3}; O_3 ranged from 3 μg m^{-3} to 145 μg m^{-3}, with a GM of 21 (GSD=1.6) μg m^{-3}; Rn ranged from 5 Bq m^{-3} to 167 Bq m^{-3}, with a GM of 34

(GSD=2.1) Bq m^{-3}; RSP ranged from 0 μg m^{-3} to 92 μg m^{-3}, with a GM of 11 (GSD=3.0) μg m^{-3}; TVOC ranged from 0.5 μg m^{-3} to 4244 μg m^{-3}, with a GM of 153 (GSD=4.0) μg m^{-3}.

Table 4.8: Common indoor air pollutant levels of air-conditioned offices of Hong Kong (Database B).

Parameter (Unit)	Assessment B1 (N=157)			Assessment B2 (N=82)		
	Range	AM (ASD)	GM (GSD)	Range	AM (ASD)	GM(GSD)
T (°C) [b]	20.3-29.1	23.4(1.3)	23.3(1.1)	19.5-25.6	22.6(1.2)	22.6(1.1)
RH (%) [b]	45-72	59(6)	58(1.1)	42-69	51(6)	51(1.1)
V (m s^{-1}) [b]	0.01-0.41	0.10(0.06)	0.06(1.93)	0.01-0.31	0.08(0.05)	0.07(1.93)
CO_2 (ppm) [a]	345-993	589(144)	572(1.3)	455-970	671(114)	662(1.2)
CO (ug m^{-3}) [a]	230-2734	470(338)	400(1.7)	0-2025	520(489)	373(2.5)
HCHO (ug m^{-3}) [a]	8-63	30(14)	26(1.7)	3-92	23(21)	15(2.6)
NO_2 (ug m^{-3}) [a]	20-138	70(29)	63(1.6)	4-79	27(22)	17(3.1)
O_3 (ug m^{-3}) [a]	3-145	25(22)	21(1.6)	0-61	17(10)	14(2.7)
Rn (Bq m^{-3}) [a]	5-167	44(32)	34(2.1)	1-153	24(35)	12(2.9)
RSP (ug m^{-3}) [a]	0-92	18(17)	11(3.0)	6-37	17(5)	16(1.4)
TVOC (ug m^{-3}) [a]	0.5-4244	279(404)	153(4.0)	9.2-1274	208(182)	158(2.1)

[a] The readings are geometrically distributed.

[b] The readings are normally distributed.

The regional cross-section of indoor bioaerosols showed that the airborne bacteria and fungi are detected in all the indoor air samples. These offices are located in typical commercial buildings equipped with the MVAC system. The age of these buildings ranged from 1 to 50 year and located at both suburban (N=20) and urban areas (N=137). No obvious indoor fungal source, no water damages and no visual fungal growth on walls and ceilings were reported. The indoor bioaerosols levels (i.e. AM, ASD, GM, GSD, range) are summarized in Table 4.9. The indoor ABC and AFC recorded at these typical air-conditioned offices were approximated by a geometric distribution ($p>0.05$, Chi-square test) and presented in Figure 4.9.

The indoor ABC ranged from 17 to 1231 CFU m^{-3} and the AM and GM were 465 (ASD=246) CFU m^{-3} and 397 (GSD=1.8) CFU m^{-3} respectively. The 50^{th}, 75^{th} and 90^{th} percentiles of indoor ABC were 425, 598 and 817 CFU m^{-3}. More than half of the samples (62%) had bacterial concentrations less than 500 CFU m^{-3}, while 35% of

samples larger than 500 CFU m^{-3} but less than 1000 CFU m^{-3} and 3% of samples larger than 1000 CFU m^{-3}. According to the HKEPD (2003), 62% and 97% of studied offices fulfilled the 'Excellent Class' and 'Good Class' requirements for indoor bacteria respectively. The corresponding outdoor ABC ranged from 15 to 1274 CFU m^{-3} and the AM and GM were 195 (ASD=232) CFU m^{-3} and 118 (GSD=2.7) CFU m^{-3} respectively. No significant correlation between the indoor ABC and the outdoor ABC was reported ($p>0.05$). The indoor ABCs recorded in 85% of the offices were higher than the outdoor ones, and the indoor concentrations recorded in these offices were approximately 6.7 times greater than outdoor levels. The higher ABC in indoor environments suggested the presence of indoor source. The ABC in offices located at the urban areas were significantly higher when compared with those in the suburban areas ($p<0.0001$), the AM were 495 (ASD=245) CFU m^{-3} and 270 (ASD=145) CFU m^{-3} respectively. However, the reported ABC in the outdoor environment of the offices located at suburban areas were higher but not significant when compared with the urban areas, the AM was 218 (ASD=429) CFU m^{-3} and 191 (ASD=186) CFU m^{-3} respectively. In addition, there is a weak but significant correlation between the indoor ABC of the offices and the age of building ($R=0.24$, $p<0.005$). A total of 148358 bacterial isolates were grouped into gram-positive and gram-negative bacteria and the majority of the isolated bacteria belonged to gram-positive (77.7%), while 16.2% of isolates were gram-negative and 6.1% of isolates did not grow after subcultured.

Table 4.9: Common indoor air pollutant levels of air-conditioned offices of Hong Kong.

Assessment	Indoor				Outdoor			
	N	Range	AM (ASD)	GM (GSD)	N	Range	AM (ASD)	GM (GSD)
ABC								
B1	157	17-1231	465(246)	397(1.8)	53	15-1274	195(232)	118(2.7)
B2	82	60-488	206(98)	185(1.6)	26	26-120	63(29)	57(1.6)
AFC								
B1	157	12-776	165(118)	127 (2.2)	53	76-878	177(114)	158(1.6)
B2	82	0-92	29(22)	20(2.8)	26	20-212	94(47)	82(1.8)

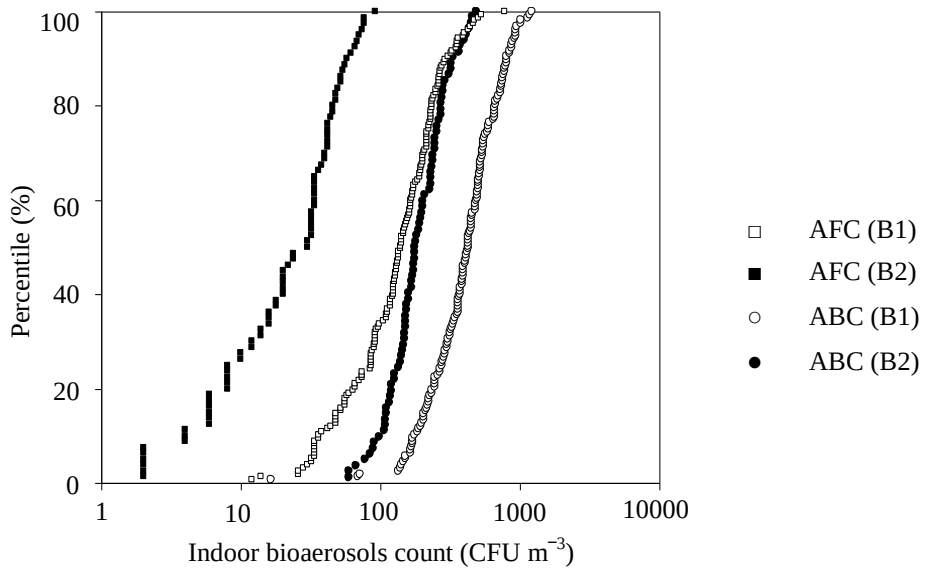


Figure 4.9: Distribution of indoor bioaerosols counts in air-conditioned offices in Hong Kong.

The regional cross-sectional assessment of indoor airborne fungi in the surveyed offices showed that the AFC ranged from 12 to 776 CFU m^{-3} and the AM and GM were 165 (ASD=118) CFU m^{-3} and 127 (GSD=2.2) CFU m^{-3} respectively. The 50^{th}, 75^{th} and 90^{th} percentiles of indoor AFC were 140, 222 and 308 CFU m^{-3} respectively. The corresponding outdoor AFC ranged from 76 to 878 CFU m^{-3} and the AM and GM were 177 (ASD=114) CFU m^{-3} and 158 (GSD=1.6) CFU m^{-3} respectively. No significant correlation between the indoor AFC and the outdoor AFC was reported ($p=0.71$). The AFC in offices located in urban areas were significantly higher when compared with those in the suburban areas ($p<0.05$), the AM were 171 (ASD=122) CFU m^{-3} and 127 (ASD=71) CFU m^{-3} respectively. However, the outdoor AFC of the offices located in suburban areas were significantly higher when compared with those in the urban areas, the AM were 205 (ASD=4) CFU m^{-3} and 173 (ASD=120) CFU m^{-3} respectively. These findings agreed with my previous studies which were focused on outdoor airborne fungi in Hong Kong, where the outdoor AFC was significantly higher in suburban areas when compared with those in the urban areas (Chan 2006). In addition, there is no correlation between the indoor AFC and the age of building ($R=0.06$, $p=0.48$). A total of 17983 and 4756 fungal isolates belonging to 20 and 19 fungal genera were identified in the indoor and outdoor samples, respectively. The results are summarized in Table 4.10. For the outdoor air samples, *Penicillium*, *Cladosporium* and *Aspergillus* with an average

AFC of 52, 37 and 25 CFU m^{-3} were reported dominant and were detected in 86.6%, 79.0% and 79.0% samples; while they contributed to 31.5%, 22.3% and 17.9% of total AFC, respectively. Fungal genera *Acremonium*, *Alternaria*, *Chaetomium*, *Curvularia* and *Paceilomyces* were present in 20.8–28.3% of the outdoor samples. Similar to the outdoor airborne fungal composition, *Penicillium*, *Aspergillus* and *Cladosporium* were also dominant in the indoor environments, the average AFCs were 48, 43 and 37 CFU m^{-3}, which were detected in 90.4%, 80.9% and 75.2% of sampling locations and represented 27.5%, 20.0% and 19.7% of total AFC, repectively. In regards to the composition of the dominant fungal genera, the following results were recorded. A total of eleven *Penicillium* spp. were isolated and identified with the relative abundance: *P. aurantiogriseum* (0.1%), *P. brevicompatum* (5.0%), *P. chrysogenum* (5.0%), *P. citrinum* (5.3%), *P. commue* (0.1%), *P. corylophilum* (0.4%), *P. digitatum* (0.2%), *P. expansum* (<0.1%), *P. glabrum* (3.7%), *P. griseofulvum* (0.2%), *P. olsonii* (0.1%) and unidentified *Penicillium* spp. (6.4%); while ten *Aspergillus* spp. were found which included *A. flavus* (1.7%), *A. niger* (6.5%), *A. ochraceus* (2.6%), *A. penicillioides* (0.1%), *A. sydowii* (1.7%), *A. tamari* (0.1%), *A. terreus* (0.1%), *A. ustus* (4.1%), *A. wentii* (0.2%), *A. versicolor* (1.0%) and unidentified *Aspergillus* spp. (1.8%); and a total of three *Cladosporium* spp. were recorded: *C. cladosporioides* (11.1%), *C. herbarum* (2.1%) and *C. sphaerospermum* (6.5%) respectively.

Table 4.10: Profile of airborne fungi in the regional typical air-conditioned offices in Hong Kong (Assessment B1).

Fungal genus/ species	Indoor (N=157)				Outdoor (N=53)				I/O ratio		RIFE
	Distribution (%)		Count (CFU m^{-3})		Distribution (%)		Count (CFU m^{-3})		AM	>1 (%)	
	OF	RA	Range	AM(ASD)	OF	RA	Range	AM(ASD)			
Total	100	-	12-776	165(118)	100	-	76-878	177(114)	1.1	47.1	
Acremonium strictum	26.1	3.1	2-80	19(20)	21.0	3.5	4-86	27(26)	0.9	5.1	1.04
Alternaria alternata	7.0	0.2	2-8	5(2)	19.7	3.0	2-58	25(14)	0.1	0.6	5.33
Total *Aspergillus*	75.2	20.0	2-240	43(50)	79.0	17.9	2-96	29(26)	2.6	31.2	0.85
A. flavus	22.3	1.7	2-32	12(8)	21.0	1.5	2-24	12(8)	0.7	1.9	0.94
A. niger	31.8	6.5	2-182	34(44)	45.9	8.1	2-94	29(19)	0.5	3.8	0.86
A. ochraceus	22.3	2.6	2-120	19(26)	19.1	1.8	2-44	15(12)	0.5	6.4	0.81
A. penicillioides	5.1	0.1	2-6	4(2)	0	-	-	-	a	a	a
A. sydowii	20.4	1.7	2-98	14(18)	19.1	1.6	2-26	14(8)	0.3	3.2	1.01
A. tamarii	1.3	0.1	4-12	8(6)	0.0	0.0	-	-	a	a	a
A. terreus	3.8	0.1	2-14	6(5)	3.8	0.3	2-20	11(10)	0.1	0	3.00
A. ustus	23.6	4.1	2-240	29(51)	35.0	3.0	2-52	14(14)	2.8	7.0	0.49
A. wentii	2.5	0.2	2-40	14(18)	1.9	<0.1	2-2	2	a	a	a
A. versicolor	15.3	1.0	2-28	10(7)	7.6	0.2	2-6	5(2)	0.3	1.3	0.40
Unidentified *Aspergillus* spp.	25.5	1.8	2-76	12(14)	17.2	1.4	4-32	13(9)	0.7	1.9	1.15
Aureobasidium pullulans	19.7	1.5	2-60	13(12)	17.8	2.1	2-72	19(18)	0.2	0.6	1.55
Chaetomium globosum	22.3	1.3	2-30	10(8)	20.8	1.9	2-86	16(26)	0.5	3.2	1.57
Total *Cladosporium*	80.9	19.7	2-288	37(39)	79.0	22.3	2-214	37(40)	1.2	30.6	1.16
C. cladosporioides	62.4	11.1	2-214	29(32)	59.2	14.6	2-136	41(33)	1.5	15.3	1.39
C. herbarum	31.2	2.1	2-68	11(12)	22.9	2.2	2-76	16(20)	1.0	3.2	1.43
C. sphaerospermum	46.5	6.5	2-120	23(24)	28.7	5.5	6-180	32(42)	1.0	8.3	1.37
Coelomyces	7.0	0.3	2-18	7(5)	11.5	1.4	4-76	20(26)	0.1	0.6	2.84

[a] The genus was detected in both indoor and outdoor samples but not correspondingly.

Table 4.10: Profile of airborne fungi in the regional typical air-conditioned offices in Hong Kong (Assessment B1) (Continue).

Fungal genus/ species	Indoor (N=157)				Outdoor (N=53)				I/O ratio		RIFE
	Distribution (%)		Count (CFU m^{-3})		Distribution (%)		Count (CFU m^{-3})		AM	>1 (%)	
	OF	RA	Range	AM(ASD)	OF	RA	Range	AM(ASD)			
Curvularia lunata	31.8	2.6	2-92	13(15)	24.8	1.6	2-24	11(7)	1.2	7.6	0.79
Curvularia geniculata	3.8	0.8	4-112	36(41)	1.9	0.2	14	14	2.7	0.6	0.50
Eurotium sp.	5.1	0.4	2-68	13(23)	7.6	0.5	8-12	11(2)	-	-	a
Fusarium sp.	19.7	1.7	2-44	14(23)	19.1	0.8	2-24	7(6)	1.2	5.1	0.49
Geotrichum candidum	5.1	0.1	2-8	4(2)	7.6	0.3	2-12	6(4)	-	-	2.01
Mucor sp.	1.3	0.1	6-24	15(13)	1.9	0.7	64	64	-	-	4.79
Paecilomyces sp.	30.6	3.0	2-132	16(21)	27.4	2.5	2-38	15(13)	0.9	5.7	0.93
Total *Penicillium*	90.4	27.5	2-440	48(51)	86.6	31.5	2-774	52(107)	2.1	40.1	1.20
P. aurantiogriseum	4.5	0.1	2-10	5(3)	1.9	0.1	6	6	0.4	0.6	2.37
P. brevicompactum	38.2	5.0	2-136	22(26)	33.1	5.5	2-108	28(29)	0.9	4.5	1.27
P. chrysogenum	36.3	5.0	2-300	28(44)	36.3	12.6	2-772	57(170)	0.9	7.6	2.52
P. citrinum	36.9	5.3	2-126	22(25)	26.8	3.5	2-78	21(21)	0.5	3.8	0.91
P. commue	2.5	0.1	4-8	6(2)	3.8	0.5	12-30	21(10)	-	-	3.29
P. corylophilum	4.5	0.4	2-50	15(17)	3.8	0.3	2-24	13(12)	-	-	0.89
P. digitatum	3.8	0.2	2-40	9(15)	1.9	0.4	32	32	-	-	4.00
P. expansum	1.3	<0.1	2	2(0)	1.9	0.0	2	2	-	-	0.07
P. glabrum	33.8	3.7	2-116	18(21)	25.5	3.5	4-78	23(18)	0.6	4.5	1.25
P. griseofulvum	2.5	0.2	4-18	11(7)	1.9	0.0	2	2	-	-	0.07
P. olsonii	3.2	0.1	2-12	6(5)	1.9	0.1	8	8	-	-	1.68
Unidentified *Penicillium spp.*	56.7	6.4	2-86	19(19)	47.8	5.1	2-44	17(11)	1.1	10.8	0.95
Phialophora sp.	3.8	0.2	4-12	7(3)	3.8	0.1	4-6	5(1)	0.6	1.3	0.50
Phoma sp.	19.7	0.7	2-24	6(6)	11.5	1.5	4-66	22(24)	0.1	0	3.67

[a] The genus was detected in both indoor and outdoor samples but not correspondingly.

Table 4.10: Profile of airborne fungi in the regional typical air-conditioned offices in Hong Kong (Assessment B1) (Continued).

Fungal genus/ species	Indoor (N=157)				Outdoor (N=53)				I/O ratio		RIFE
	Distribution (%)		Count (CFU m^{-3})		Distribution (%)		Count (CFU m^{-3})		AM	>1 (%)	
	OF	RA	Range	AM(ASD)	OF	RA	Range	AM(ASD)			
Rhizopus stolonifer	15.3	2.4	2-94	26(24)	7.6	0.5	2-32	12(13)	1.7	3.2	0.42
Scopulariopsis sp.	7.0	0.2	2-14	5(4)	0	-	-	-	-	-	a
Trichoderma sp.	7.6	0.3	2-24	7(6)	13.4	1.0	2-32	13(10)	0.1	0.6	1.89
Yeasts	18.5	1.1	2-44	10(10)	13.4	0.6	4-14	8(4)	0.7	2.5	0.75
Non-sporulating spp.	62.4	9.7	2-152	26(31)	61.8	11.3	2-168	30(35)	1.6	15.9	1.18
Unknown spp.	37.6	3.1	2-76	14(18)	21.0	2.1	2-38	16(12)	1.5	4.5	1.21

[a] The genus was detected in both indoor and outdoor samples but not correspondingly.

The IAQ assessment results of 82 air-conditioned offices in a single building are summarized in Table 4.11. The AM, ASD, GM, GSD of 11 indoor air pollutant levels are presented. Same as the regional cross-sectional study, the thermal comfort parameters (i.e. T, RH and V) of the surveyed offices can be approximated by normal distribution ($p>0.05$, Chi-square test) and the remaining 8 IAQ parameters are geometrically distributed ($p>0.05$, Chi-square test). The T, RH and V recorded in these locations in office hours are ranged from 19.5°C to 25.6°C, 42% to 69% and <0.05 m s^{-1} to 0.3 m s^{-1} respectively and the AM were 22.6 (ASD=1.2) °C, 51 (ASD=6) % and 0.08 (ASD=0.05) m s^{-1} respectively. It was reported that the CO_2 ranged from 455ppm to 970ppm, with a GM of 662 (GSD=1.2) µg m^{-3}; CO ranged from 0µg m^{-3} to 2025 µg m^{-3}, with a GM of 373 (GSD=2.5) µg m^{-3}; HCHO ranged from 3 µg m^{-3} to 92 µg m^{-3}, with a GM of 15 (GSD=2.6) µg m^{-3}; NO_2 ranged from 4 µg m^{-3} to 79 µg m^{-3}, with a GM of 17 (GSD=3.1) µg m^{-3}; O_3 ranged from 1 µg m^{-3} to 153 µg m^{-3}, with a GM of 14 (GSD=2.7) µg m^{-3}; Rn ranged from 1 Bq m^{-3} to 153 Bq m^{-3}, with a GM of 12 (GSD=2.9) Bq m^{-3}; RSP ranged from 6 µg m^{-3} to 37 µg m^{-3}, with a GM of 16 (GSD=1.4) µg m^{-3}; TVOC ranged from 9.2 µg m^{-3} to 1274 µg m^{-3}, with a GM of 158 (GSD=2.1) µg m^{-3}.

Table 4.11: Common air pollutant levels of outdoor of Hong Kong.

Parameter (Unit)	Assessment B1 (N=53)			Assessment B2 (N=86)		
	Range	AM (ASD)	GM (GSD)	Range	AM (ASD)	GM(GSD)
T (°C) [b]	20.9-35.9	28.5(3.0)	28.4(1.1)	22.2-32.0	26(2.3)	25.9(1.1)
RH (%) [b]	33-93	68(12)	67(1.2)	46-77	62(11)	61(1.2)
V (m s^{-1}) [b]	0.06-6.29	0.76(1.0)	0.49(2.46)	0.16-2.29	1.10(0.58)	0.93(1.93)
CO_2 (ppm) [a]	288-547	354(48)	352(1.1)	356-678	424(64)	421(1.1)
CO (ug m^{-3}) [a]	230-2874	1226(621)	1053(1.8)	0-2663	1060(784)	794(3.3)
HCHO (ug m^{-3}) [a]	0-35	9(7)	8(1.6)	-	-	-
NO_2 (ug m^{-3}) [a]	23-300	143(66)	126(1.7)	-	-	-
O_3 (ug m^{-3}) [a]	0-593	35(85)	22(1.9)	0-174	28(38)	12(10)
Rn (Bq m^{-3}) [a]	0-87	26(17)	22(1.9)	4-116	17(24)	11(2.5)
RSP (ug m^{-3}) [a]	0-458	61(69)	36(3.4)	11-220	102(64)	77(2.4)
TVOC (ug m^{-3}) [a]	0-2338	161(457)	25(9.7)	0-248	53(77)	18(6.5)

[a] The readings are geometrically distributed.

[b] The readings are normally distributed.

Indoor bioaerosols in Assessment B2 were approximated by a geometric distribution in this study ($p>0.05$, Chi-square test) (Figure 4.9). The airborne bacteria and fungi were detected in 100% and 97.6% of indoor air samples, respectively. No obvious indoor fungal source and no water damages and no visual fungal growth on walls and ceilings were reported. The indoor bioaerosols levels are summarized in Table 4.9. It is observed that both ABC and AFC recorded in offices with excellent IAQ (A2) were significantly lower when compared with other typical offices located in different regions of Hong Kong (B1). Compared with these typical offices of Hong Kong, better control for thermal conditions in the offices with excellent IAQ should be helpful in maintaining a lower indoor ABC and AFC levels when the system is operating, as fine-tuned operating conditions and proper maintenance of the MVAC system and use of effective filter to preventing indoor microbial contamination associated with outdoor sources (Kemp et al. 2003; Araujo et al. 2008).

The ABC ranged from 60 to 488 CFU m^{-3} and the AM and GM were 206 (ASD=98) CFU m^{-3} and 185 (GSD=1.6) CFU m^{-3} respectively. The 50^{th}, 75^{th} and 90^{th} percentiles of indoor ABC were 179, 257 and 357 CFU m^{-3} respectively. All samples had bacterial concentrations less than 500 CFU m^{-3}, which fulfilled the 'Excellent Class' requirements for indoor bacteria (HKEPD 2003). The corresponding outdoor ABC ranged from 26 to 120 CFU m^{-3} and the AM and GM were 63 (ASD=29) CFU m^{-3} and 57 (GSD=1.6) CFU m^{-3} respectively. No significant correlation between the indoor ABC and the outdoor ABC was established ($p>0.05$). The indoor ABCs recorded in all the offices were higher than the outdoor, the indoor concentrations recorded in these offices were approximately 3.9 times greater than the outdoor levels. The higher ABC in the indoor environments suggested the presence of indoor source. A total of 148358 bacterial isolates were grouped into gram-positive and gram-negative bacteria and the majority of the isolated bacteria belonged to gram-positive (77.7%), while 16.2% of isolates are gram-negative and 6.1% of isolates did not grow after re-subcultured.

While the indoor AFC ranged from 0 to 92 CFU m^{-3} and the AM and GM were 29 (ASD=22) CFU m^{-3} and 20 (GSD=2.8) CFU m^{-3} respectively. The 50^{th}, 75^{th} and 90^{th} percentiles of indoor AFC were 27 CFU m^{-3}, 42 CFU m^{-3} and 61 CFU m^{-3}. The indoor AFC was correlated to the outdoor AFC in the offices ($p<0.05$, t-test). The correlation was expressed as the outdoor AFC was approximately four times of the indoor AFC. The outdoor AFC ranged from 20 CFU m^{-3} to 212 CFU m^{-3} and the

AM and GM were 94 (ASD=47) and 82 (GSD=1.8) respectively. The outdoor AFC in this study was comparatively lower ($p<0.05$, t-test) as compared with the Hong Kong year-round average of 158 CFU m^{-3} (Chan 2006). The indoor AFCs recorded in 7.3% of the offices were higher than the outdoor, the indoor concentrations recorded in these offices were approximately 1.6 times greater than the outdoor levels. The composition of the indoor airborne fungi recorded in the air-conditioned offices of this single building is presented in Table 4.12. A total of 2368 and 2444 fungi isolates belonging to 13 and 18 fungal genera were identified in the indoor and outdoor samples respectively. For the outdoor air samples, *Alternaria, Cladosporium*, *Penicillium* and *Aspergillus* with an average AFC of 24 CFU m^{-3}, 19 CFU m^{-3}, 19 CFU m^{-3} and 14 CFU m^{-3} were reported dominant and were detected in (i.e. OF) 92.3%, 92.3%, 84.6% and 88.5% samples; they contributed to (i.e. RA) 23.8%, 18.2%, 16.9% and 13.3% of total AFC, respectively. Fungal genera *Acremonium, Drechslera*, *Fusarium, and Pestalotiopsis* were present in 19.2% to 50.0% of the outdoor air samples only (Table 4.12). In this study, the three *Alternaria* spp. recorded were *A. alternate, A. citri,* and *A. longipes*. However, there was no record of *Alternaria* in the indoor air samples of the present study. It is believed that these large spores were trapped by the filters in the ventilation system or this fungus might become stressed and thus contributed to the count of non-sporulating fungi. *Aspergillus*, *Penicillium* and *Cladosporium* with an average AFCs of 16 CFU m^{-3}, 13 CFU m^{-3} and 10 CFU m^{-3} were reported as dominant indoor fungal genera and were detected in 50.0%, 56.1% and 48.8% of the sampling locations, with OF of 28.5%, 25.9% and 16.5 %, respectively. In regards to the composition of the dominant fungal genera, the following results were recorded. A total of eight *Aspergillus* spp. were isolated and the RA belonging to *A. caespitosus* (0.4%), *A. flavus* (3.8%), *A. japonicus* (0.1%), *A. niger* (6.1%), *A. nivens* (2.0%), *A. sclerotiorum* (1.8%), *A. sydowi* (5.4%), *A. veriscolor* (0.2%) and unidentified *Aspergillus* spp. (8.7%); five *Penicillium* spp. were isolated, including *P. citreonigrum* (3.2%), *P. citrinum* (10.2%), *P. decumbens* (0.4%), *P. glabrum* (9.7%), *P. viridicatum* (0.2%) and unidentified *Penicillium* spp (2.2%); and five *Cladosporium* spp. were recorded, including *C. cladosporioides* (1.7%), *C. cucumerinum* (2.6%), *C. musae* (3.0%), *C. oxysporum* (0.6%) and *C. sphaerospermum* (8.6%) respectively.

Table 4.12: Profile of airborne fungi in the excellent IAQ air-conditioned offices (Assessment B2) and outdoor environment of Hong Kong.

Fungal genus/ species	Indoor (N=82)				Outdoor (N=26)				I/O ratio		RIFE
	Distribution (%)		Count (CFU m^{-3})		Distribution (%)		Count (CFU m^{-3})		AM	>1 (%)	
	OF	RA	Range	AM(ASD)	OF	RA	Range	AM(ASD)			
Total	97.6	–	2-92	29(22)	100	–	20-212	94(47)	0.5	8.5	b
Acremonium	0	0	0	0	23.1	3.1	4-28	12(10)	b	b	b
Alternaria	0	0	0	0	92.3	23.8	6-60	24(15)	b	b	b
Arithinium	11.0	3.6	2-20	10(6)	42.3	1.5	2-8	3(2)	0.2	2.4	0.62
Total *Aspergillus*	50.0	28.5	2-70	16(16)	88.5	13.3	2-36	14(9)	1.0	20.7	1.21
A. caespitosus	4.9	0.4	2-4	3(1)	30.8	1.6	2-8	5(3)	0.1	1.2	0.04
A. flavus	9.8	3.8	2-54	11(18)	26.9	1.7	2-16	6(5)	0.2	2.4	0.80
A. japonicus	1.2	0.1	2	2(0)	30.8	2.6	2-18	8(7)	b	b	<0.01
A. niger	18.3	6.1	2-30	10(8)	42.3	2.9	2-16	7(6)	0.5	3.7	0.90
A. nivens	8.5	2.0	2-20	7(7)	23.1	1.2	2-14	5(5)	b	b	0.60
A. sclerotiorum	6.1	1.8	2-16	8(6)	15.4	0.8	2-8	5(3)	<0.1	0	0.87
A. sydowii	9.8	5.4	4-36	16(12)	15.4	0.7	2-10	4(4)	b	b	5.23
A. versicolor	1.2	0.2	4	4(0)	19.2	0.7	2-6	4(2)	b	b	0.02
Unidentified spp.	28.0	8.7	2-26	8(8)	23.1	1.0	2-8	4(3)	0.1	0	10.55
Total *Cladosporium*	48.8	16.5	2-36	10(10)	92.3	18.2	2-48	19(14)	0.5	15.9	0.48
C. cladosporioides	3.7	1.7	18-20	19(1)	80.8	7.7	2-30	9(8)	0.1	2.4	0.01
C. cucumerinum	13.4	2.6	2-20	6(6)	53.8	4.1	2-12	7(3)	0.3	2.4	0.16
C. musae	7.3	3.0	2-28	12(9)	38.5	2.0	2-18	5(5)	0.5	0	0.29
C. oxysporum	4.9	0.6	2-4	4(1)	42.3	2.8	2-12	6(4)	<0.1	0	0.02
C. sphaerospermum	25.6	8.6	2-36	10(12)	30.8	1.7	2-12	5(5)	1.2	4.9	4.17
Coleomyces	6.1	1.6	2-22	8(8)	15.4	0.8	2-10	5(3)	b	b	0.79

[a] The range and AM of AFC in detected samples (i.e. count > 1 CFU m^{-3}) were calculated.
[b] The genus was detected in both indoor and outdoor samples but not correspondingly.

Table 4.12: Profile of airborne fungi in the excellent IAQ air-conditioned offices (Assessment B2) and outdoor environment of Hong Kong (Continue).

Fungal genus / species	Indoor (N=82)				Outdoor (N=26)				I/O ratio		RIFE
	Distribution (%)		Count (CFU m^{-3})		Distribution (%)		Count (CFU m^{-3})		AM	>1 (%)	
	OF	RA	Range	AM(ASD)	OF	RA	Range	AM(ASD)			
Curvularia	11.0	2.9	2-28	8(9)	38.5	2.4	2-12	6(4)	0.7	2.4	0.36
Drechslera	0	0	0	0	34.6	1.8	2-8	3(2)	0	–	0
Eurotium	9.8	1.4	2-10	4(3)	30.8	1.4	2-12	4(3)	0.3	1.2	0.32
Fusarium	0	0	0	0	19.2	0.5	2-4	2(1)	0	–	0
Geotrichum	7.3	0.9	2-6	4(2)	7.7	0.2	2	2(0)	0.2	0	4.27
Total *Penicillium*	56.1	25.9	2-54	13(13)	84.6	16.9	4-86	19(19)	0.6	13.4	1.02
P. citreonigrum	9.8	3.2	2-24	10(9)	53.8	3.4	2-28	6(8)	0.2	2.4	0.17
P. citrinum	23.2	10.2	2-48	13(13)	61.5	3.1	2-14	5(3)	0.4	6.1	1.24
P. decumbens	4.9	0.4	2-4	3(1)	53.8	3.5	2-24	6(7)	<0.1	0	0.01
P. glabrum	25.6	9.7	2-54	11(13)	42.3	3.1	2-14	5(3)	0.1	2.4	1.89
P. viridicatum	1.2	0.2	4	4(0)	3.8	0.2	2-12	7(4)	0.3	0	0.26
Unidentified spp.	11.0	2.2	2-16	6(5)	53.8	3.5	2-20	6(6)	0.3	2.4	0.13
Paceilomyces	8.5	2.5	2-20	8(7)	38.5	1.5	2-8	4(3)	0.2	2.4	0.35
Pestalotiopsis	0	0	0	0	50.0	3.1	2-18	6(5)	0	–	0
Phialophora	2.4	0.8	2-16	9(10)	23.1	0.9	2-6	4(2)	b	–	0.09
Trichobotrys	14.6	2.3	2-8	5(2)	15.4	0.4	2-4	3(1)	0.5	2.4	5.45
Trichoderma	2.4	1.1	10-16	13(4)	15.4	0.5	2-6	3(2)	0.7	1.2	0.34
Yeast	13.4	4.5	2-24	10(7)	19.2	2.5	2-38	12(15)	1.6	2.4	1.26
Non-sporulating	29.3	5.4	2-18	5(5)	53.8	4.8	2-20	8(6)	0.4	3.7	0.61
Sporulating	7.3	2.1	2-32	8(12)	30.8	2.5	2-12	8(4)	0.3	1.2	0.20

[a] The range and AM of AFC in detected samples (i.e. count > 1 CFU m^{-3}) were calculated.
[b] The genus was detected in both indoor and outdoor samples but not correspondingly.

Comparison with the typical air-conditioned offices in other countries

This study revealed a relatively high ABC in air-conditioned offices when compared with other countries. It is observed that the indoor ABC recorded in Hong Kong offices were significantly higher when compared with the study conducted in 100 large US office buildings (AM=100.3±49.6 CFU m^{-3}) (Tsai and Macher 2005), 34 mold damaged buildings (GM=122±4 CFU m^{-3}) and 43 non-problem buildings (GM=62±5 CFU m^{-3}) in Southern Finland (Salonen et al. 2007). However, the recorded indoor ABC in Hong Kong offices were similar when compared with that of a study conducted in Taiwan with similar climatic conditions with Hong Kong (Wu et al. 2005). Wu et al. (2005) reported that GM of ABC in office buildings with air-handling units (AHU, N=5) and fan coil units (FCU, N=7) were 390 CFU m^{-3} and 715 CFU m^{-3} respectively. When compared with the mean indoor ABC recorded from the public buildings with different usage in Korea, a lower indoor ABC were recorded in Hong Kong. The GM of indoor ABC recorded in hospital (N=10), childcare center (N=10), elderly welfare facility (N=10) and maternity recuperation center (N=10) were 382 (GSD=108 CFU m^{-3}), 536 (GSD=208 CFU m^{-3}), 334 (GSD=139 CFU m^{-3}) and 371 (GSD=114 CFU m^{-3}), respectively (Kim and Kim 2007).

When compared with the offices with unknown IAQ conducted in Hong Kong and other countries, a significantly lower AFC was recorded ($p<0.05$, t-test). Many studies have been conducted on the indoor airborne fungal assessment (Table 2.4); however, the detailed information on the composition (e.g. RA of each fungal genus) was usually limited. It was reported that the mean AFC recorded in typical buildings in other countries were AM=210 CFU m^{-3} and ASD=110 CFU m^{-3} (Shelton et al. 2002; Kemp et al. 2003; Wu et al. 2005).

In general, the fungal genera recorded dominant in the studied typical offices (B1) and offices with excellent IAQ (B2) in Hong Kong were also reported dominant in some other regions (Shelton et al. 2002; Kemp et al. 2003; Wu et al. 2005) (Figure 4.10). In general, a significant different pattern of fungal composition was reported in this study ($p<0.01$, Chi-square test). Apart from *Penicillium*, yeast and other spp. where there were no significant differences in the RA ($p\geq0.3$, t-test), *Aspergillus* had a significantly higher RA (28.5%) while *Cladosporium* had a lower one (16.5%) ($p<0.05$, t-test). No *Alternaria* (0%) was detected indoors in this study and it is

consistent with some studies that the RA was from 0% to 4.2% (Wu et al. 2005). It is believed that most large-spore fungal genera like *Alternaria* were trapped by air filters in the ventilation system. This fungus might also become stressed and thus contributed to the count of non-sporulating fungi.

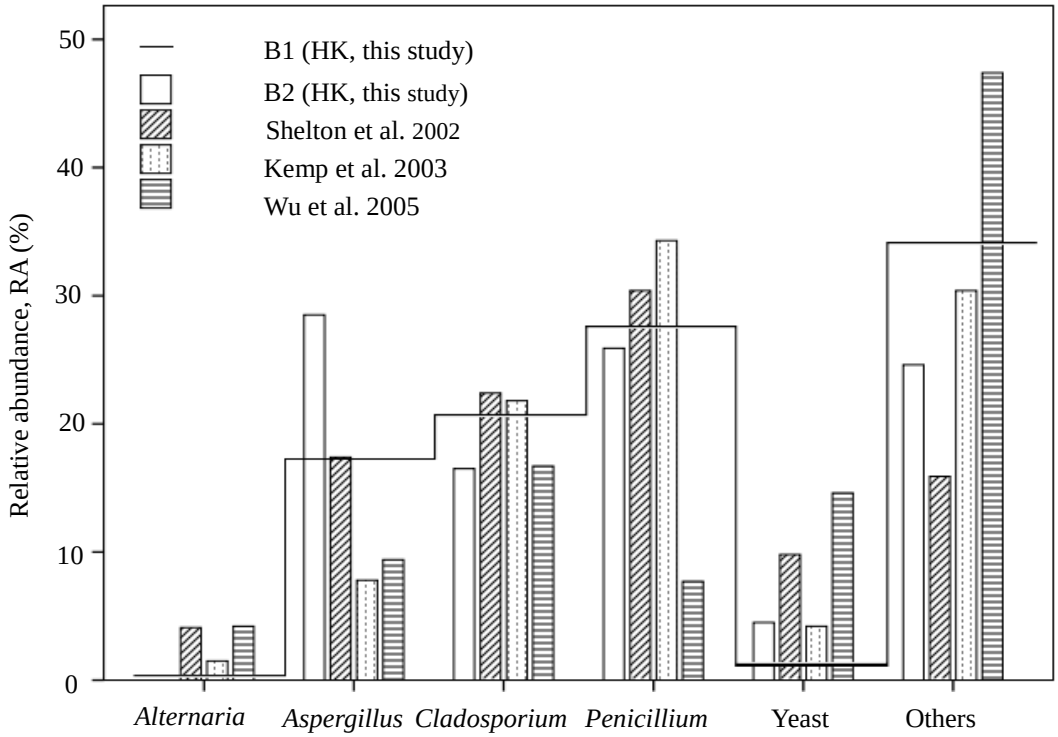


Figure 4.10: Comparison of profile of indoor fungi of air-conditioned offices in the present study and the other countries.

Relative Index for Exposure of Indoor Bioaerosols

The relative index for exposure of indoor bioaerosols in residential buildings is proposed in Chapter 3. This study revealed that the I/O ratio φ of bacteria in typical offices of Hong Kong (B1) ranged from 0 to 35.1 with mean φ of 5.8 (ASD=5.7). The ABC recorded in 85.4% of the offices were higher than that of outdoor, the indoor concentrations recorded in these offices were approximately 6.7 times greater than outdoor levels. The mean I/O ratio φ of bacteria of these typical offices were higher when compared with the offices with excellent IAQ (A2) although the 100% of samples collected from the offices in Assessment B2 were higher than that of outdoor. The I/O ratio φ of bacteria ranged from 1.1 to 11.4 with mean φ of 3.9 (ASD=2.5), the indoor concentrations recorded in those offices with φ >1 were approximately 3.9 times greater than outdoor levels. The reported mean I/O ratio φ

of bacteria in Hong Kong were significantly higher when compared with those in some other regions ($p>0.05$). For example, the I/O ratio φ of 100 large US office buildings ranged from 0.1 to 16.1 with mean φ^* of 1.3 (ASD=2.0) (Tsai and Macher 2005), and the mean φ of 1.06 and 1.05 in Taiwan office buildings equipped with AHU (N=5) and FCU (N=7) respectively (Wu et al. 2005). In addition to the office buildings, the GM I/O ratio φ reported for hospital, childcare center, elderly welfare facility and maternity recuperation center were 0.56 (GSD=0.26), 0.72 (GSD=0.21), 0.33 (GSD=0.18) and 0.66 (GSD=0.19) respectively (Kim and Kim 2007).

For the airborne fungi, the indoor AFCs recorded in 47.1% of the offices in the regional cross-sectional survey (B1) were higher than that of the outdoor, the indoor AFC recorded in these offices were approximately 1.5 times greater than outdoor levels (Table 4.9). The I/O ratio φ of fungi in these typical offices ranged from 0 to 4.9 with mean φ of 1.1 (ASD=0.9). This I/O ratio φ was significantly higher when compared with those offices with excellent IAQ (B2), which are summarized in Table 4.12. The I/O ratio φ of fungi ranged from 0.0 to 2.9 in the excellent IAQ air-conditioned offices with the mean φ was 0.5 (ASD=0.5). When compared with results in other regions, the I/O ratio φ of AFC in typical offices of Hong Kong (B1) were higher while the offices with excellent IAQ of Hong Kong (B2) were lower but similar to other countries with φ=0.5 (ASD=0.5) and ranged from 0.0 to 200 (Shelton et al. 2002; NIOSH 2003; Kemp et al. 2003; Wu et al. 2005; Kleinheinz et al. 2006). It was also reported that 8.5% of office samples had an I/O ratio greater than 1, which indicated the indoor AFCs in some offices were higher than the outdoor ones.

The relative exposure risk from fungi in the offices located in a single building with similar outdoor sources (Assessment B1) was chosen as an example for illustration. The RIFE ranged from <0.01 to 5.45 (Table 4.12) with regard to some example fungi groups of concern and are presented in Figure 4.11 with the corresponding I/O ratios shown for illustration.

Aspergillus and *Penicillium* were the dominant indoor airborne fungi, and their average I/O ratios were φ* =1.0 (ASD=2.1) and 0.6 (ASD=1). This might not give a clear indication of indoor sources. However, careful examination revealed that 20.7% and 13.4% of air samples had I/O ratios greater than 1, which indicated possible presence of indoor sources in some offices for these fungi. It was also

reported that the RIFE ϖ* of *Aspergillus* and *Penicillium* were 1.21 and 1.02 respectively, which indicated a higher relative indoor exposure risk as compared with that of the outdoors. *Aspergillus* and *Penicillium* can induce allergic diseases or syndromes, infectious diseases like Aspergillosis, and the genus produces a wide range of mycotoxins, including aflatoxin B1, ochratoxin A, and sterigmatocystin; while *P. glabrum* is also known to produce trypacidin and citromycetin and *P. ctrinum* has been reported to produce the 32–34 kDa alkaline allergens and is associated with asthma (Kurup et al. 2002; Jarvis and Miller 2005). Yeast grows mainly indoors in this region with an I/O ratio φ* of 1.6 (ASD=4). A high relative exposure risk of Yeast in the office was reported by a high RIFE of 1.26 (shown in Figure 4.12). *Cladosporium* was generally reported to be more abundant outdoors than indoors ($p<0.05$, t-test). The presence of *Cladosporium* indoors was mainly due to the outdoor sources (I/O ratio was φ*=0.5). The low relative exposure risk indicated by the RIFE was $\varpi_i^* = 0.48$. The results indicated, in terms of the total example fungi related health concerns that the air-conditioned offices in this office building with excellent IAQ was associated with a low exposure risk (i.e., $\varpi_i^* <1$) overall as compared with the outdoor environment. Furthermore, there is a difference in the RIFE of these dominant fungal groups between the samples collected in Assessment B1&B2 (Figure 4.11). The RIFE of *Aspergillus*, *Cladosporium* and *Penicillium* were 0.85, 1.16 and 1.20 respectively. The highest RIFE in regional typical offices and offices with excellent IAQ were *Alternaria alternate* (5.33) and *Trichobotrys* sp. (5.45).

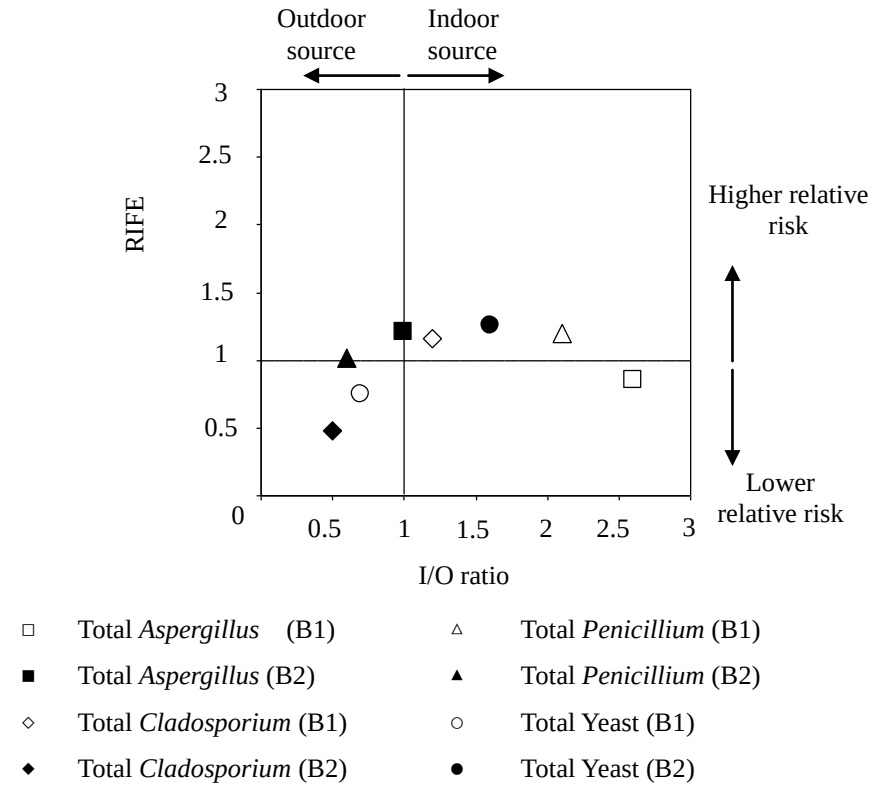


Figure 4.11: Comparisons of I/O ratios and RIFE of example fungi groups.

Trends of indoor bioaerosols level in air-conditioned offices of Hong Kong

As mentioned in Chapter 2, the development of the current IAQ policy could be traced back to early 1990's and a review of IAQ guidance notes (GN) and a voluntary IAQ certification scheme were implemented in Hong Kong in 2003 (IAQMG 2003; HKEPD 2003). Hui et al. (2006) evaluated the changes of indoor air pollutants levels in air-conditioned offices of Hong Kong by comparing the findings recorded in the assessments conducted from 1996 to 2003. It was revealed that the level of CO_2, HCHO and ABC were decreased and the predicted satisfactory rates were enhanced with the GN implementation from 1999 to 2003. However, in this study, the airborne bacterium is the only bioaerosols assessed parameter and the airborne fungus is not evaluated. By comparing the indoor bioaerosols level in the assessments conducted before and after the implementation of the current IAQ policy in 2003, the possible influences of the IAQ policy on the bioaerosols exposure levels in air-conditioned offices of Hong Kong can be investigated.

The indoor bioaerosols investigations in previous studies in Hong Kong (Table 2.5) and Assessment B1&2 (Table 4.9) were regarded as before and after the implementation of current IAQ policy, respectively. It is observed that both ABC and AFC recorded in previous studies were significantly higher when compared with those in Assessment B1&2 ($p<0.001$, t-test). The indoor ABC and AFC are good indicators of the cleanliness of the MVAC system as well as the potential source in the indoor environment. These parameters are important to evaluate the IAQ and appropriate remedial actions will be taken when the office is considered as 'unsatisfactory'.

The estimated unsatisfactory rates of ABC and AFC for the offices in Hong Kong against the 'Good level' defined by the IAQ certification scheme are determined by Equation 4.1 and the failure percentage is presented in Figure 4.12. The results in the previous studies revealed that the highest failure percentage of both ABC and AFC and were significantly higher when compared with B1&2 ($p<0.05$, t-test). The failure percentage of ABC decreased from 15% to 7% (B1) and 0% (B2) while the failure percentage of AFC decreased from 55% to 1% (B1) and 1% (B2), respectively. This is a matter of concern since various human health and comfort implications associated as the MVAC system is also responsible for providing a path to transport microorganisms from the source of contamination to occupants in the vicinity of the building (Law et al. 2001; Seino et al. 2005).

The improvements in reducing the indoor bioaerosols in air-conditioned offices can be explained by the implementation of GN and IAQ certification scheme by the HKEPD in 2003 (HKEPD 2003). The HKEPD recommended the ways to improve IAQ by controlling the indoor air pollutants through source control and dilution by ventilation (IAQMG 1999). Therefore, most developers and maintenance staff has adopted the approach of increasing the fresh air supply in order to improve the IAQ thus removing the indoor bioaerosols. The enhancement of the ventilation can be proved by the decrease in the failure percentage CO_2 level from 60% to 10% (B1) and 8% (B2).

Apart from increasing the fresh air supply, HKEPD recommended several ways to improve the IAQ. These include air cleaning and administrative action (HKEPD 2003). The ventilation systems of many office buildings have scheduled maintenance targeted for an excellent indoor environment. The maintenance includes cleaning the

ventilation systems and replacing of the filters. In addition, the HKEPD (2003) recommended the use of particulate filters with high dust spot efficiency (85% or higher) and electrostatic precipitators can mitigate problems caused by the particulate pollution or fungal spores.

It is known that RH and T are the important parameters to control the survival. Hui et al. (2006) reported that the high predicted unsatisfactory rates for RH and T recorded in A was due to the fact that most existing air-conditioning systems had not yet been renovated to cater for the increased fresh air loads. Therefore, the trend of decrease of the unsatisfactory rates are not surprising, as the operating conditions of the occupied period in these in-use offices were fine-tuned so that a good balance between the occupant's satisfaction of thermal comfort and energy conservation of air-conditioning offices would be achieved (Mui and Wong 2007a,b; Mui et al. 2007). Furthermore, the enhancement of the dehumidification of the system in the offices studied in B1&2 resulted in the significantly lower average RH (50%) compared with the average office RH of 60% in Hong Kong ($p<0.05$, t-test), which should be helpful in maintaining a lower indoor ABC and AFC levels when the system was operating.

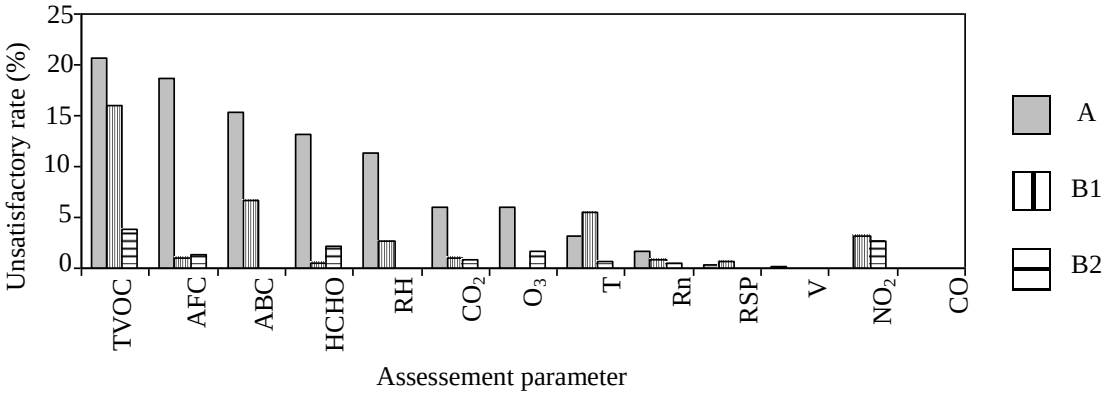


Figure 4.12: Comparison of expected unsatisfactory rates of environmental parameters in air-conditioned offices obtained in Database A and B.

Case study 1: Effects of different operation conditions of the ventilation system on the profile of indoor bioaerosols

Apart from the indoor environmental conditions (e.g. T, RH, etc.), the operation of the ventilation system is also one of the major factors affecting the indoor bioaerosols levels. Improper maintenance or contaminations of MVAC system are known to lower down the IAQ. Studies show that the operation of the MVAC system in offices has significant influence on both the indoor airborne bioaerosols levels (Chow et al. 2005). During the main MVAC system off period, the bacteria and fungi levels were significantly higher than that measured when the system was operating as shown in Law et al. (2001). It was believed that when the main MVAC system was not in operation, T increased and water vapor condensed on the indoor building materials as well as inside the system, which had provided a favourable condition for indoor microbial growth (Wong 1997; Chow et al. 2005). The accumulation of the organic and inorganic matters in the system provides a favorable condition with moisture and plenty of nutrients for microbial growth (Kemp et al. 2001). In addition, differences in the mechanical design of the ventilation systems, such as differences between FCU and AHU, also affect the indoor bioaerosols levels (Wu et al. 2005).

Therefore, a better understanding of the effect of the operation of the MVAC system on the indoor bioaerosols (airborne bacteria and fungi) level are required in order to improve the IAQ. An unoccupied office equipped with MVAC system was chosen to evaluate the variations of indoor bioaerosols in order to minimize the possible effects due to the fluctuation of the presence of humans. This part of study aims to investigate the background level of indoor bioaerosols in an office with "excellent" provisions under different operations of the MVAC system. This study can provide a useful source of information to policymakers in operating the MVAC systems in respects of the IAQ.

An unoccupied (2 months) open-planned office was chosen in the same Grade A office building in Assessment B2 (Figure 4.8). All the furniture inside the office was removed and entry was restricted. The office was served by a single AHU and the size is 384 m^2. An 8-day assessment was conducted during 21st to 28th December 2006. The assessment period consisted of both working and non-working days. The working day included weekday (WD), weekend (WE) and weekday after holiday

(AH); while non-working days included Sunday and Christmas Holiday (SH). Therefore, the air-conditioning system was operated under different modes during the assessment period and thus the environmental conditions in the office would be different. The schedule for operation of the MVAC system and the indoor bioaerosols and IAQ monitoring are presented in Table 4.14. The air-conditioning and ventilation system performance during the sampling period was measured by using Sulphur Hexafluiride (SF_6) constant concentration method (Mui 2002). The ventilation rates were measured under ventilation system ON and OFF conditions. Air samples were taken at 1m above the floor at the center of the office. The indoor bioaerosols samples were collected 07:30 to 21:30 during period WD, WE and AH from 08:30 to 20:30 during period SH. The thermal comfort parameters (i.e. T and RH) were monitored continuously throughout the sampling period. In order to monitor the operation mode of the AHU system, variations of T were recorded at the AHU room (i.e. air outlet, mixing chamber and the outdoor air inlet) continuously.

Table 4.13: Sampling schedule of indoor bioaerosols in unoccupied air-conditioned office.

Day	Sampling period	Normal office hour	MVAC system (On)	Measurement	
				Bioaerosols [a]	IAQ parameter [b]
1-2	Weekday (WD)	09:00 to 18:00	07:00 to 19:00	07:30 to 21:30	00:00 to 24:00
3	Weekend (WE)	09:00 to 13:00	07:00 to 13:00		
4-6	Sun & Holiday (SH)	–	–	08:30 to 20:30	
7	After holiday (AH)	09:00 to 18:00	07:00 to 19:00	07:30 to 21:30	

[a] Bioaerosols samples were collected every 1 hour in the office area.

[b] 6 IAQ parameters (i.e. T, RH, CO_2, CO, PM_{10} and TVOC) were recorded every 5 minutes in the office area; T were recorded every 10 minutes automatically in the AHU room (air inlet, mixing chamber and air outlet).

The air change rate per hour (ACH) recorded under the ventilation system ON and OFF conditions were 1.31 and 0.17 respectively. The air change rate recorded under the ventilation system OFF condition was due to infiltration. The distributions of the thermal comfort parameters (i.e. T and RH) and 2 bioaerosols (i.e. airborne bacteria and fungi) are shown in Table 4.14 and 4.15 respectively. The distributions of the assessed parameters were tested and described by a geometric distribution for bioaerosols and by a normal distribution for thermal comfort parameters.

The T recorded in the AHU room fluctuated under different operation modes of the

MVAC system (Figure 4.13). The T of outdoor air supply was 20.68±0.89°C. During system on period, the average T recorded at the air return, AHU air outlet and office area were 17.80±0.62°C, 14.20±1.10°C and 18.00±0.95°C respectively. Significantly higher temperature ($p<0.01$) were recorded when the AHU was switched off during working day mode, with average temperature of 19.3±0.8°C, 19.9±0.9°C and 20.2±1.2°C recorded at the air return, AHU air outlet and office area respectively. During period SH, the variation of T recorded in the AHU room was quite similar and increased for 1.3°C to 1.9°C. Higher fluctuation of T was observed in the office area, the T increased by 2.6°C after 72 hr after switched off of the system and the average was 21±0.7°C.

Table 4.14: Variation of indoor environmental parameters in an occupied office.

Parameter [a]	T (°C)		RH (%)	
MVAC system	**ON**	**OFF**	**ON**	**OFF**
Day 1 (WD)	17.7 (0.7)	19.7 (0.8)	15.2 (21.8)	73.4 (1.4)
Day 2 (WD)	17.5 (0.7)	19.8 (0.8)	11.5 (13.9)	95.3 (1.4)
Day 3 (WE)	17.9 (1.2)	19.7 (0.9)	29.7 (22.0)	48.8 (1.4)
Day 4 (SH)	-	20.4 (0.5)	-	47.5 (1.0)
Day 5 (SH)	-	20.8 (0.5)	-	47.8 (1.0)
Day 6 (SH)	-	21.7 (0.2)	-	46.6 (1.0)
Day 7 (AH)	18.5 (1.0)	20.9 (1.1)	90.0 (75.4)	36.1 (1.4)

[a] The readings are normally distributed and AM (ASD) are shown.

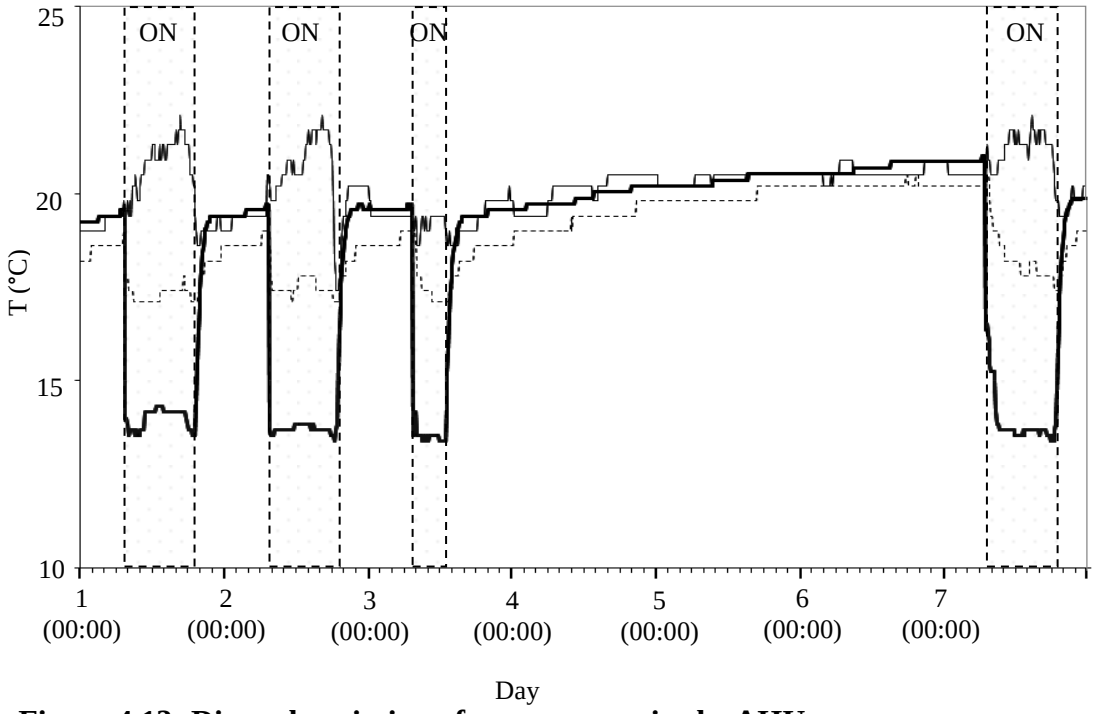


Figure 4.13: Diurnal variation of temperature in the AHU room.

The daily average of indoor bacteria and fungi levels during the operation of the MVAC system on and off period are presented in Table 4.15. In general, the overall average ABC recorded during period SH (i.e. Day 4 to 6) were the highest and significantly higher than period WD (i.e. Day 1 and 2), followed by AH (i.e. Day 7) and WE (i.e. Day 3) ($p<0.05$), the GM were 105±0.4 CFU m^{-3}, 94±1.5 CFU m^{-3}, 75±2.4 CFU m^{-3}, 61±2.0 CFU m^{-3} respectively. It may probably due to the higher T during period SH when the system was off ($r = 0.36$, $p<0.05$). Therefore, the growth of indoor bacteria increased and accumulated, which were not diluted by the ventilation. In addition the I/O ratios of ABC were the highest during period AH and SH, followed by WD and WE, which were 4.8±7.3, 4.1±5.8, 1.9±1.5 and 1.4±1.2 respectively.

It is also revealed that indoor ABC in the unoccupied office during the period with system on is significantly lower when compared with the average levels recorded in typical offices located in different regions of Hong Kong as well as in the other occupied offices within the same building ($p <0.05$) (Table 4.9). It is not surprising that since the major source of airborne bacteria indoors are due to the presence of human as well as generated from different human activities, therefore, relatively lower counts were expected in an unoccupied area. The average (GM) of indoor bacteria level were 87±1.5 CFU m^{-3}, 49±1.4 CFU m^{-3} and 75±2.5 CFU m^{-3} during system on at period WD, WE and AH respectively.

Table 4.15: Variation of indoor and outdoor bioaerosols in an occupied office.

Parameter [a]	Indoor				Outdoor			
	ABC (CFU m^{-3})		AFC (CFU m^{-3})		ABC (CFU m^{-3})		AFC (CFU m^{3})	
MVAC system	ON	OFF	ON	OFF	ON	OFF	ON	OFF
Day 1 (WD)	73 (1.4)	130 (1.8)	12 (3.2)	22 (1.5)	77 (1.3)	68	92 (1.5)	118
Day 2 (WD)	95 (1.4)	166 (1.2)	12 (2.2)	23 (1.8)	66 (2.0)	52	92 (1.7)	174
Day 3 (WE)	49 (1.4)	70 (2.3)	20 (3.4)	11 (2.2)	34	69 (1.7)	180	100 (1.7)
Day 4 (SH)		93 (1.3)		29 (2.3)		24 (2.5)		138 (1.7)
Day 5 (SH)	-	124 (1.3)	-	26 (1.9)	-	40 (1.3)	-	145 (1.7)
Day 6 (SH)		100 (1.6)		33 (2.7)		42 (1.4)		150 (1.7)
Day 7 (AH)	75 (2.5)	76 (2.1)	65 (2.4)	15 (1.8)	32 (2.1)	64	179 (1.5)	292

[a] The readings are geometrically distributed and GM(GSD) are shown.

The variations of indoor airborne bacteria level during the sampling day at different periods are shown in Figure 4.14. It is observed that the indoor airborne bacteria level varied a lot during the day. As shown in Figure 4.14a, during period WD, no obvious trend of ABC was observed. However, the ABC increased after shutting down the system at 19:00, which was 1.5 times significantly higher than that within the system on period (i.e. 07:00 to 19:00) ($p<0.05$). Similarly, the ABC also increased after shutting down the system at 13:00 during period WE, the GM was 1.6 higher (not significantly) than that during the system on period (i.e. 07:00 to 13:00) (Figure 4.14b). As shown in Figure 4.14c, there is no general trend during period SH and the ABC among the samples within the same period shows to be not significant ($p>0.05$). During period AH, the ABC increased from 07:30 to the peak at 08:30 and then decreased afterward (Figure 4.14d). The ABC recorded at 08:30 was 252 CFU m^{-3}, which was 1.1 to 9.7 times higher than those at other sampling times during the day.

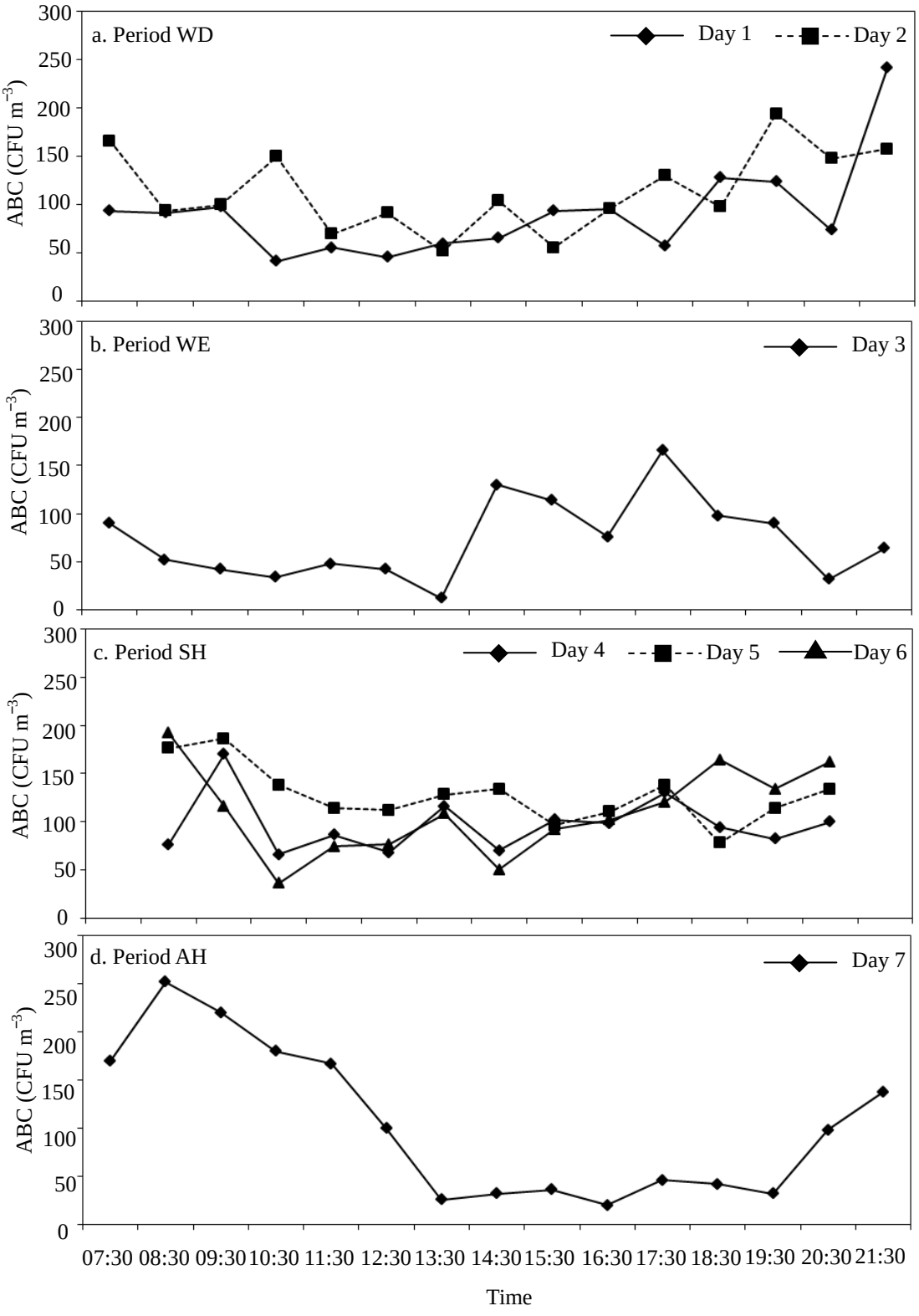


Figure 4.14: Variation of indoor airborne bacteria level during the day.

As shown in Table 4.15, the variations of AFC were different from that of ABC. The overall average AFC recorded during period AH were the highest, which was significantly higher when compared those with WE and SH ($p<0.05$), while higher (not significantly) than that with WD ($p>0.05$). The overall average (GM) AFC were 48±2.7 CFU m^{-3}, 29±2.3 CFU m^{-3}, 14±2.7 CFU m^{-3} and 11±2.5 CFU m^{-3} respectively. Similar to indoor bacteria, the I/O ratios of AFC were higher during period AH and SH, followed by WD and WE, which were 0.4±0.4, 0.3±0.2, 0.2±0.3 and 0.2±0.1 respectively. Similar to indoor bacteria, it is also revealed that indoor AFC in the unoccupied office during the period with the system on was significantly lower when compared with the average levels recorded in typical offices located in different regions of Hong Kong as well as in the other occupied offices within the same building ($p <0.05$) (Table 4.9). The average (GM) of indoor fungi level were 10 ± 2.7 CFU m^{-3}, 20 ± 3.4 CFU m^{-3} and 65 ± 2.4 CFU m^{-3} during system on at period WD, WE and AH respectively.

The variations of indoor airborne fungi level during the sampling day at different periods are shown in Figure 4.15. Except the peak at 9:30 of period WD and 8:30 of period WE, the fluctuation of AFC during the sampling day was small (Figure 4.15a and b). The fluctuation of AFC during period SH was higher; however, no obvious trend was observed (Figure 4.15c). After shutting down the system for 3 days, the AFC increased from 07:30 to a peak at 08:30 and then decreased throughout the day with a small peak at 13:30. The AFC recorded at 08:30 was 236 CFU m^{-3}, which was 1.0 to 29.5 times higher than those in other sampling times during the day.

A peak in the early morning of both ABC and AFC were revealed during period AH in this study. This observation was also reported in the occupied offices, with the peak bioaerosols levels in daily profiles usually occurred in the early morning (Wong 1997; Chao et al. 2001; Law et al. 2001; Chan et al. 2003; Chow et al. 2005). It was probably due to amplification of bioaerosols during shut down period of the MVAC system, and the situation is more obvious in this sampling period as the system was shut down for 3 days (period SH). Microorganisms amplified on the interior surfaces of the air ductworks and the filters. Once the system was operated again in the morning, the microorganisms were brought into the building premises through the air supply inlet and then spread out (Flannigan 2001; Chow et al. 2005). The air was filtered through the system so that the indoor bioaerosols was decreased more in the afternoon during system on period. In addition, it is observed that both ABC and

AFC recorded during early morning (i.e. 09:00 to 10:00) on Monday (N=13) in other occupied offices within the same building were higher (not significantly) than the counts recorded on other working days (i.e. Tuesday to Friday, N=69) (Assessment B2). The GM of ABC recorded were 208±1.4 CFU m^{-3} and 180±1.6 CFU m^{-3} in early morning of Monday and other working days respectively, while the GM of AFC were 29±2.9 CFU $m^{-3}$and 19±3.0 CFU m^{-3} respectively.

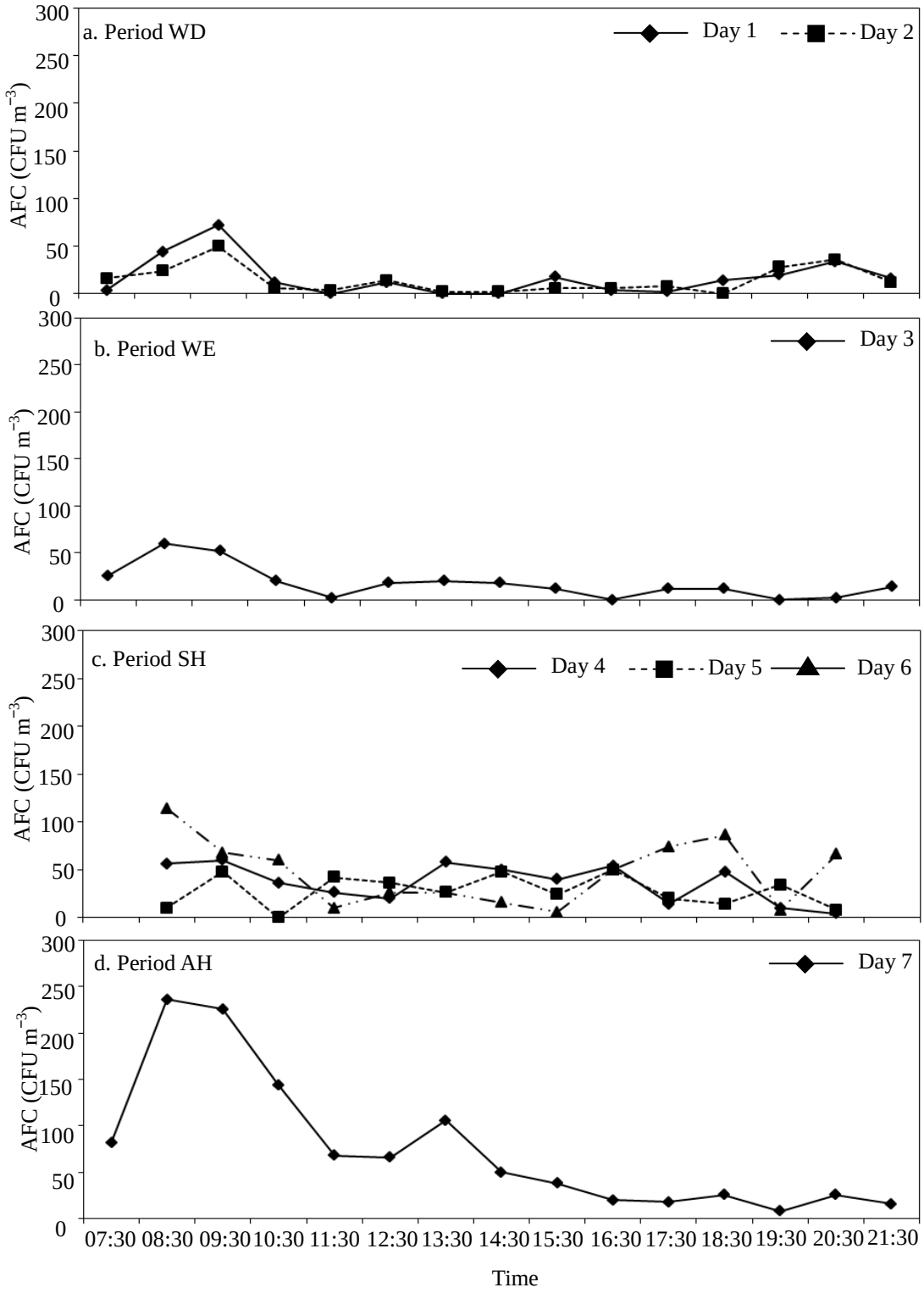


Figure 4.15: Variation of indoor fungi level during the day.

Case study 2: Indoor bioaerosols in air-conditioned washrooms

Bioaerosols contaminations of washrooms have received a lot of attention since the rapid global outbreak of Severe Acute Respiratory Symptoms (SARS) in 2003. In Hong Kong, 1755 people was infected and more than 17% (>300 cases) of patients lived in the Amoy Gardens Estate and 41% of them lived in Block E (DH 2004). One of the hypotheses of this community outbreak was the improper maintenance of the floor drain traps (WHO 2003; Yu et al. 2004). The WHO (2003) team found that the floor drain traps in many apartments had not been filled with water for long periods at the time of the outbreak, the seals in the traps was dried out and an open connection to the soil stack (drainage pipe) was generated. When the exhaust fan was turned with a closed door, the fine droplet and aerosols were drawn out from the soil stack into the bathroom through the unsealed floor drain and contaminated the bathroom and thus infected the residents (WHO 2003).

Apart from the floor drain, in both domestic and commercial buildings, flushing the toilet can also generate bioaerosols and contaminate the bathrooms and washrooms (Gerba et al. 1975, Barker and Bloomfield 2000, Barker and Jones 2005). Microorganisms have been isolated from the water tap, sink, toilet seat and lid, flush handle, door knob and floor (Gerba et al. 1975; Barker and Bloomfield 2000; Barker and Jones 2005). Barker and Jones (2005) conducted a toilet seeding experiment and measured the level of bioaerosols generated due to flushing of the toilet. It was reported that the abundance of *Serratia marcesens* in air increased sharply from 0 CFU m^{-3} to 1370 CFU m^{-3} after the first flushing and decreased in further flushing (Barker and Jones 2005). The risk of contamination was greatest during actual diarrhoeal diseases when billions of microorganisms were being flushed down the toilet. The common airborne bacteria genera isolated in washrooms were *Bacillus*, coliforms, *Micrococcus*, *Pseudomonas* and *Staphylococcus* (Lee 2006).

In Hong Kong, the contaminated air in washroom is generally removed via exhaust air grilles at ceiling levels at a mechanical ventilation rate varied from 6 to 10 air changes per hour (BSRIA 2001; CIBSE 2005). However, there is lack of information on microbiological air quality of washrooms. It has also been reported that the ABC varied within a day due to different occupancy load and operation modes of the MVAC system (Law et al. 2001; Chow et al. 2005). As the occupancy load and operation of the MVAC system in washrooms varied throughout the day, therefore the ABC in washrooms may also vary (Wong and Mui 2006; 2007). This study

investigated the microbiological air quality in a washroom of a typical high-rise office building in Hong Kong.

Site descriptions

An assessment of indoor airborne bacteria of washrooms in Assessment B2 was conducted. This study consisted of 2 parts: Part A – air sample was collected randomly from 50 washrooms (i.e. 25 male and 25 female washrooms) during working days (weekdays, WD); Part B – air sample was collected at a washroom at 11th Floor from 08:00 to 20:00 at a time interval of 4 hours during different periods (i.e. WD, WE, SH and AH). 500 L airborne bacteria samples were taken at 1m height at the center between the water closet cubicle and the washbasin by using the RCS with agar strips TC. The T and RH were also recorded during the sampling and are presented in Table 4.16.

Indoor bacteria levels in washrooms

The outdoor T of this period ranged from 15°C to 23°C and daily average T was 17.5 °C to 19 °C. The daily average RH in the period was from 50 % to 80 %. Daily sunshine was from 8 to 10.5 hr and no rainfall was recorded. The average T and RH recorded in washrooms (N=50) were 21.9±1.1% and 57.2±8.3% respectively (Table 4.16). It is observed that the T is similar to the offices of the same building but with higher RH (compared with B2 in Table 4.8). The overall ABC ranged from 20 CFU m^{-3} to 829 CFU m^{-3} and the GM was 572±2.3 CFU m^{-3}. It is interesting that the ABC in female washrooms were significantly higher than that in the males', which were 664±2.3 CFU m^{-3} and 492±2.2 CFU m^{-3} respectively.

The ABC recorded in this study was significantly higher than the reported means of the studies in other countries, which ranged from 24 CFU m^{-3} to 528 CFU m^{-3}, with an average of 179±112 CFU m^{-3} ($p<0.05$) (Taylor et al. 2000; Lee 2006). Moreover, the ABC recorded in the washrooms was also more significant than the offices of the same building. The result is not surprising as the bacteria sources in washroom are more abundant when compared with offices which include the toilet, used paper, hand towel, cleansing equipment and rubbish bin (Gerba et al. 1975; Talyor et al. 2000; Ojima et al. 2002). And the relatively higher RH recorded in washrooms also favor the growth of bacteria (Flannigan 2001).

Table 4.16: Schedule of operation of the MVAC system in the office building during sampling period.

Sampling period	Operation of the MVAC system		Normal office hour	Average T (°C)	Average RH (%)
	On	Off			
Part A					
WD	07:00-19:00	19:00-07:00	09:00-18:00	21.9 ± 1.1	57.2 ± 8.3
Part B					
Day 1 and 2 (WD)	07:00-19:00	19:00-07:00	09:00-18:00	21.3±0.6	53.9±6.3
Day 3 (WE)					
Day 4 to 6 (SH)	-	0:00-24:00	-	23.3±0.6	68.5±4.2
Day 7 (AH)	07:00-19:00	19:00-07:00	09:00-18:00	22.1±0.8	51.0±2.8

In order to evaluate the effect of occupancy load on the microbiological quality of air in washrooms, it was assessed by the ABC in air and comparison of the ABC was made across the samples collected at different time of a day and different periods. The ABC should be different due to different occupancy load as well as different operation mode of the MVAC system. These hypotheses were tested against the measured counts with the t-statistic at a level of significance $p<0.05$, where $\overline{X}_a$ (CFU m^{-3}) is the expected count, S_a (CFU m^{-3}) is the sample standard deviation and n is the sample size.

$$t_{statistic} = \frac{\overline{X}_a}{S_a / \sqrt{n}_a} \quad \text{... (Eq. 4.12)}$$

The variation of ABC at different period and sampling time are presented in Table 4.17. It is reported that the indoor ABC varied from 230 CFU m^{-3} to 1505 CFU m^{-3} with an overall average of 639±1.6 CFU m^{-3}. The I/O ratios of ABC varied from 9.1 to 65.0 with an overall average of 25.9±15.8.

Table 4.17: The average ABC and I/O ratio at a washroom in a high-rise office building of Hong Kong.

Time	WD (2 days)		WE (1day)		SH (3 days)		AH (1 day)	
	Count (CFU m^{-3})	I/O ratio	Count (CFU m^{-3})	I/O ratio	Count (CFU m^{-3})	I/O ratio	Count (CFU m^{-3})	I/O ratio
08:00	384	4.1	625	39	1121	63.4	980	4.7
	±1.3	±1.3			±1.3	±64.2		
12:00	541	7.0	630	45	904	16.9	500	4.8
	±1.1	±2.7			±1.3	±1.9		
16:00	576	11.6	780	65	892	29.8	500	10.3
	±1.2	±4.4			±1.2	±12.2		
20:00	297	6.6	230	16	876	28.1	330	9.4
	±1.3	±2.9			±1.0	±9.6		
Daily average	434	7.3	516±1.7	41±20	943	34.5	533	24.1
	±1.4	±3.8			±1.2	±33.5	±1.6	±30.8

The ABC among the samples within the same period showed no significant difference ($p>0.05$). The daily average of airborne bacteria count recorded in the samples of period WD, WE, SH and AH were 437±1.4 CFU m^{-3}, 516±1.7 CFU m^{-3}, 943±1.2 CFU m^{-3} and 533±1.6 CFU m^{-3} and with daily average of I/O ratios of 7.3±3.8, 34.5±33.5 and 24.1±30.8, respectively. The results showed that both ABC and I/O ratio at period SH were the highest which were 1.5 to 3.1 times and 2.9 to 15.3 times significantly higher than the samples collected during the other periods ($p<0.05$). The MVAC system of the office building was shut down in the period SH (Table 4.16). Although lower occupancy load in period SH was expected, significantly high ABC was recorded in offices during the main MVAC system off period as the T increased and water vapor condensed on the indoor building materials as well as inside the system which favored the growth of microorganisms (Law et al. 2001; Chow et al. 2005). A significantly higher T and RH were also recorded in period SH when compared with those in the other periods and the average T and RH were 23.3±0.6 °C and 68.5±4.2 % respectively ($p<0.05$).

No significant difference was observed among the samples collected in period WD and AH ($p>0.05$) but different variation patterns were observed. In period WD, the ABC increased from morning to the highest level at 16:00 and then decreased to the lowest level at 20:00. The pattern may be due to the increasing occupancy load. It is reported that the airborne bacteria count at a toilet of an empty children centre was

165 CFU m^{-3} and then the count increased from 655 CFU m^{-3} to 1995 CFU m^{-3} before and after lunchtime respectively (Lee 2006). In period AH, a relatively higher airborne bacteria count recorded at morning session (08:00) when compared with that in period WD, and then decreased throughout the day. The ABC at 08:00 was 3 times higher than the levels recorded at 20:00. Similar to office areas, it is believed that microorganisms accumulated in the MVAC system after the system has been shut down for a long period.

Conclusions

The importance of the assessment of indoor bioaerosols in IAQ assessment in air-conditioned commercial buildings revealed in this part of the study was recognized. Based on the previous published data (Database A) on the bioaerosols in Hong Kong, it was observed that the AFC and ABC were the 2nd and 3rd ranked contributors for the unsatisfactory rates of IAQ. An epistemic approach for assessing the acceptance of air-conditioned spaces against bioaerosols, as well as the correlation between the bioaerosols level and thermal environmental parameters (i.e. 19ºC ≤ T ≤ 25ºC and 50% ≤ RH ≤ 80%) in air-**c**onditioned offices were proposed. In order to understand the exposure level of the indoor bioaerosols, a regional database (Database B) of indoor bioaerosols in air-conditioned office buildings of Hong Kong was constructed. Air samples were collected from 239 offices, indicating an average indoor ABC and AFC in offices (N=157) with unknown IAQ of 465 CFU m^{-3} and 165 CFU m^{-3} respectively; and an average indoor ABC and AFC in offices (N=82) with excellent IAQ of 206 CFU m^{-3} and 29 CFU m^{-3} respectively. Moreover, the result of the case study in an unoccupied offices and washrooms revealed the strong effects of different ventilation conditions on indoor bioaerosols exposure level.

Chapter 5 Spatial Distribution of Indoor Bioaerosols

Introduction

Chapters 3 and 4 revealed that several airborne bacterial and fungal genera were commonly found in this region, and the strong effects of ventilation on the bioaerosols exposure level. In order to investigate the deposition of these commonly isolated bioaerosols in the indoor space, this chapter aims (1) to develop a method for understanding the deposition of some common indoor airborne bacteria and fungi; (2) to design an experimental setup for measuring the deposition of common indoor airborne bacteria and fungi, in a common type of air distribution system; (3) to delve into the influences of various airflow rates and mixing conditions on the deposition; (4) to study the size effects of indoor airborne bacteria and fungi on the deposition; and (5) to apply a computational fluid dynamics (CFD) model to simulate the particle movement under the same condition by using an Eulerian-Lagrangian approach comparing the experimental results.

Design of a ventilated chamber for investigation of bioaerosols deposition

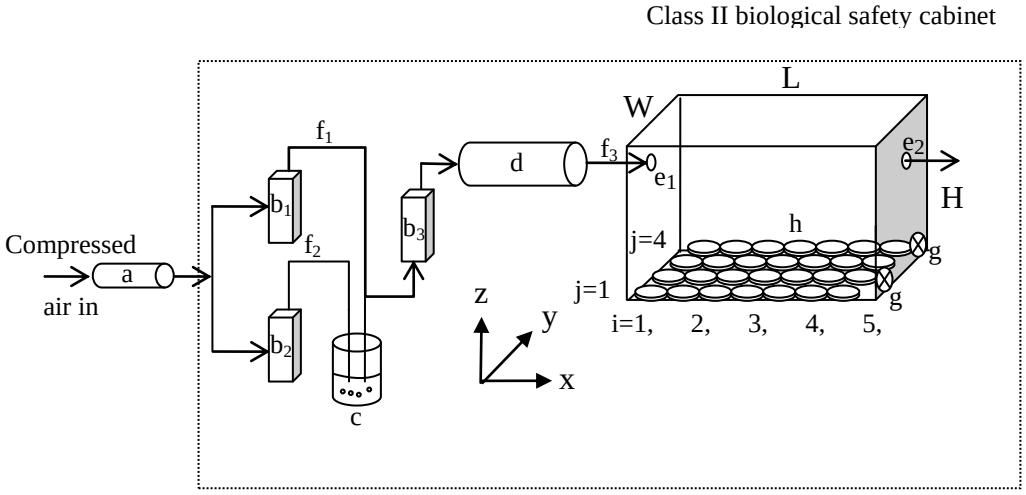
Development of an ventilated chamber

Table 5.1 summarized the previous studies which focused on the deposition of bioaerosols in chamber. Although two studies are conducted in a real-room chamber (Kanaani et al. 2008a; Sze To et al. 2008), a small ventilated chamber which is placed inside a Class II biological safety cabinet was constructed in order to have a better control of the experimental parameters, and to minimize the disturbance from the background and prevent contamination.

Table 5.1: Previous studies on dynamic of bioaerosols in a chamber

Tested bioaerosols	Aim	Chamber size (W × L × H, m)	Chamber condition (V, T and RH)	Measuring instrument	Reference
Penicillium, *Cladosporium* and *Alternaria*	whether the observed deposition fluxes can be predicted for relatively simple but realistic flow situations	2 × 1 × 0.37	Flow velocity (0.18 m s^{-1}); T (20 °C)	Passive sampling by Petri dishes	Reck et al. (2002)
Aspergillus niger and *Penicillium* sp	deposition rates of fungal particles	2.38 × 3.57 × 2.40	Air change rate (2.5 h^{-1}, ceiling-mixed type); T (22–27 °C); RH (43–55%)	Ultraviolet Aerodynamic Particle Sizer Spectrometer (UVAPS)	Kanaani et al. (2008a)
Escherichia coli bacteriophage	spatial distribution patterns of bacteriophage in an experimental ward	5.9 × 6.6 × 2.35	Air change rate (11.6 h^{-1}, ceiling-mixed type); T (21.5 °C); RH (60%)	Andersen sampler	Sze To et al. (2008)

Deposition patterns of bioaerosols were measured inside a 70L ventilated chamber of size 0.650 m (L) × 0.380 m (W) × 0.284 m (H) (Fig. 5.1). The chamber was constructed of tempered glasses, which was assumed to have smooth surfaces (Lai 2005). Openings on the chamber surfaces allowed tests to be conducted under some ventilation arrangements. The experimental setup was shown in Figure 5.1.



Test chamber L × W × H = 0.650m × 0.380m × 0.284 m

a	filtration system	e_2	outlet
b	flow meter	f	airflow path
c	6-jet collision nebulizer	g	mixing fan
d	diffusion dryer	h	Agar plate array in i=1...7 columns by j=1...4 rows
e_1	inlet		

Figure 5.1: Experiment setup for deposition of bioaerosols.

Compressed air was filtered through an air filtration system ‘a’, so that the oil, moisture, impurities and fine particles in the air could be removed by passing through two prefilters, an filter membrane and a high-efficiency filter (Model 3074B, TSI). The clean air was then entered the cabinet via two air paths f_1 and f_2, and then passed into air path f_3. f_1 was for the adjustment of aerosol concentration by volume while f_2 was connected to a 6-jet collision nebulizer ‘c’ (BGI Inc. Waltham, MA) for bioaerosol generation. The volume flow rates in f_1 (ranged from 0 to 20 L min^{-1}), f_2 (fixed at 15 L min^{-1}) and f_3 could be conditioned and were gauged by the flow meters ‘b_1’, ‘b_2’ and ‘b_3’ respectively. Moisture was removed again in f_3 via a diffusion dryer ‘d’ (Model 3062, TSI). Desiccant was used in the dryer and the moisture in the air was removed by diffusional capture when the air path passed through it. The desiccant was sterilized at 121 °C for 15 min before and after each experiment. The processed air was finally supplied to the chamber through a high sidewall inlet ‘e_1’ and exhausted through an outlet ‘e_2’ aligned on the opposite chamber wall. This composition was one of the common ventilation configurations; the isothermal air diffusion performance in a room of similar layout had been investigated in a previous study (Chow and Wong 1998c). Both the inlet and outlet were circular with a diameter of 0.016 m. Two identical small muffin fans ‘g_1’ and ‘g_2’ were installed in the chamber to enhance air mixing.

Leakage of chamber

Trace gas concentration decay method was used to evaluate the leakage of the chamber, which had been used for a wide range of diagnostic techniques in ventilation assessments, including leakage detection. The leakage test was based on references to standards on ventilation and leak measurements (ASTM 1995, ASTM 2000). By measuring the decay of the CO_2 concentration in the chamber with all opening covered, the leakage rate was determined.

In order to determine the chamber leakage rate, TSI Q-Trak Plus (Model 8554) was placed at the center of the chamber as shown in Figure 5.2 with the logging time of 1 min. After the door and all openings were closed and covered tightly, the logger was started to log for 10 min in order to measure the background CO_2 level. After 10 min, the inlet e_1 was opened for the injection of CO_2 into the chamber. High purity CO_2 (>99.8%) was supplied by gas cylinder with pressure gauge of 840 psig at 15 °C for 3s. The inlet e_1 was closed after the CO_2 injection and the CO_2 level was monitored

for 180 min after steady at an average initial concentration of 4,000 ppm.

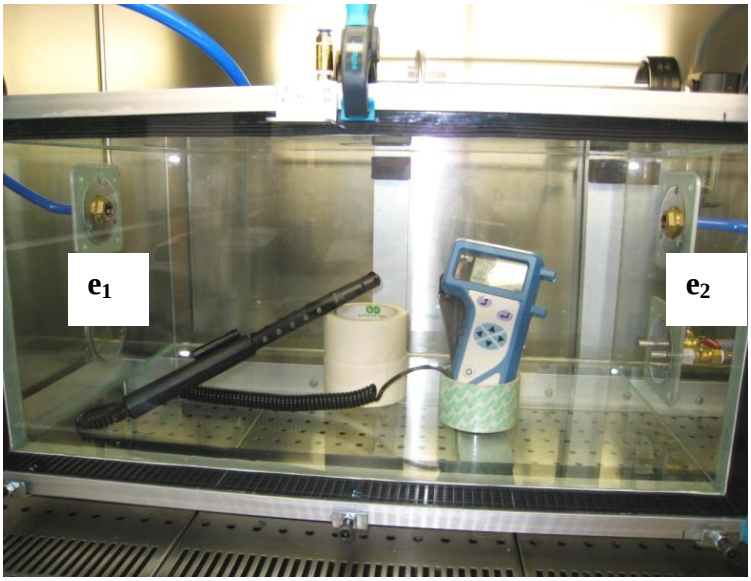


Figure 5.2: Setup for measuring the leakage rate.

The CO_2 decay rate measured and the number of air changes (AC) per unit of time (min) is equal to the negative gradient of the natural log concentration/time line,

$$AC = \frac{\ln(\Phi_e) - \ln(\Phi_i - \Phi_e)}{t} \quad \ldots \text{(Eq. 5.1)}$$

Where Φ_o = CO_2 concentration at t=0,

Φ_i = CO_2 concentration at time t,

and Φ_e = outdoor CO_2 concentration.

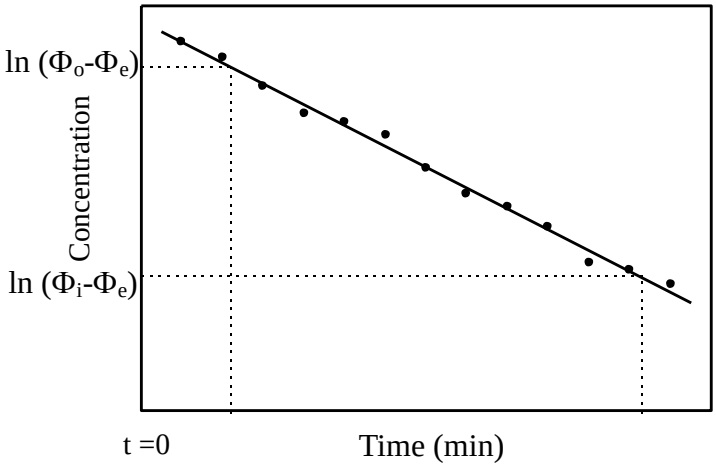


Figure 5.3: Logarithmic plot of decay data.

The leakage tests were repeated twice and the leakage rate found was 2.4×10^{-3} min^{-1}.

Environmental conditions of chamber

In order to determine the variations of T and RH inside the chamber during the experiment, three trial operations (each lasted 3 h) were conducted. Eight data logger (HOBO U10-003) were placed at the center and corners of the chamber as shown in Figure 5.4. The resolution of the logger for T and RH were ±0.54°C from 0°C to 50°C and ±3.5% from 25% to 85% respectively. The T and RH were recorded every 5s for 3hr. It was observed that all deviations of T and RH recorded in the center and corners of the chamber showed insignificant differences (≤0.2°C and ≤3%, respectively) and would be normally distributed ($p \geq 0.3$, Shapiro-Wilk test). Therefore, isothermal conditions were assumed throughout for the experiments.

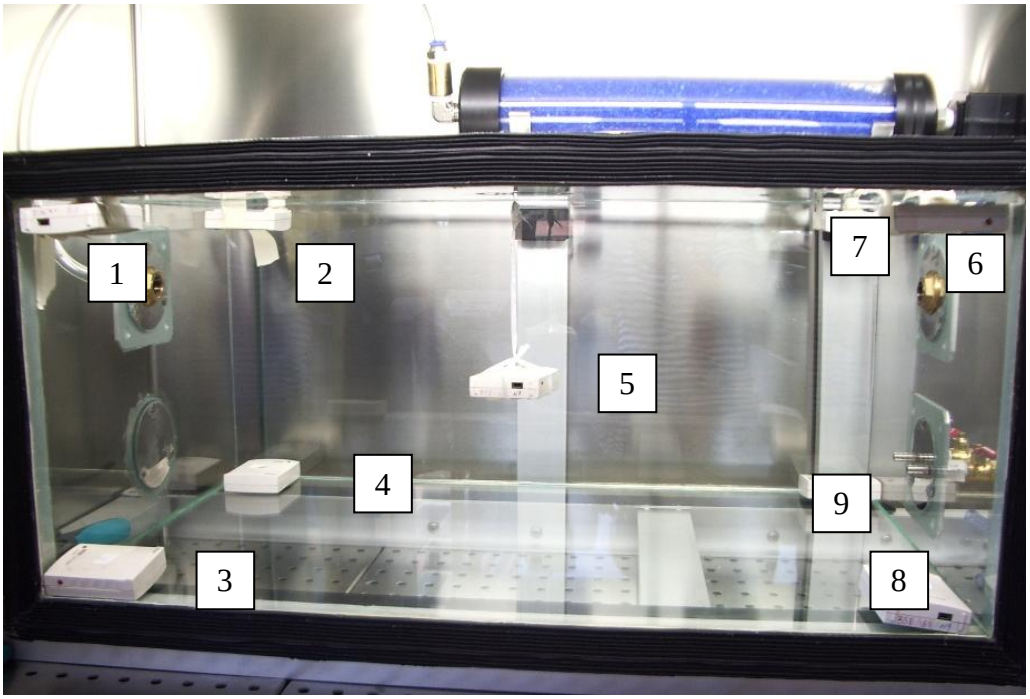


Figure 5.4: Setup for measuring the temperature and relative humidity.

Different testing ventilation rates

Effects of ventilation rates on the deposition distribution of bioaerosols were evaluated in this study. The minimum outdoor airflow required in the breathing zone of the occupiable space or spaces in a ventilation zone at breathing level should be ranged from 0.3 L $s^{-1}m^{-2}$ to 2.4 L $s^{-1}m^{-2}$ (ANSI/ASHRAE 2010).

Both inlet (e_1) and outlet (e_2) were circular with a diameter of 0.016m. The inlet velocities at e_1 were regulated by the flow rate f_1 which passed through the flowmeter b_2, so that the flow rate f_3 were 2 L min^{-1}, 7 L min^{-1}, 12 L min^{-1}, 17 L min^{-1}, and 22 L min^{-1} respectively. Five inlet velocities 0.17 ms^{-1}, 0.58 ms^{-1}, 1.0 ms^{-1}, 1.4 ms^{-1}, and 1.8 ms^{-1} were chosen for this study, which corresponded to ventilation rates 1.7 h^{-1}, 6 h^{-1}, 10.3 h^{-1}, 14.5 h^{-1}, and 18.8 h^{-1}. The selected ventilation rates in this study between 1 h^{-1} to 19 h^{-1} are typical range for ventilated enclosures.

Tested bioaerosols

This study investigates the spatial distribution and deposition of five commonly isolated bioaerosols in a ventilated chamber. These bioaerosols included two bacterial species – *Micrococcus luteus, Staphylococcus aureus* and three fungal species – *Aspergillus niger*, *Penicillium cirtinum* and *Rhizopus* sp.. The average diameter (*d*) of the bacterial cell and fungal spores of these cultures ranged from 0.8

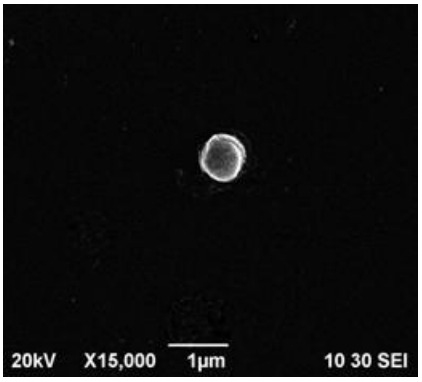
to 10 μm and within the normal range of commonly isolated indoor bioaerosols (Cox and Wathes 1995; Samson et al. 2002). *Micrococcus* and *Staphylococcus* are two major indoor (cultivable) gram-positive cocci, which represented 38% of the airborne bacterial composition in a survey of 100 USA buildings while equaled 100% of the sampled dwellings in a Poland study (Górny and Dutkiewicz 2002; Tsai and Macher 2005). These bacteria are common indoor inhabitants shed from human skin surfaces, in addition, *S. aureus* is a major multidrug-resistant pathogen which is the most prevalent cause of hospital- and community-acquired bloodstream, skin, soft tissue, and lower respiratory infections (Gandara et al. 2006). *Aspergillus* and *Penicillium* are two dominant indoor fungal genera which can be transported from outdoor through ventilation systems, infiltrated through doors and windows and brought in with humans, and generated from contaminated building materials, air conditioning systems and plants (Gots et al. 2003; Wu et al. 2005). Some of the species of these genera are associated with adverse health effects included allergy, hypersensitivity pneumonitis, toxic or irritant, direct infection such as Aspergillosis (Madelin and Madelin 1995; Castón-Osorio et al. 2008). *Rhizopus* is also commonly found indoors but less frequently than *Aspergillus* and *Penicillium* (Shelton et al. 2002). Some species of this genus are associated with allergy, infection such as Zygomycosis (Castón-Osorio et al. 2008).

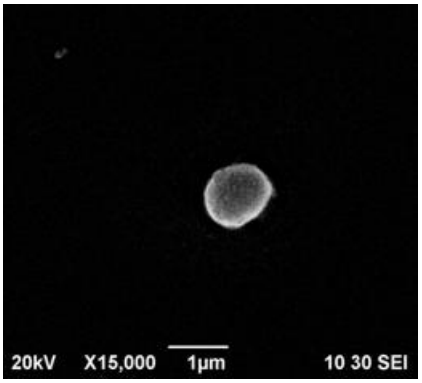
The most abundant indoor airborne bacteria are gram-positive cocci, such as *Micrococcus* and *Staphylococcus* which represented 38% of the composition of airborne bacteria discovered in a survey of 100 buildings in USA while equaled 100% of what was found inside the sampled dwellings in a Poland study (Górny and Dutkiewicz 2002; Tsai and Macher 2005). *Micrococcus* spp. and *Staphylococcus* spp. are common indoor inhabitants shed from human skin surfaces. When *Staphylococcus aureus* is facultative anaerobic, *Micrococcus luteus* is strictly aerobic. Both of them may occur singly, in pairs, tetrads or irregular clusters. It is known that *Staphylococcus aureus* is a major multidrug-resistant pathogen that is the most prevalent cause of hospital- and community-acquired bloodstream, skin, soft tissue, and lower respiratory infections (Gandara et al. 2006).

Different size of tested bioaerosols

Bioaerosols used in this study were grouped according to their cell diameter *d*: (1) *d*=0.8 μm to 1.2 μm bacteria (*Micrococcus luteus*, American Type Culture Collection,

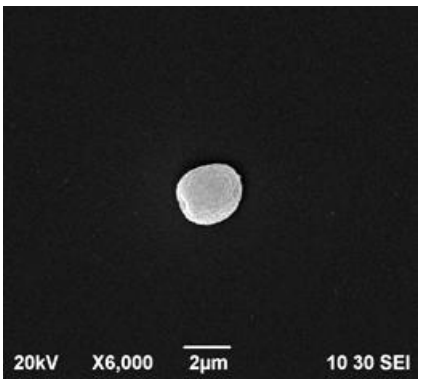
ATCC 4698 and *Staphylococcus aureus*, ATCC 6538), (2) *d*=3 µm to 4 µm fungi (*Aspergillus niger*, *Penicillium citrinum* (ATCC 6849) and (3) *d*=10 µm fungi (*Rhizopus* sp). The image of cells and spores were viewed under scanning electron microscopy as shown in Figure 5.5. The bioaerosols were in shape globose, ovoid, or elliptical and the cell diameters were determined from 100 cells or spores under the compound light microscopy (400X).

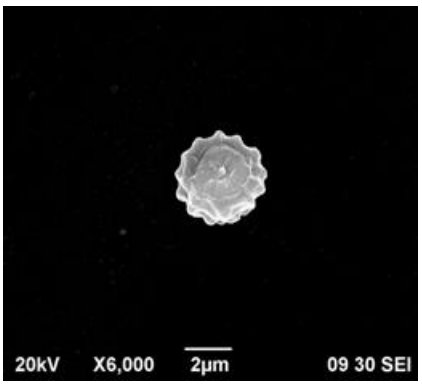




S. aureus *M. luteus*

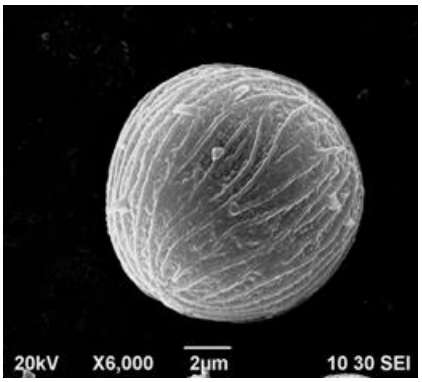
Group 1 (*d*=0.8µm to 1.2µm)





P. citrinum *A. niger*

Group 2 (*d*=3 µm to 4 µm)



Rhizopus sp.

Group 3 (*d*=10 µm)

Figure 5.5: SEM photos of tested bioaerosols.

Preparation for bioaerosols generation

A method of the preparation of the vegetative bacterial cell for Group (1) bioaerosols and fungal spore suspension for Groups (2) bioaerosols followed (Agranovski et al. 2003; Kanaani et al. 2008b). Initially, the bacterial cultures were inoculated on tryptone soya agar (TSA, Oxoid) at 30°C for 24 hours. After that, a single colony was picked from the TSA, inoculated into 10 ml tryptone soya broth (TSB, Oxoid) and incubated at 30°C under aerobic conditions for another 24 hours. The bacterial cells of Group (1) were harvested at phrase of exponential growth. Then 1ml bacterial suspension was transferred to a 1.5 ml sterilized centrifuge tube. The bacterial cells were harvested by centrifugation at 1000g for 15 min under room temperature. The supernatant were discarded, and washed three times and then resuspended in 50 ml of sterilized distilled water.

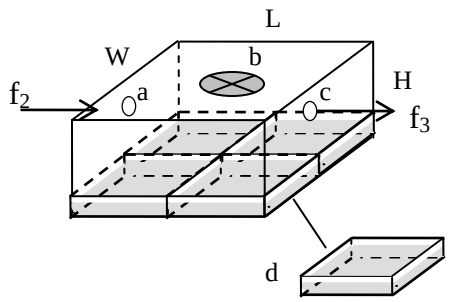
Similarly, the fungal cultures of Group (2) bioaerosols were inoculated on 2% MEA (Oxoid) at 25°C for 1 week; a single colony was picked and incubated to another 2% MEA plate and incubated at 25°C for another week. 10 ml sterilized distilled water was added to the plate, and then the plate was shaked gently. Each ml suspension was transferred to each 1.5 ml sterilized centrifuge tube. The fungal spores were harvested by centrifugation at 1000g for 15 min under room temperature. The supernatant were discarded, and washed three times with sterilized distilled water and then resuspended in 50 ml of sterilized distilled water and stored in a collision nebulizer (BGI CN 25, BGI Inc. Waltham, MA) for aerosolization. The mass median diameter of the generated particle of the collision nebulizer is 2.5 μm (GSD = 1.8) (BGI 2007). According to the output distribution of the generated particles, the diameter of 68% particles varied form 1.4 μm to 4.5 μm (1 SD), 95% of particles varied from 0.78 μm to 9.0 μm (2 SD), and 99% of particles varied from 0.43 μm to 16.2 μm (3 SD), respectively.

0.01 ml suspension in the nebulizer was transferred to a microscopic slide to check whether the vegetative bacteria cells (Group 1) or fungal spores (Group 2) appeared singly and without impurities (e.g. mycelium of Group 2). The vegetative bacteria cells of Group (1) bioaerosols were first gram-stained. The slides were examined under the compound light microscopy (400X). The whole suspension (50 ml) would be discarded if 2 out of 3 samples with 2% of examined vegetative bacteria cells or fungal spores are not appeared singly or present of impurities such as mycelium.

A substantial amount of microorganisms were found to losetheir viability after

neublization for various reasons such as the rapid loss of water (Sze To et al. 2008). Therefore, the viability of the tested bioaerosols was also investigated after neublization and dehumidification. 0.1 ml suspension was tested for initial concentration of viable cells and then 0.1 ml suspension was also collected at the e_1 of the chamber. A 1.5 ml sterilized centrifuge tube was connected to the e_1 of the chamber by a plastic tube. Serial dilutions of suspension were prepared by using sterilized Ringer's solution and then spread on triplicate suitable agar plates (i.e. TSA for Group (1) and MEA for Group (2)). The plates were then incubated at 30 °C for 24 hr and 25 °C for 1 week for Group (1) and Group (2) respectively. The concentration was expressed as CFU ml^{-1} after incubation. It was observed that there were 10% to 15% of bacterial cells or fungal spores lost after the nebulization and dehumidification process.

Due to the apparatus' limit, the collision nebulizer was tested to be not suitable in generating Group (3) bioaerosols as the sizes of spore were too large. A tailor-made chamber with a mixing fan which directed an air jet to the cultured fungi on agar was used for aerosolization, which is shown in Figure 5.6. The *Rhizopus* sp. was incubated into the container 'n' for a week. The cultures were observed everyday under microscopy to check the maturity of the spores (brownish-black at maturity) and the wall of the sporangium. When the spores were mature and the sporangium wall was broken, then the culture was suitable for aerosolization. Preliminary tests were carried out to investigate the suitable time for the aerosolization of the spores from the culture without the formation of mycelium. A slide with gelatin gel was placed inside the chamber which was directly facing the inlet, therefore the spore generated was collected on the slide. The slide was then stained with lactophenol cotton blue and examined under compound light microscopy (400X). It was observed that when the fan was operated for 10 min for aerosolization, no airborne mycelium was found.



a	Inlet (diameter - 0.009m)	
b	Mixing fan	Aerosolization chamber W x L x H =
c	Outlet (diameter - 0.009m)	0.145m x 0.145m x 0.065m
d	*Rhizopus* sp. on agar	

Figure 5.6: Aerosolization chamber for *Rhizopus* sp.

Sampling of bioaerosols

Prior to all deposition tests, 0.1 m^3 air samples were collected by the Biostage Single-stage Viable Cascade Impactors placed in the chamber to determine the original bioaerosol concentrations. Throughout the operating period, bioaerosol concentrations were measured to ensure a steady state inside the chamber. As found in five trial operations (each lasted 3 hours), the variations of concentration of bioaerosols generated were from 3% to 6% (with an exception of +15%). No significant concentration trend was observed during the sampling periods of all trials ($p \geq 0.3$, t-test). Therefore, it was assumed that the bioaerosols generated throughout the experiments were in steady state.

A total of 28 TSA plates (for Group (1) bioaerosols) or MEA plates (for Group (2)&(3) bioaerosols) organized in an array of 7 columns by 4 rows were placed on the chamber floor to record the bioaerosol patterns. The arrangement is depicted in Figure 5.1. For each deposition test, bioaerosols were supplied into the chamber through inlet 'e_1' for 60 minutes in the form of an air jet under isothermal conditions. The plates were then collected and incubated at 30°C for 24 h for Group (1) bioaerosols and 25°C for 1 week for Group (2), and 25 °C for 48 h for Group (3) bioaerosols respectively. The colonies were counted and expressed in CFU (Figure 5.7). Repeated measurements were conducted at inlet velocities 0.17 ms^{-1}, 0.58 ms^{-1}, 1.0 ms^{-1}, 1.4 ms^{-1} and 1.8 ms^{-1} (Section 5.2). Same measurements were reiterated for

well-mixed scenarios with the two fans 'g_1' and 'g_2' on. The chamber was sterilized before and after each measurement by 75% ethanol and a 30-min ultraviolet light irradiation. Air samples collected for airborne bacterial and fungal counts were used to examine the chamber cleanliness.

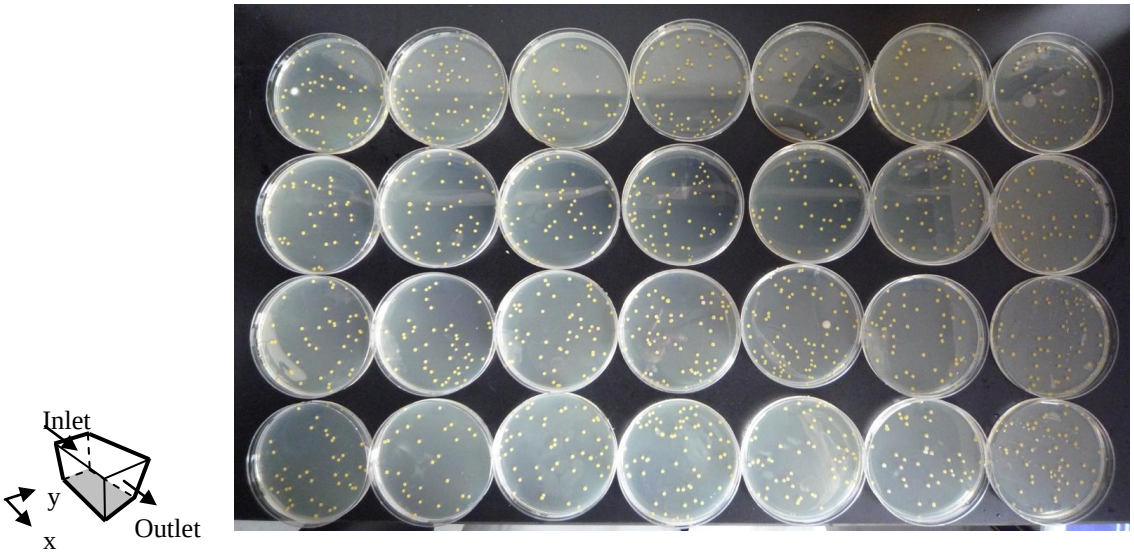


Figure 5.7: Spatial distribution of *S. aureus* in the chamber with mixing under with inlet velocity of 1.0 ms^{-1}.

Study of bioaerosols deposition in the ventilated chamber

In this study, a total of 10 test conditions (i.e. 5 ventilation rates V_R and 2 air mixing scenarios) were conducted for Group 1 bioaerosols (i.e. *M. luteus* and *S. aureus*); while a total of 6 test conditions (i.e. 3 V_R and 2 air mixing scenarios) were conducted for Group 2 (*A. niger* and *P. citrinum*) and Group 3 bioaerosols (*Rhizopus* sp), respectively.

Fractional count

Deposition patterns of the bioaerosols are expressed by the factional count FC_{ij} given by an equation below, where Φ_{ij} is the total counts at location ij, i=1…7 and j=1…4 are the array coordinates corresponding to the chamber fractional length x/L=0.069, 0.208, 0.346, 0.485, 0.623, 0.762, 0.9 and the chamber fractional width y/W=0.125, 0.375, 0.625, 0.875 respectively. It is assumed that each colony formed on the TSA and MEA plates were developed from one bacterial cell and fungal spore,

respectively.

$$FC_{ij} = \frac{\Phi_{ij}}{\sum_i \sum_j \Phi_{ij}} \quad \text{... (Eq. 5.2)}$$

Each test condition was repeated with N trials. Uniformity of the longitudinal deposition patterns can be evaluated by Chi-square test (Kanji 2006). The uniformity of the longitudinal deposition pattern can be described by the fractional bioaerosols counts FC_i along x/L at i. With an expected fractional count FC_e=1/7, FC_i were computed by,

$$FC_i = \frac{\sum_j \Phi_{ij}}{\sum_i \sum_j \Phi_{ij}} \quad \text{… (Eq. 5.3)}$$

The deposition ratio in the chamber ω is a measure to present the longitudinal deposition pattern and can be expressed by,

$$\omega = \frac{\sum_{i=5}^{7} FC_i}{\sum_{i=1}^{3} FC_i} \quad \text{…(Eq. 5.4)}$$

Effect of mixing on distribution of bioaerosols

In order to investigate the effects of mixing on the deposition of tested bioaerosols in the ventilated chamber, the Group 1 bioaerosols (i.e. *S. aureus* and *M. luteus*) were chosen as an example for investigation. The mixing scenarios were controlled by the operation of two mixing fans in the ventilation chamber, either on or off.

For both mixing scenarios, the spatial deposition of *S. aureus* and *M. luteus* were investigated under 5 different ventilation rates. Each testing condition was repeated for 2 to 4 times, the average fractional bioaerosols count was presented in Figure 5.8. It is also noted that the maximum and minimum values of each average case are not significantly different from the corresponding average value ($p \geq 0.3$, t-test). Figures

5.8(a) and 5.8(b) exhibit the deposition pattern of the fractional bacteria counts with the mixing fans on at V_R=1.7 h^{-1}, 6 h^{-1}, 10.3 h^{-1}, 14.5 h^{-1} and 18.8 h^{-1}; Figures 5.8(c) and 5.8(d) are those with the fans off. Preliminary visual inspections indicate that relatively uniform deposition pattern in the chamber could be achieved via air mixing. Higher fractional bacteria counts were observed close to the outlet on plates i=6 and 7 in a number of ventilation rates with the mixing fans off.

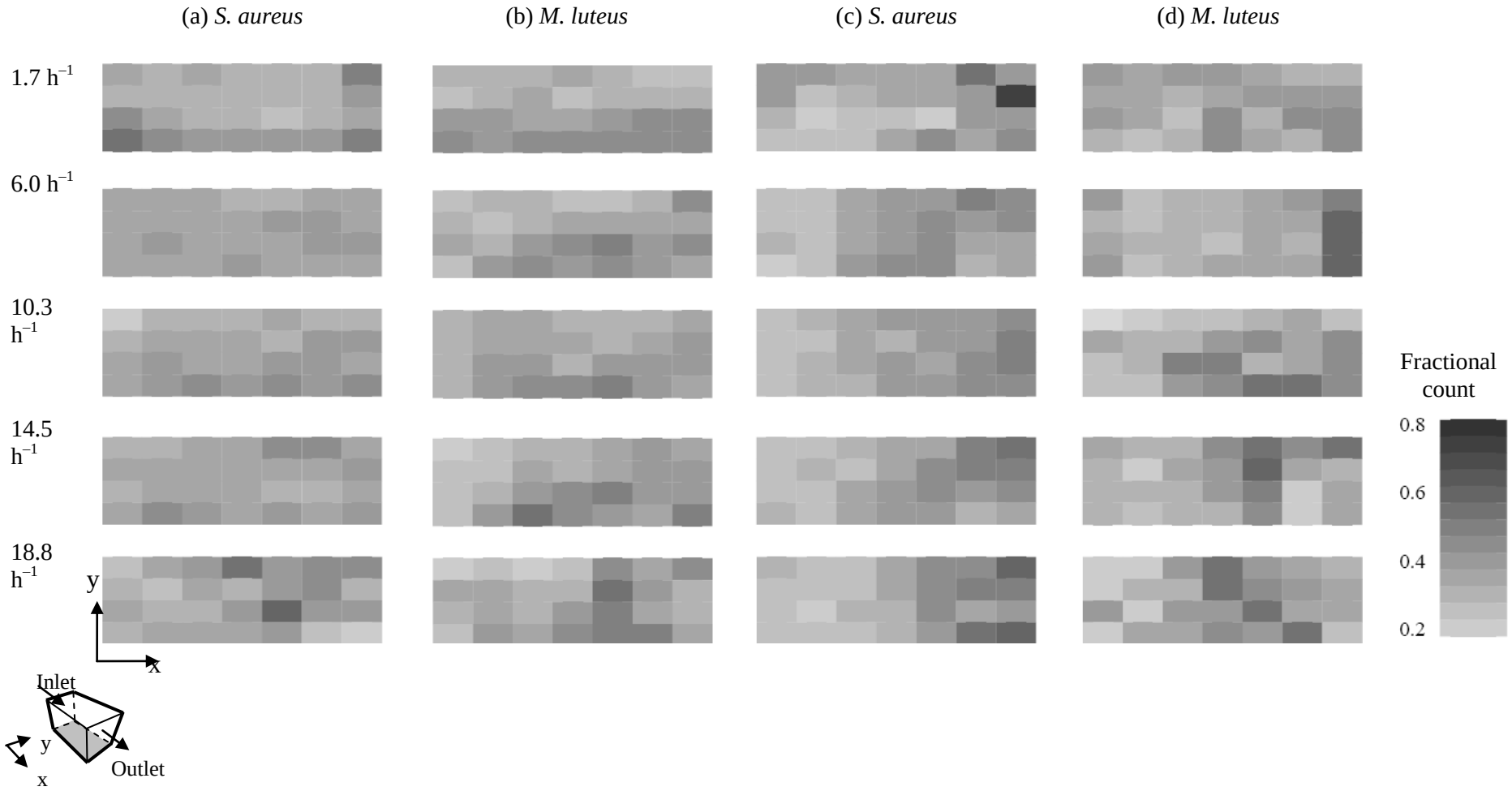


Figure 5.8: Measured fractional bacteria counts of Group 1 bioaerosols on TSA plate array (i,j)=7×4 on the test chamber floor.

The longitudinal deposition patterns of this Group bioaerosols are presented in Table 5.2 and Figure 5.9. Pattern of FC_i was assumed to be normally distributed ($p \geq 0.1$, Chi-square test). Error bars shown for one standard error of the average FC_i. It is observed that different deposition patterns are shown for tests conducted with and without mixing fans. When the mixing fans were operating, the longitudinal deposition patterns (i.e. i along x-axis) of FC_i found in all test conditions, except for the test of *S. aureus* at V_R of 1.7 h^{-1} as well as the test of *M. luteus* at V_R of 14.5 h^{-1} and 18.8 h^{-1} were uniform ($p \geq 0.05$, Chi-square test). When the mixing fans were not operating, all test conditions apart from the test of *M. luteus* at V_R of 1.7 h^{-1} gave non-uniform longitudinal deposition patterns of FC_i ($p \leq 0.0005$, Chi-square test).

When the mixing fans were not operating, despite there were some noted differences between the deposition patterns of test of *M. luteus* at V_R of 6.0 h^{-1} and 18.8 h^{-1} ($p=0.06$, Chi-square test), the longitudinal deposition patterns of FC_i for all ventilation rates were not significantly different ($p>0.2$, Chi-square test). Although the longitudinal FC on plates i=4 (i.e. at x/L=0.485) were not significantly lower than the expected counts ($p \geq 0.25$, t-test), those on plates i=1…3 (i.e. at $x/L \leq 0.346$) were ($p<0.1$, t-test). The total longitudinal fractional bacteria counts at i=1…3 were also significantly lower than those at i=5…7 ($p<0.0001$, t-test). In other words, both *S. aureus* and *M. luteus* showed a significant increasing trend ($p \leq 0.01$, t-test).

Table 5.2: Deposition pattern of Group 1 bioaerosols.

Case	Ventilation rate V_R (h^{-1})	Trials N	Fractional counts FC_i on TSA plate i at a fractional distance x/L from the inlet							Deposition ratio ω
			i=1	2	3	4	5	6	7	
			x/L=0.069	0.208	0.346	0.485	0.623	0.762	0.900	
Scenario (1): With mixing fans										
(a) *S. aureus*	(1) 1.7	3	0.165	0.141	0.133	0.130	0.120	0.131	0.179	0.98
	(2) 6.0	4	0.141	0.144	0.136	0.139	0.142	0.153	0.145	1.04
	(3) 10.3	3	0.121	0.144	0.142	0.136	0.153	0.155	0.149	1.12
	(4) 14.5	4	0.133	0.143	0.139	0.142	0.149	0.146	0.147	1.06
	(5) 18.8	3	0.120	0.123	0.139	0.155	0.178	0.153	0.131	1.21
(b) *M. luteus*	(1) 1.7	3	0.138	0.136	0.145	0.141	0.149	0.143	0.147	1.05
	(2) 6.0	4	0.111	0.124	0.148	0.150	0.155	0.148	0.164	1.22
	(3) 10.3	3	0.118	0.150	0.152	0.139	0.148	0.144	0.150	1.05
	(4) 14.5	4	0.092	0.122	0.160	0.144	0.159	0.156	0.166	1.28
	(5) 18.8	3	0.109	0.131	0.119	0.139	0.201	0.160	0.141	1.40
Scenario (2): Without mixing fans										
(c) *S. aureus*	(1) 1.7	2	0.131	0.115	0.115	0.132	0.138	0.167	0.201	1.40
	(2) 6.0	3	0.104	0.098	0.143	0.165	0.171	0.157	0.163	1.42
	(3) 10.3	3	0.105	0.113	0.127	0.145	0.154	0.168	0.188	1.48
	(4) 14.5	3	0.103	0.107	0.124	0.152	0.162	0.170	0.182	1.54
	(5) 18.8	3	0.104	0.097	0.100	0.129	0.183	0.182	0.204	1.89
(d) *M. luteus*	(1) 1.7	3	0.139	0.133	0.128	0.159	0.139	0.143	0.160	1.10
	(2) 6.0	2	0.147	0.104	0.120	0.121	0.139	0.139	0.231	1.37
	(3) 10.3	2	0.099	0.107	0.143	0.161	0.164	0.167	0.159	1.41
	(4) 14.5	2	0.120	0.106	0.127	0.156	0.211	0.122	0.158	1.39
	(5) 18.8	2	0.096	0.105	0.141	0.190	0.172	0.168	0.129	1.37

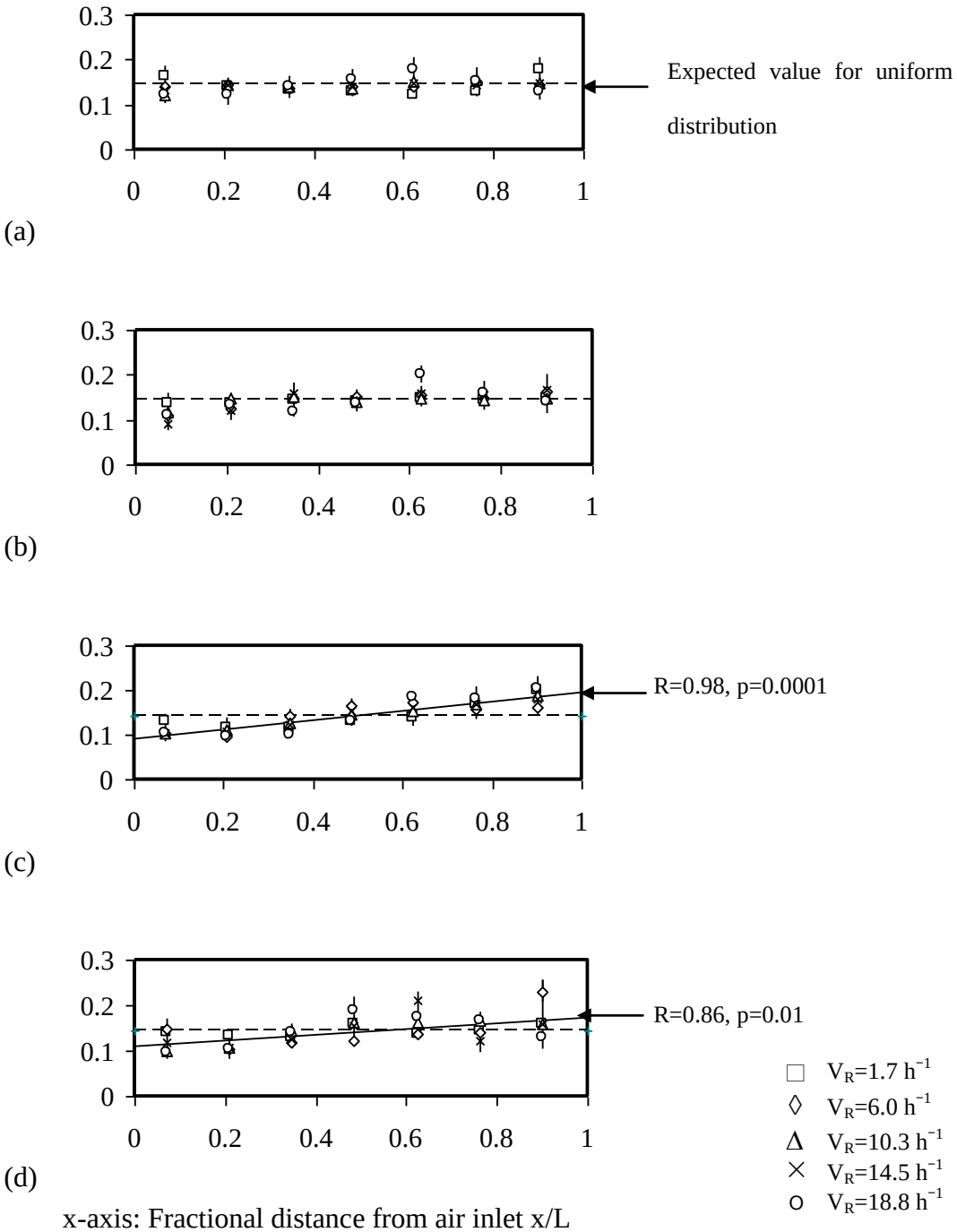


Figure 5.9: Fractional counts of Group 1 bioaerosols along the test chamber fractional length; (a)&(b) with mixing fan operation; (c)&(d) without mixing fan operation.

The deposition ratios ω presented in Table 5.2 for cases (a) and (b) were not significantly larger than 1 ($p \geq 0.1$, t-test) whereas for cases (c) and (d) they were ($p \leq 0.005$, t-test). This result also confirms the uniform deposition pattern of Group 1 bioaerosols under testing conditions with mixing fan operating. These figures reveal that more bacteria of Group 1 bioaerosols were deposited in the floor section near the chamber wall opposite to the air inlet when air mixing was not enhanced by the mixing fans. These findings confirm those reported by Bouilly et al. (2005).

It can be seen in Figure 5.10 that the deposition ratio ω is directly proportional to the ventilation rate. The correlations for both air mixing scenarios are significant ($R \geq 0.91$, $p < 0.05$, t-test). As the bioaerosols selected in this study were in the size range 0.7 μm to 1.8 μm, their movements were strongly influenced by the airflow pattern. It is noted that the higher the inlet velocity (or the ventilation rate), the higher is the air jet momentum (Chow and Wong 1998c). The observed increased deposition was due to increased particle collisions with the chamber walls (Kanaani et al. 2008b).

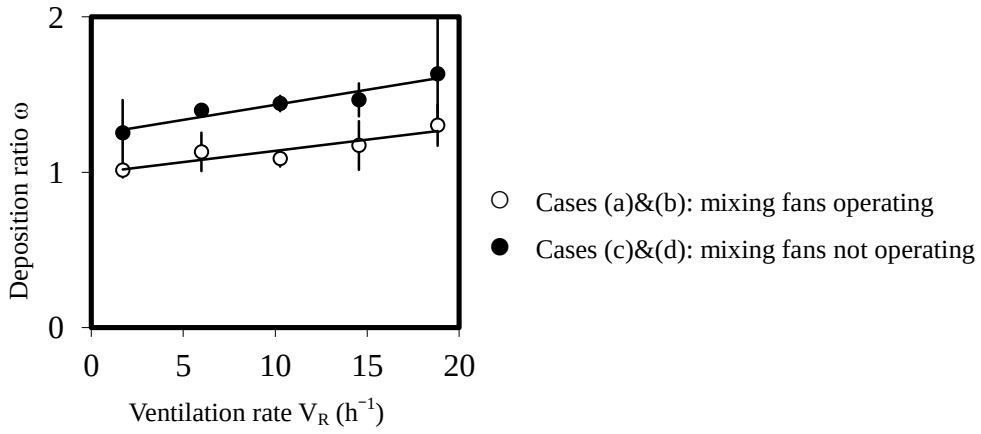


Figure 5.10: Deposition ratios of Group 1 bioaerosols.

When the mixing fans were off during the tests, the average deposition ratios ranged from 1.10 to 1.89; on average 0.3 times of the average ratios obtained from those tests where the fans were on (i.e. ranged from 0.98 to 1.40). This difference reflects enhanced air mixing in the test chamber by operating the fans. Despite the fact that air jet momentum was slightly affected by the fan operation, the slopes of the two regression lines in Figure 5.10 were not significantly different ($p > 0.05$, t-test).

It is demonstrated that the airflow rate has an influence on the concentration homogeneity. It is revealed that a small mixing fan inside the chamber prompted very effective mixing while non-homogeneity is observed even at a very high ventilation rate. The implication is significant that the ventilation rate and mixing conditions have influence on the bioaerosol deposition in a test chamber.

Effect of size of the bioaerosols

It is found that the deposition rates of aerosols are affected by the size of aerosols (Lai 2002; Nazaroff 2004; Bouilly et al. 2005). Since the indoor air is comprised of bioaerosols with different size (the aerodynamic diameter ranged from 0.3 μm to 100 μm), and the diameter of common bacterial cells and fungal spores ranged from 0.3 μm to 11 μm, the deposition of bioaerosols with different size range in the ventilated chamber were investigated in this study (Cox and Wathes 1995; Samson et al. 2002).

The deposition pattern of Group 2 (with d_p=3 μm to 4 μm) and Group 3 (d_p=10 μm) bioaerosols were investigated under 3 V_R (i.e. 1.7 h^{-1}, 10.3 h^{-1} and 18.8 h^{-1}) and no mixing fan conditions, and the tests were repeated for two to four times. The deposition patterns should be dominated by the momentum, the gravitational and the drag forces acted on bioaerosols cells. Cell diameter is therefore an explanatory parameter in addition to the airflow conditions; test conditions with bioaerosols of similar cell diameters are pooled into the same group for discussion below.

Figure 5.11 presents the average fractional counts FC_{ij}. It is observed in general the larger fractional count variations longitudinal direction as compared with the meridian direction. Significant trends ($p \leq 0.1$, t-test) are reported for longitudinal fractional counts in 80% experiment cases but not for the meridian direction in over 95% measurement cases ($p > 0.1$, t-test). Moreover, the factional counts along the meridian direction (FC_j) in over 80% measurement cases are normally distributed ($p \geq 0.05$, Shapiro-Wilk test). Spatially longitudinal deposition patterns were therefore studied and the results are presented in Table 5.3 and Figure 5.12.

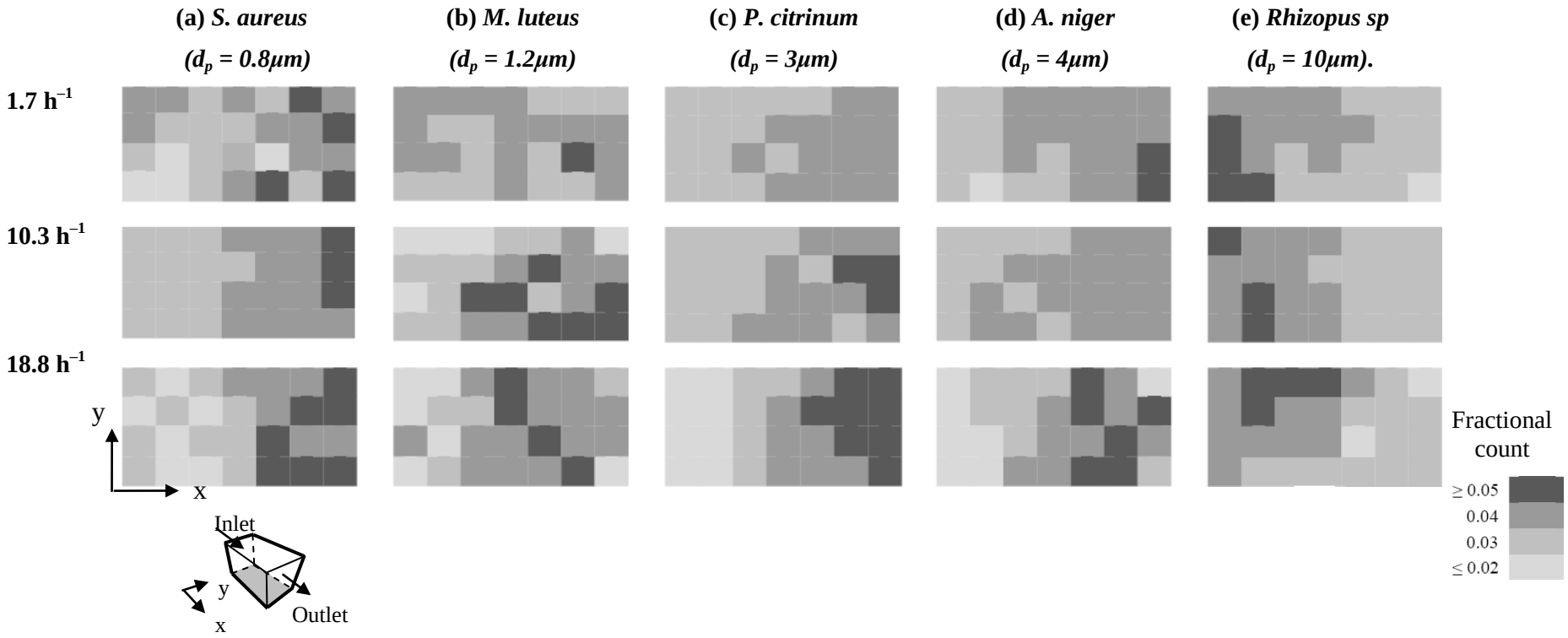


Figure 5.11: Measured factional counts (FC_{ij}) on agar plate array.

Table 5.3: Deposition pattern of Group 2 and 3 bioaerosols.

Case		Ventilation rate V_R (h^{-1})	Trials N	Fractional counts FC_i on MEA plate i at a fractional distance x/L from the inlet							Deposition ratio ω
				i=1	2	3	4	5	6	7	
				x/L=0.069	0.208	0.346	0.485	0.623	0.762	0.900	
Group 2 (d_p= 3 µm to 4 µm)											
P. citrinum	(1)	1.7	3	0.126	0.125	0.136	0.14	0.147	0.162	0.165	1.23
	(2)	10.3	3	0.121	0.119	0.124	0.147	0.148	0.16	0.181	1.34
	(3)	18.8	3	0.080	0.093	0.123	0.146	0.175	0.192	0.192	1.89
A. niger	(1)	1.7	4	0.115	0.11	0.133	0.141	0.159	0.164	0.177	1.39
	(2)	10.3	4	0.130	0.135	0.140	0.137	0.148	0.157	0.154	1.13
	(3)	18.8	3	0.082	0.103	0.135	0.154	0.203	0.177	0.145	1.64
Group 3 (d_p= 10 µm)											
	(1)	1.7	4	0.185	0.163	0.138	0.152	0.133	0.117	0.113	0.75
Rhizopus sp.	(2)	10.3	3	0.181	0.184	0.162	0.145	0.113	0.111	0.105	0.62
	(3)	18.8	3	0.165	0.177	0.155	0.152	0.124	0.113	0.113	0.70

The longitudinal deposition patterns were tested to be non-uniform for Group (2) bioaerosols at the largest ventilation rate V_R=18.8 h^{-1} and would be non-uniform for Group (3) bioaerosols (p=0.02 to 0.09, Chi-square test). This study confirms that the spatial distributions of bioaerosols in ventilated space are related to the particle size and ventilation rate (Wong et al. 2010). It is also qualitatively agreed with the understandings of particle deposition (Hinds 1999; Lai 2002; Nazaroff 2004; Bouilly et al. 2005; Zhao and Wu 2009). Theoretically, the settling velocity is directly proportional to the particle size and the settling distance is indirectly proportional to the particle size. The movements of small size particles are strongly influenced by the airflow pattern while the movements of large size particles are dominated by the gravity. The higher the inlet velocity (indicated by the ventilation rate), the higher is the air jet momentum and a longer settling distance (Chow and Wong 1998c). Increased deposition near the outlet at conditions of the higher jet momentum is due to the increased particle collisions with chamber walls (Kanaani et al. 2008b).

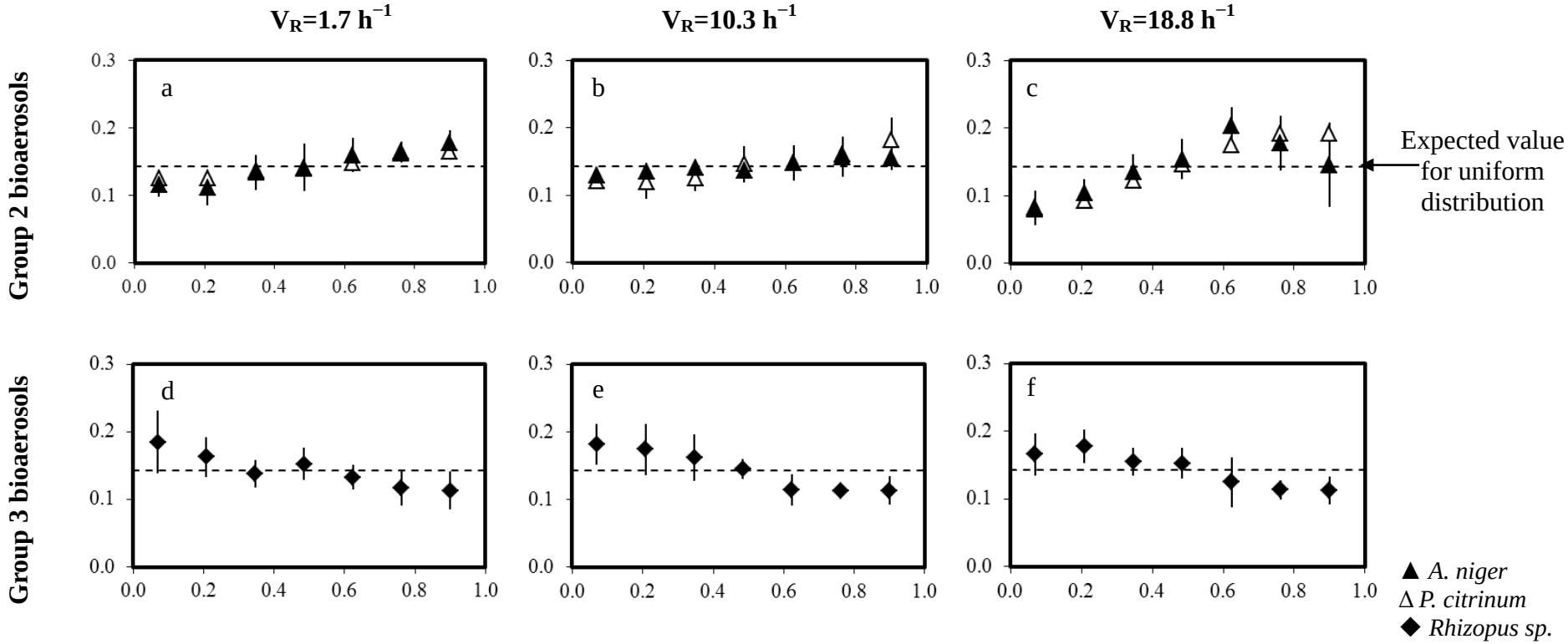


Figure 5.12: Fractional counts of Group 2 and Group 3 bioaerosols along the test chamber fractional length.

As shown in Figure 5.12, significant trends ($p \leq 0.05$, t-test) of longitudinal fractional counts (i.e. FC_i against x/L) are observed. When compared with the Group (1) in Figure 5.8c and 5.8d, positive slopes of the longitudinal fractional counts against the fractional length x/L are reported for Group (1) and Group (2) bioaerosols but negative ones are found for Group (3) bioaerosols. It is also reported for Group (1) and Group (2) bioaerosols that the slopes increased for higher ventilation rates V_R but no noticeable increment is observed for Group (3) bioaerosols. The deposition ratios ω given in Table 5.2 are plotted against the ventilation rate V_R as shown in Figure 5.13.

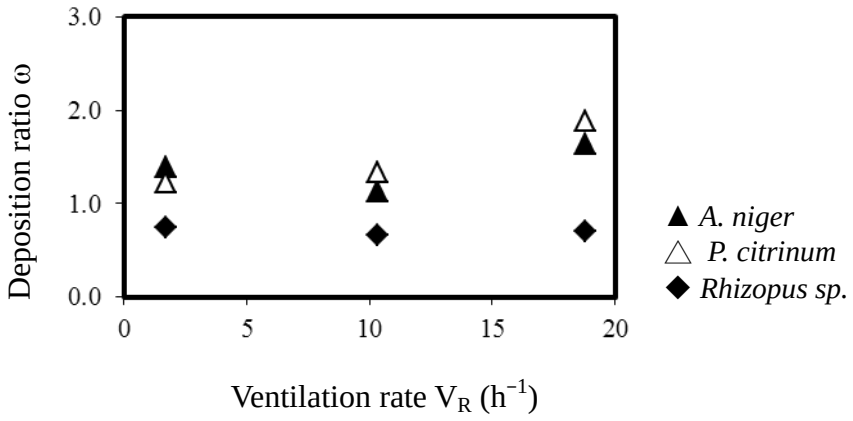


Figure 5.13: Deposition ratio of Group 2 bioaerosols.

It is noted that the fractional counts FC_i at i=4 have not been included in the calculation of the deposition ratio as their values are not significantly different from the expected counts ($p > 0.1$, t-test). When compared with Figure 5.10, positive slopes are reported for Groups (1) and (2) bioaerosols and negative ones are reported for Group (3) bioaerosols. As expected, smaller particles are predominated by airflow so that significant correlations ($p \leq 0.03$, t-test) for Group (1) bioaerosols but insignificant correlations ($p \geq 0.2$, t-test) for Group (3) bioaerosols are shown. The tested ventilation rates have very little effect on the deposition ratios of the 10μm (Group 3) bioaerosols.

This study reveals a different deposition pattern of the larger size bioaerosols – *Rhizopus* sp. (with average cell diameter of 10.0 μm). As depicted in Figures 5.11 and 5.12, the *Rhizopus* spores tend to deposit once entered the chamber and higher fractional counts are observed on the plates near the inlet. It is recorded that the distribution patterns at all V_R are non-uniform ($p \leq 0.05$, Chi-square test). The

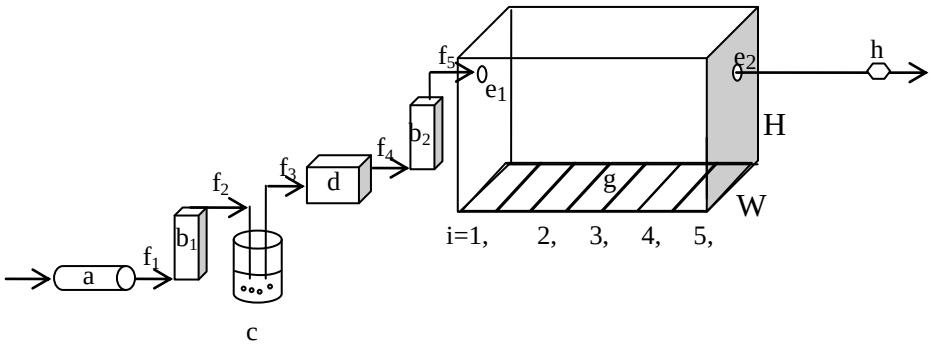
decreasing trends of FC_i along x/L at all V_R are indirectly proportional significantly ($R > 0.94$, $p \leq 0.05$, t-test). The V_R has negligible effect on the disposition pattern, there is no significant difference among the longitudinal spatial distribution pattern and ω of *Rhizopus* sp. at all V_R ($p > 0.45$, chi-square test) (Figure 5.12 and 5.13).

A case study on deposition pattern with microsphere particle

Although particle depositions of non-biological aerosols in test chamber have been studied, comparisons between two non-biological and biological of aerosols in the same configuration have never been detailed. The objectives of this part of study are to measure the deposition pattern of 1 μm fluorescent particle inside a ventilated chamber and to reveal the similarity between the pattern of florescence particle and biological aerosols.

Experimental setup

A ventilated chamber with the same configuration was used for studying the spatial deposition of the microsphere fluorescing particles. Instead of using petri dish for collection, a total of 7 glass plates organized in parallel were placed on the chamber floor to record the deposition patterns of the particles and the arrangement is depicted in Figure 5.14.



Test chamber L × W × H = 0.650m × 0.380m × 0.284 m

a	filtration system	e_2	Outlet
b	flow meter	f	airflow path
c	6-jet collision nebulizer	g	glass plate array in i=1…7 columns
d	heater	h	microfiber filter
e_1	inlet		

Figure 5.14: Experiment setup for deposition of microsphere particle.

Compressed air, first filtered through an air filtration system 'a' (Model 3074B, TSI) for moisture and impurities removal, entered the cabinet via two air paths f_1 and f_2, and then passed into air path f_3. f_1 was for the adjustment of aerosol concentration by volume while f_2 was connected to a 6-jet collision nebulizer 'c' (BGI Inc. Waltham, MA) for particle generation. The volume flow rates in f_1 (ranged from 0 to 20 L min^{-1}), f_2 (fixed at 15 L min^{-1}) and f_3 could be conditioned and were gauged by the flow meters 'b_1', 'b_2' and 'b_3' respectively. Moisture was removed again in f_3 via a heater 'd'. The processed air was finally supplied to the chamber through a high sidewall inlet 'e_1' and exhausted through an outlet 'e_2' aligned on the opposite chamber wall. A microfiber filter 'h' (with retention rate of 99.999% of 0.6μm particles) was connected with the outlet pipe for preventing environmental contamination. During the experiment, particle in the air was deposited onto the bottom of the chamber and was collected by those seven glass plates.

Generation and measurement of deposition pattern of particle

Polymer microsphere green fluorescing particle with 1 μm diameter was used in this study (Thermo Fisher Scientific, USA). The refractive index of the particle was 1.59 and the density was 1.06g cm^{-3}. According to the preliminary tests, 50 mL of particle suspension was prepared by adding 8 drops of the fluorescent particles.

Before each experimental run, the chamber was flushed with filtered air at a high velocity until the particle count on the particle counter (Model 983, Fluke) was zero in order to remove the background impurities. Before each run, the glass plates were cleaned thoroughly with buffer (Xylene, Sigma-Aldrich) and followed by denionzed water. After dying, the clean glass plates were covered by a clean tissue paper to prevent inadvertent contamination.

Particles were supplied into the chamber through inlet 'e_1' for 5 hr in the form of an air jet under isothermal conditions. The particles were injected at 5 different inlet velocities which were same as for the bioaerosols. It has been shown that in a similar sized ventilated chamber, the majority of the particles of size 1 μm were transported outside the chamber (Lai and Chen 2006). In addition, the average airborne particle concentration was measured from time-integrated filter samples where 1 filter sample was collected by drawing air (total volume was 350L) through the membrane filter (pore size was 0.45 μm, Millipore) at a constant rate throughout the sampling period (Lai and Nazaroff 2005). At the end of each experimental run, the collision

nebulizer was stopped, and clean air was supplied for 10 min or until the particle count on the counter was again effectively zero.

After the exposure period, each glass plate was removed carefully at the end of each test and transferred to the flame cupboard by using a clean aluminum container. The particles were extracted from the deposition surface and the filter samples using a 20 mL buffer solution (Xylene, Sigma-Aldrich) and the amount of fluorescent material was quantified by measuring the extracts with a fluorometer (TrilogyTM Laboratory Fluorometer, Turner Design USA). The relative concentration of the particle was expressed as relative fluorescence units (RFU).

In addition, the airborne particle concentration was determined by using the in-line filter holder with 0.45 µm filter paper (Advantec Inc.). A total of 350L air sample was collected by using an air sampling pump operated at 7 L min^{-1} for 10 minutes.

Spatial deposition pattern of particle in the ventilated chamber

A preliminary study for testing the particle coagulation was conducted by placing 3 glass slides (18 mm X 18 mm) on each glass plate (N=7) in the chamber. The test was conducted at a ventilation rate of 1.7 h^{-1} for 5 hr by using the same particle concentration as other tests. The glass slides were then put into separate sealed container and then examined under SEM (Figure 5.15). As no coagulation of particle was found on these slides, therefore, this assumption applied to other ventilation rates as well.

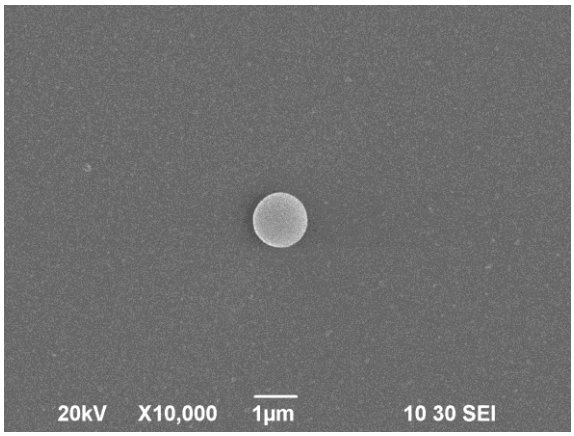


Figure 5.15: SEM photos of polymer microsphere green fluorescing particle.

Two trials were conducted at each ventilation rate and the fractional concentration FC_i represents the particle deposition on the seven glass plates in the testing chamber.

The uniformity of the longitudinal deposition pattern can be described by the fractional particle concentration FC_i (RFU) along x/L at i as displayed in Table 5.4 and presented in Figure 5.16. With an expected fractional particle concentration FC_e=1/7, FC_i were computed by,

$$FC_i = \frac{\Phi_i}{\sum_i \Phi_i} \quad \text{… (Eq. 5.5)}$$

where Φ_i is the total particle concentration at location i (glass plate i=1…7).

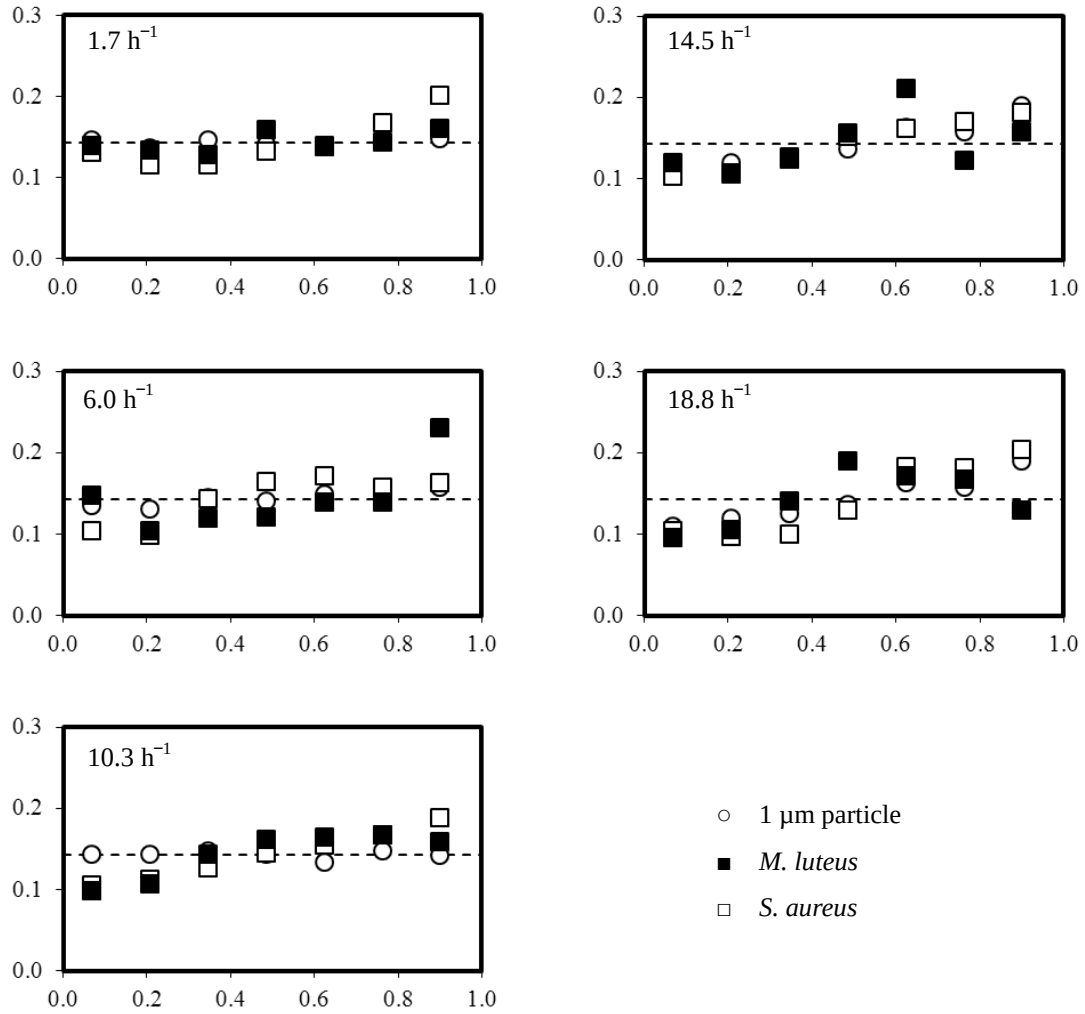
The ventilation effects on the deposition pattern of particle are studied. It is noted that the uniformity of the deposition pattern are evaluated with an expected fractional count FC_e = 1/7. Under lower V_R (1.7 h^{-1} to 10.3 h^{-1}), there is no significant difference of the deposition pattern ($p \geq 0.05$, Chi-square test) and uniform pattern are observed ($p \geq 0.05$, Chi-square test). While under higher V_R (14.5 h^{-1} and 18.8 h^{-1}), significant different of the deposition pattern ($p \leq 0.05$, Chi-square test) and non-uniform pattern are observed ($p \geq 0.05$, Chi-square test). On the other hand, expect for the V_R at 10.3 h^{-1}, there is an increasing trend of FC_i from the inlet to the outlet and significant when V_R at 6.0 h^{-1} and 14.5 h^{-1} ($p<0.05$, t-test). This phenomenon is also reflected by the ω, the ω ranged from 0.98 to 1.09 when under lower V_R (1.7 h^{-1} to 10.3 h^{-1}) and from 1.32 to 1.44 when under higher V_R (14.5 h^{-1} and 18.8 h^{-1}). It is believed that higher ventilation rate results in a larger air flow speed and larger particle jet momentum in the indoor environment.

Table 5.4: Deposition pattern of 1 µm microsphere fluorescing particle.

Case	Ventilation rate V_R (h^{-1})	Trials N	Fractional concentration (FC_i) on glass plate i of fractional distance (x/L) from the inlet							Deposition ratio ω
			i=1	2	3	4	5	6	7	
			x/L=0.069	0.208	0.346	0.485	0.623	0.762	0.900	
1 µm particle	(1) 1.7	2	0.146	0.136	0.146	0.141	0.138	0.147	0.147	1.01
	(2) 6.0	2	0.135	0.131	0.145	0.140	0.149	0.142	0.157	1.09
	(3) 10.3	2	0.143	0.143	0.148	0.143	0.134	0.147	0.142	0.98
	(4) 14.5	2	0.110	0.119	0.125	0.137	0.163	0.157	0.190	1.44
	(5) 18.8	2	0.135	0.128	0.116	0.121	0.124	0.134	0.242	1.32

Comparison of deposition pattern between particle and bioaerosols

This study reveals the differences between the deposition pattern of non-biological aerosols and biological aerosols in the chamber under the same configuration and ventilation condition. Since the size and shape of the tested fine particles and tested Group 1 bioaerosols are similar, therefore the deposition pattern is comparable and the results are presented in Figure 5.16. Although the measurement unit for the particle (i.e. RFU) and bioaerosols (CFU) are different, the use of FC_i to compare the spatial distribution in the chamber can eliminate this issue.



x-axis: Fractional distance from air inlet x/L
y-axis: Fractional concentration/ count along chamber length, FC_i

Figure 5.16: Fractional concentration/counts of 1 µm particle and Group 1 bioaerosols along the test chamber fractional length.

Since the size of the bacterial cells (spherical cell with average diameter ranged from

0.7 μm to 1.2 μm) and particle are similar, it is believed that the deposition pattern may be similar. Except for 10.3 h^{-1} of particle, similar increasing deposition trends are observed in both of particle and the bioaerosols while the significant similarity are observed at V_R = 1.7 h^{-1} and 14.5 h^{-1} ($p \geq 0.05$, Chi-square test) only (Figure 5.16). The ω of Group 1 bioaerosols ranged from 1.1 to 1.89, which is 0.9 to 1.5 times higher than that of the particle (Table 5.2 and 5.4). It is believed that the discrepancy of pattern between the particles and bioaerosols may probably due to the difference in sampling surface and the shape of the aerosols. The sampling surface used for the particles is glass plate while for the bioaerosols is agar plate. It is known that the deposition of the particles will be affected by the roughness of the surface (Abadie et al. 2001; Lai 2002). Basically both glass and agar surface are considered as smooth, therefore, the difference in roughness may not be significant. However, the moisture level on the agar plate will induce different surface viscosity between agar and glass plate. Different deposition patterns are observed on the surface with different viscosity, it has been reported that the deposition efficiency of a greased surface is higher when compared with a dry one which promotes a deeper penetration into the grease layer (Turner and Hering 1987; Peters and Leith 2004). Although the viscosity of the agar surface is not as high as that of grease, it is higher than the dry glass surface. On the other hand, the shapes of the two reference bioaerosols are not perfectly spherical and the density is not same as the particles, therefore the deposition properties may be different.

Prediction of the bioaerosols deposition pattern by computational method

An understanding of the role of ventilation in bioaerosol deposition is essential in assessing bioaerosols exposure and preventing airborne infection indoors (Lai 2002; Li et al. 2007; Wan and Chao 2007; Gao and Niu 2007; Zhao et al. 2005; Nazaroff 2004). Therefore, predicting the bioaerosols dispersion and deposition in a space is a must. A drift-flux model for particle distribution and deposition in indoor environments was applied for investigation of spatial and temporal particle concentration in enclosures even the well-mixed assumption cannot hold for coarse particles (Lai and Cheng 2007).

A mathematical method is designed to simulate the particle deposition process on

computer by using CFD software and FLUENT is one of the most popular software. However, CFD predictions of bioaerosols distribution patterns in a specific type of air distribution system over a wide range of ventilation rates have never been detailed. Therefore, a numerical model is developed to predicting the bioaerosols distribution and the experimental and numerical results are compared.

Eulerian-Lagrangian model

Deposition patterns of bioaerosols at the airflow characteristics in the chamber were calculated. An enclosure with dimensions of 0.650 m (L) × 0.380 m (W) × 0.284 m (H) was modeled (Figure 5.1). In the numerical model, the airflow characteristics and deposition of bioaerosols in the chamber without the mixing fans operating were investigated. Particles were injected continuously through the inlet. All of the airflow parameters chosen were based on the experimental values. Air was taken as 23ºC under isothermal conditions and five different inlet velocities (i.e. same as the experiment) were simulated. The airflow and particle motion were modeled under steady-state conditions since the deposition of bioaerosols is a very slow process (details below).

One important input parameter is the particle shape which affects the particle motion, so that it was assumed spherical. Three particle sizes were simulated, which is 1 μm, 4 μm and 10 μm, which are similar to the average size of Group 1 to 3 bioaerosols. Because the densities of the reference bioaerosols are not available in the literature, parametric sensitivity analysis allowing a range of densities from 1.0 g cm^{-3} to 1.3 g cm^{-3} was adopted for better assessment of how particle density could affect the numerical results.

An Eulerian-Lagrangian approach was used to resolve the two-phase problem. The airflow issue was answered in an Eulerian framework while the transport and deposition of microorganisms were realized in a Lagrangian framework. Governing equations for the airflow and the discrete phase were solved by a commercial finite volume based CFD code FLUENT (version 6.3) with a second-order solution scheme for the airflow. The renormalization group (RNG) *k*-turbulence model, which has been applied successfully to shape various indoor environments (Lai and Cheng 2007; Chao et al. 2008; Qian et al. 2009), was taken up to simulate the airflow for the present environment. To couple the pressure and velocity fields, the PISO algorithm was employed. The grid convergence test was conducted with three mesh

sizes by examining a set of airflow simulations. The three grid systems were 160 k, 320 k and 640 k. The mean velocity for a horizontal line along the inlet and outlet was compared. Minor differences in the calculated results were observed between the coarsest and the other two finer grids. To further analyse the convergence of the three grids, the grid convergence index (GCI) proposed by Roache (1998) was adapted to determine the relative error of the air velocity magnitude at 100 points. GCI was calculated as,

$$\mathrm{GCI(V)} = \mathrm{F_s}\,\frac{\varepsilon_{\mathrm{rms}}}{\mathrm{r^p} - 1} \qquad \ldots \text{(Eq. 5.6)}$$

where V represents the velocity, the safety factor, F_s = 3 and p = 2. $\varepsilon_{\mathrm{rms}}$ is defined as,

$$\varepsilon_{rms} = \sqrt{\frac{\sum_{i=1}^{100} \left| (u_{coarse} - u_{fine}) / u_{fine} \right|^2}{100}} \qquad \ldots \text{(Eq. 5.7)}$$

r can be estimated by the following expression,

$$r = \left(\frac{N_{fine}}{N_{coarse}} \right)^{1/3} \qquad \ldots \text{(Eq. 5.8)}$$

where N is the number of grid.

Using the 160 k grid system as a reference, the GCI for the grid 320 k and 640 k were 4.9% and 4.2% respectively. Since the GCI values were all less than 5%, it indicates that the grids should be sufficiently fine. Considering both computational time and accuracy, 320 k grid system was used in the simulations of this study and it is shown in Figure 5.17.

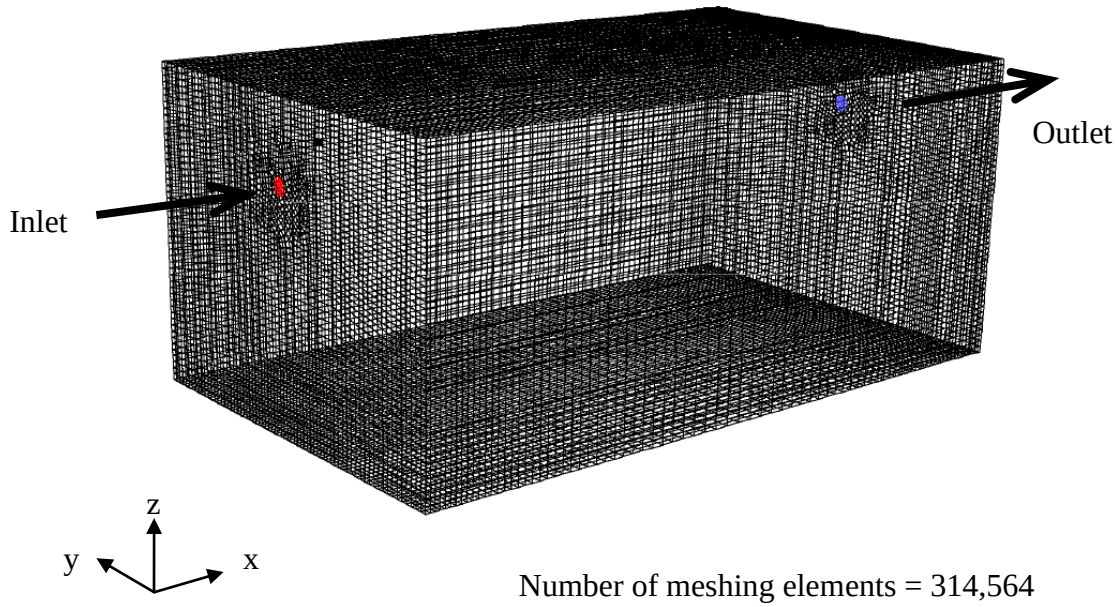


Figure 5.17: Mesh configuration of CFD prediction.

The bioaerosols concentrations measured in the chamber were low (≤5,500 CFU m^{-3}). For a low volume fraction of the dispersed second phase, we can assume the effect of particles on the turbulent flow is negligible. This one-way coupling allows the turbulence modulation effects to be neglected.

Lagrangian scheme was used to model the transport of the discrete phase where each particle released from the injection site was tracked separately for its position, velocity and residence time. The coagulation of bioaerosols was also ignored for the low bioaerosols concentration. Therefore, the equation of motion of a small aerosol particle which was calculated by integrating the force balance on the particle in terms of drag, gravity and Brownian forces is given by an equation below, where V_p and V are the particle and fluid parcel velocities, ρ_p taken at 1.1 g cm^{-3} and ρ are the particle and carrier phase densities, respectively.

$$\phi \frac{dV_p}{dt} = F_D(V - V_p) + \frac{g(\rho_p - \rho)}{\rho_p} + F_{Browian} \quad \ldots \text{(Eq. 5.9)}$$

$F_D(V_o - V)$ is the drag force per unit particle mass and F_D is defined as, where ν is the kinematic viscosity of the carrier phase, d_p is the particle diameter, and Re_p the particle Reynolds number.

$$F_D = \frac{18\nu}{d_p^2 \rho} \frac{C_D \mathrm{Re}_p}{24}; \quad \mathrm{Re}_p = \frac{\rho_p d_p \left| u_p - u \right|}{\mu} \qquad \ldots \text{(Eq. 5.10)}$$

Although the tested bioaerosols were spherical when examined under SEM, it was also recognized that the shape may not be perfectly spherical nor perfectly smooth. Similar to the non-biological aerosols, it was understood that the sphericity of the bioaerosol would be an important parameter affecting their deposition; as the increase in surface area or roughness would lead to an increase the drag force, and a decrease in the settling velocity. However, the information on the sphericity of bioaerosols is limited.

Therefore, the drag coefficient C_D of a bioaerosols particle was assumed constant at the particle surface roughness approximated by the particle sphericity τ at the airflow characteristics and determined by the equation below (Wadell 1934; Haider and Levenspiel 1989; Loth 2008),

$$\mathrm{C_D} = \frac{24}{\mathrm{Re_{sph}}}(1 + \mathrm{b_1}\,\mathrm{Re_{sph}}^{\mathrm{b_2}}) + \frac{\mathrm{b_3}\,\mathrm{Re_{sph}}}{\mathrm{b_4}\,\mathrm{Re_{sph}}}$$

$b_1 = \exp(2.3288 - 6.4581\tau + 2.4486\tau^2)$

$b_2 = 0.0964 + 0.5565\tau$

$b_3 = \exp(4.905 - 13.8944\tau + 18.4222\tau^2 - 10.2599\tau^3)$

$b_4 = \exp(1.4681 + 12.2584\tau - 20.7322\tau^2 + 15.8855\tau^3)$ … (Eq. 5.11)

The airflow rates in some scenarios were low and Brownian force affected the particle motion. For each time step, the amplitude of the Brownian force is expressed by an equation below (Li and Ahmadi 1992), where $S_o = \frac{216\nu k_B T}{\rho d_p^5 (\rho_p / \rho)^2 C_c}$, ξ_i are zero-mean, unit-variance-independent Gaussian random numbers, Δt is the time step, T is the absolute temperature of the fluid, k_B is the Boltzmann constant respectively.

$$F_{\text{Brownian}} = \varsigma_i \sqrt{\frac{\pi S_o}{\Delta t}} \quad \text{… (Eq. 5.12)}$$

Instantaneous particle velocity was determined by the discrete random walk model (DRW) which assumes the fluctuation velocities follows a Gaussian probability distribution as shown below, where *G* is a zero mean, unit variance normally distributed random number, $\sqrt{\overline{V_i^2}}$ is the root mean square (RMS) local fluctuation velocity in the *i*th direction.

$$V_i^{'} = G\sqrt{\overline{V_i^2}} \quad \text{… (Eq. 5.13)}$$

This model assumes successive encounter of particles with discrete turbulence eddies and the eddy interaction time scale can be found elsewhere (FLUENT 2006). This study also assumes that once the particles touch a surface, they are considered 'trapped' and will not resuspend. To better understand the spatial deposition inside the chamber statistically, three different particle counts were tested, viz 2,000, 5,750 and 17,250. In some limited cases, 51,250 particles were injected. A sensitive analysis showed that 17,250 injection is a good choice as further increase of particle injection has insignificant influence of the simulation results on deposition. The chamber floor was divided into seven columns by four rows along the length and the width as in the experiment; deposition counts on floor were recorded for further analysis of non-homogeneous distribution of bioaerosols deposition.

Comparison between modeling and experimental results

The CFD simulation results provided a mathematical prediction of the deposition of particle with different size and under different ventilation rates in the chamber. Velocity contours in the mid-plane x-z are shown in Figure 5.18 and 5.19. These profiles do not exhibit significant differences due to the simple inlet/outlet alignment through which inlet air travels to the outlet without creating a complex flow structure. For inlet velocities 0.17 ms^{-1} and 0.58 ms^{-1}, no observable eddies are detected (Figures 5.18 (a) and (b)). However, there are visible eddies with higher inlet velocities. The vortex velocity is found to increase with the inlet airflow rate

(Figures 5.19 (a) and (b)). Figures 5.20 (a) and (b) show the typical particle trajectories for velocity 0.17 ms^{-1} and 1.8 ms^{-1}, respectively. It can be observed that the particle motion follows closely the air streamline lines in different velocities.

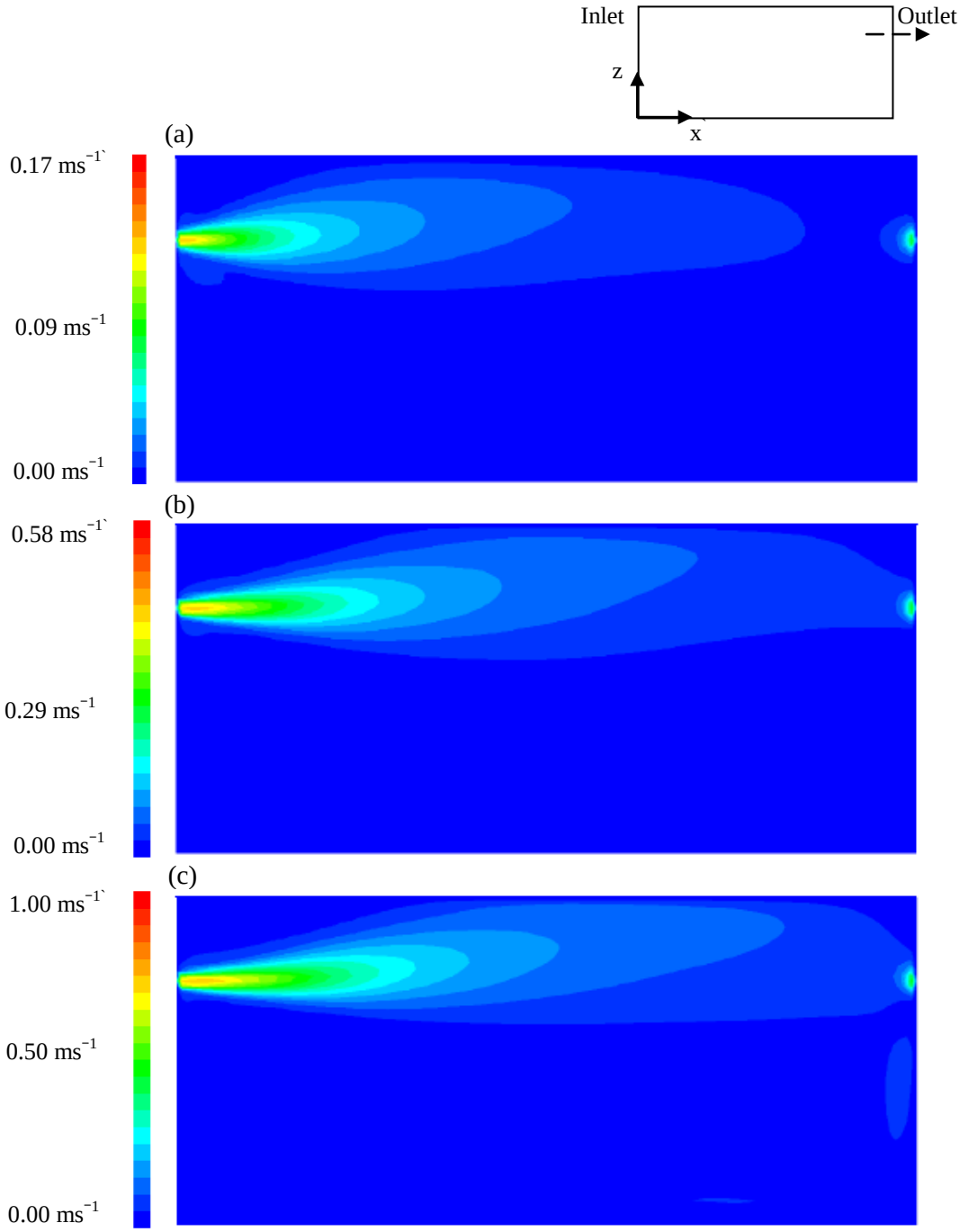


Figure 5.18: Velocity contours with inlet velocity of (a) 0.17 ms^{-1}, (b) 0.58 ms^{-1} and (c) 1 ms^{-1}.

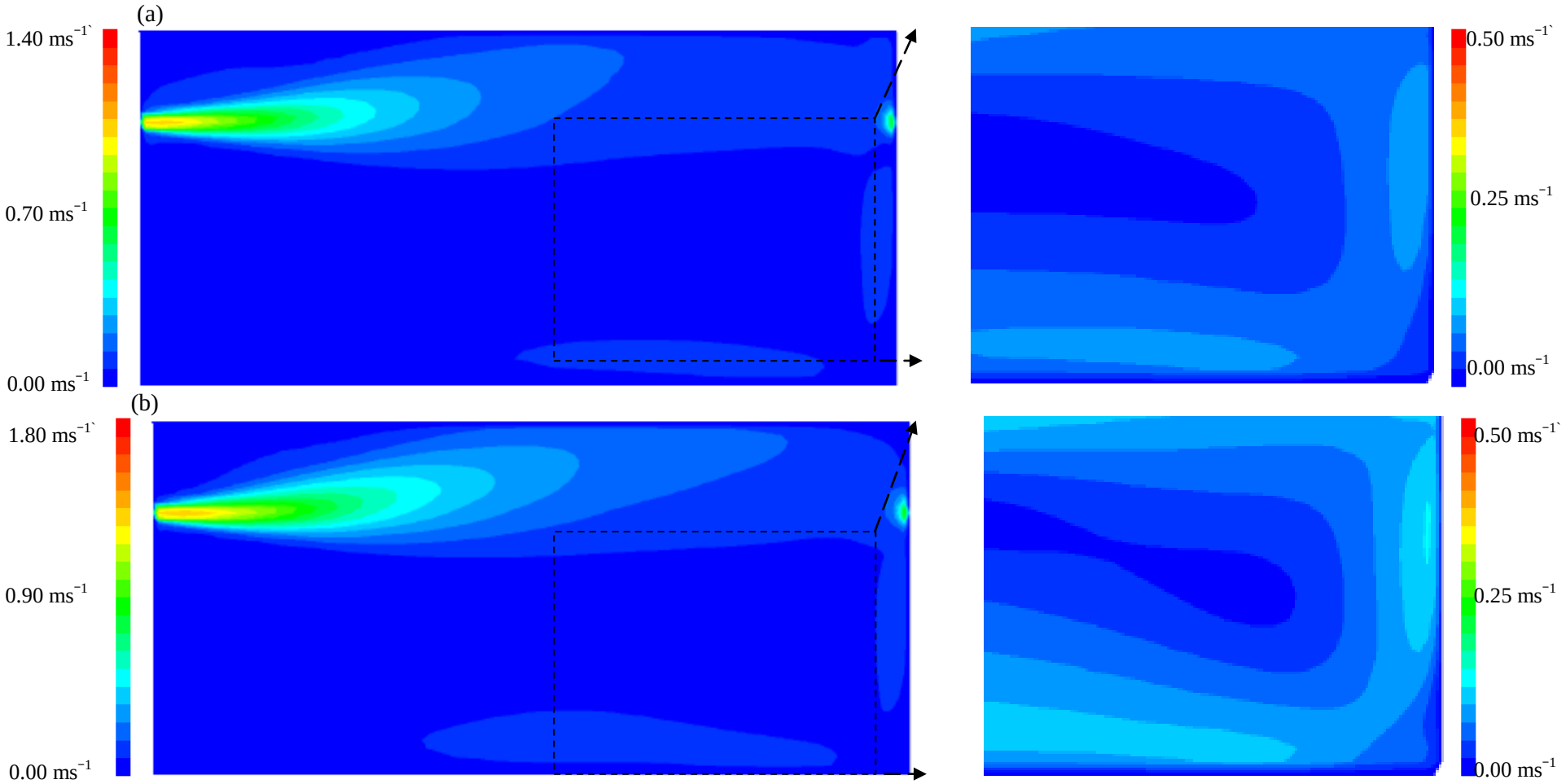
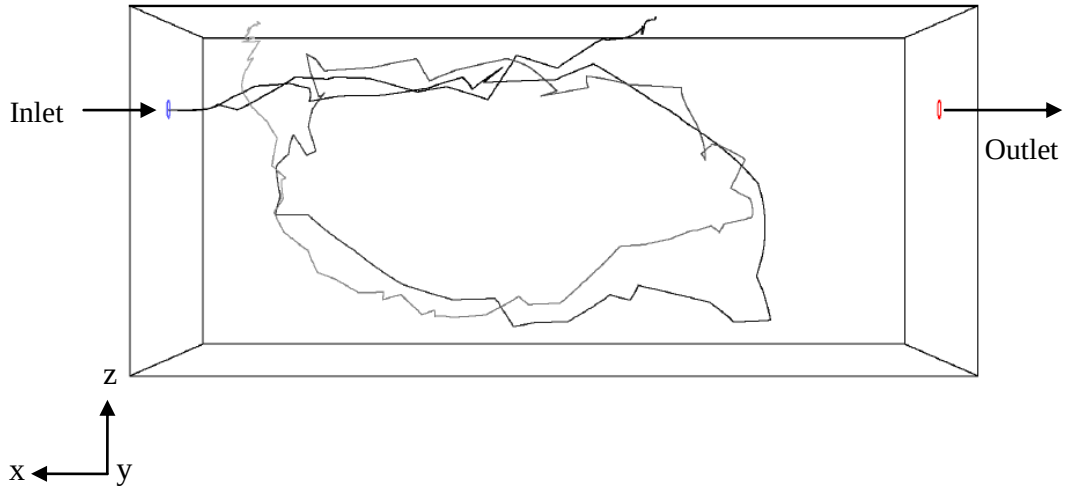


Figure 5.19: Velocity contours for inlet velocity of (a) 1.4 ms^{-1}and (b) 1.8 ms^{-1}.

(a)



(b)

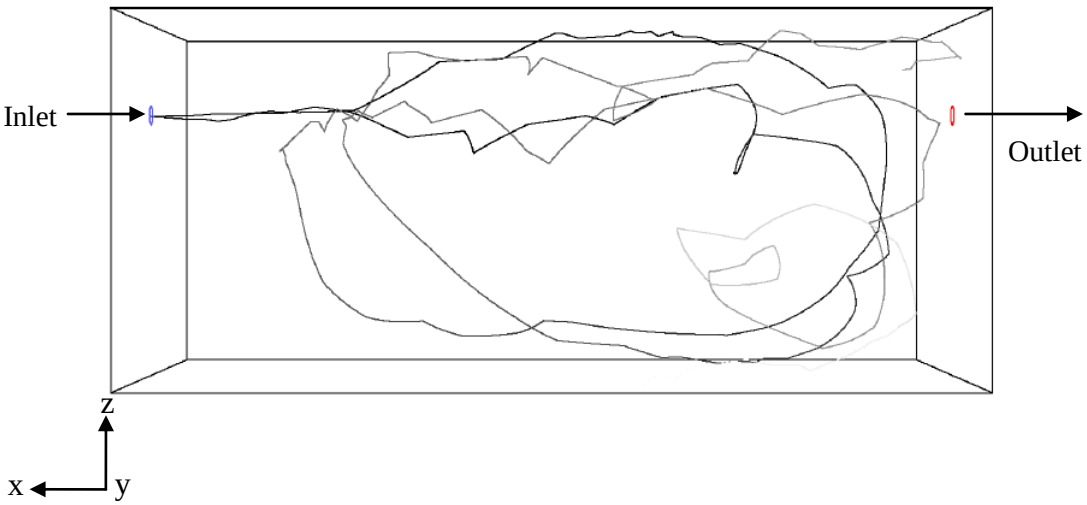
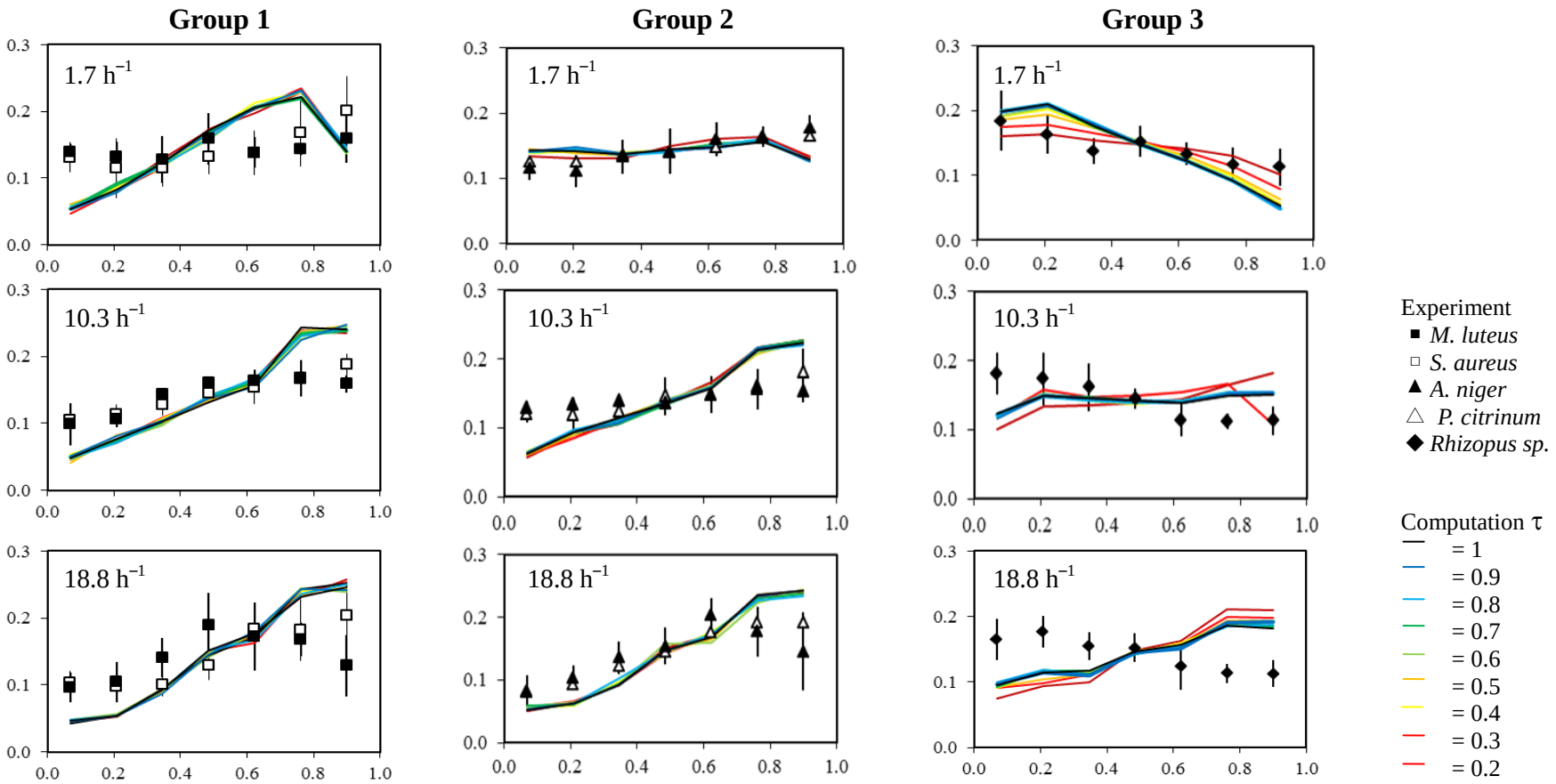


Figure 5.20: Simulated particle trajectories for inlet velocity (a) 0.17 ms^{-1} and (b) 1.8 ms^{-1}

Based on the particle tracking results, a data file of where the particles were trapped on the floor was produced and processed. First of all, the total number of particles deposited onto the floor was counted. By setting up different boundary constraints, particles deposited in the defined longitudinal floor sections $\frac{1}{7}L, \frac{2}{7}L, \ldots, \frac{7}{7}L$ were then counted as Φ_1, Φ_2, …, Φ_7 respectively. Using $FC_i = \frac{\Phi_i}{\sum_{i=1}^{7} \Phi_i}$, the fractional depositions listed in Table 5.5 were calculated and depicted at the Figure 5.21 to contrast the differences between the experimental and computational results.

Table 5.5: Computational result.

Case	Ventilation rate V_R (h^{-1})	Factional count (FC_i) of fractional distance (x/L) from the inlet							Deposition ratio ω
		i=1	2	3	4	5	6	7	
		x/L=0.069	0.208	0.346	0.485	0.623	0.762	0.900	
1 µm	(1) 1.7	0.053	0.085	0.119	0.165	0.207	0.227	0.145	2.25
	(2) 10.3	0.048	0.072	0.101	0.140	0.167	0.228	0.244	2.90
	(3) 18.8	0.048	0.054	0.090	0.150	0.173	0.246	0.241	3.45
4 µm	(1) 1.7	0.146	0.145	0.134	0.139	0.154	0.162	0.120	1.03
	(2) 10.3	0.077	0.094	0.110	0.157	0.162	0.179	0.222	2.01
	(3) 18.8	0.063	0.069	0.075	0.145	0.168	0.240	0.240	3.14
10 µm	(1) 1.7	0.198	0.207	0.176	0.150	0.121	0.094	0.054	0.46
	(2) 10.3	0.199	0.207	0.178	0.148	0.123	0.092	0.052	0.46
	(3) 18.8	0.201	0.207	0.183	0.144	0.122	0.092	0.051	0.45



x-axis: Fractional distance from air inlet x/L

y-axis: Fractional concentration/ count along chamber length, FC_i

Figure 5.21: Longitudinal fractional counts FC_i on the test chamber floor measured at three ventilation rates.

It is observed that the general trends of deposition of both experiment and numerical are quite similar especially in the inlet and center regions of the chamber. Similar trends of deposition pattern from the experimental and model results included: (1) smaller size bioaerosols with diameter from 0.8 μm to 4 μm (i.e. *M. luteus*, *S. aureus*, *A. niger* and *P. citrinum*) shows similar spatial distribution pattern, while the model also predicts similar trend of 1 μm and 4 μm particles expect the case at the V_R = 1.7 h^{-1}; (2) smaller size bioaerosols tend to disperse more farther from the inlet and higher fractional counts are observed close to the outlet, which are same as the model results of particles with size of 1 μm and 4 μm; (3) larger size bioaerosol (i.e. *Rhizopus* sp.) tend to disperse closer to the inlet and lower fractional counts are observed close to the outlet, which are same as the model results of particles with size of 10 μm; (4) ventilation rate effect on the deposition distribution of larger size bioaerosols are negligible when compared with those on smaller size, which is same as the model result; and (5) the deposition ratio ω of smaller bioaerosols is directly proportionally to the V_R, which is also reported in the model result.

The deposition ratios (ω) given in Table 5.5 are plotted against the ventilation rate V_R as shown in Figure 5.22 (with error bars shown for one standard deviation). It is noted that the fractional counts C_i at i=4 were not included in the calculation of the deposition ratio as their values were not significantly different from the expected counts ($p>0.1$, t-test). Positive slopes are reported for Groups (1) & (2) bioaerosols from and negative ones are reported for Group (2) bioaerosols from computations, which is same as the experimental results. As expected, smaller particles are predominated by airflow so that significant correlations ($p\leq0.03$, t-test) for Group (1) bioaerosols but insignificant correlations ($p\geq0.2$, t-test) for Group (3) bioaerosols are shown. The tested ventilation rates have very little effect on the deposition ratios of the 10μm (Group 3) bioaerosols. Correlation obtained from the computational results ($p=0.03$, t-test) for Group (2) bioaerosols but insufficient experimental data is available for verification ($p=0.4$, t-test).

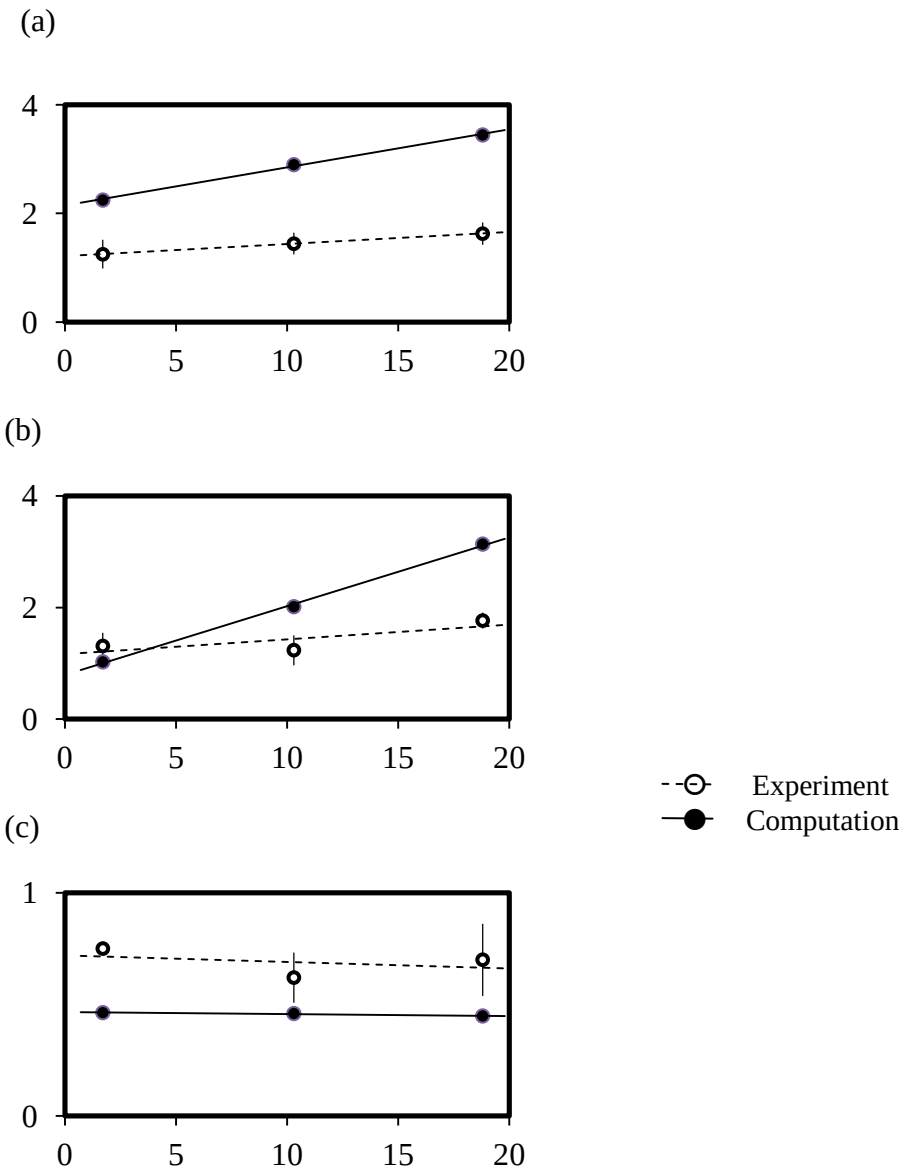


Figure 5.22: Deposition ratios

Although the general trends are similar, it is noted that the C_i obtained from the experiments are not exactly the same as the model ones. In addition, the predicted deposition ratios are from 2.25 to 3.45, 1.03 to 3.14, and 0.45 to 0.46 for particle with diameter of 1 μm, 4 μm and 10 μm, respectively (Table 5.4). The ratios are approximately 1.5 to 2.5 times higher when compared with that of the bioaerosols with average cell diameter from 0.8 μm to 4 μm, except for *P. citrinum* and *A. niger* at $V_R = 1.7\ h^{-1}$. While the predicted ratios are approximately 1.4 to 1.6 times lower when compared with that of larger bioaerosols (*Rhizopus* sp.).

Since the information on the surface area to the volume ratio of the tested bioaerosols are not available, so that the τ=0.2 – 1 are used to predict the proper effect of different τ on the deposition pattern in the chamber and presented in Figure 5.20. Discrepancy is observed between the predicted deposition patterns of particles with different sphericity. Slightly but not significant differences of predicted pattern at i=6,7 are observed for 1 μm particles at V_R=1.7 and 18.8 ms^{-1} ($p \geq 0.05$, Chi-square test). There are significant differences of the predicted patterns for 10 μm at V_R=1.7 and 18.8 ms^{-1} ($p \leq 0.05$, Chi-square test). It is interesting that the predicted pattern of 10 μm at 1.7 ms^{-1} is similar to the experimental results when τ=0.2 ($p \geq 0.05$, Chi-square test), however, the pattern is different at 18.8 ms^{-1} ($p \leq 0.05$, Chi-square test). These findings indicate that the sphericity of the bioaerosol is one of the important factors affecting their deposition. Since the increase in surface area or roughness will increase the drag force, thus decreases the settling velocity (Loth 2008). However, the information on the sphericity of bioaerosols is limited and further studies are needed.

The other possible reasons for the discrepancy between the measured and predicted results may be due to the following reasons: (1) counting of bioaerosols and repeatability level of experiments; (2) depositions are predicted within rectangular floor sections in the mathematical models whereas the depositions were measured on circular agar plates in the experiments, so that the ratio may be overestimated; (3) the height of the agar plates (1.2 cm height) have not been taken into account in the model as it may act as a barrier that may obstruct airflow around near wall which might affect deposition rate.. More efforts are needed for developing a model which is more fit to different shape of bioaerosols.

Conclusions

This study presents an experimental facility designed and built with the objective of understanding the deposition of bioaerosols in indoor environments. A forced ventilated chamber was made for investigating the deposition pattern of common indoor airborne bacteria and fungi. The experiments were operated in a common type of air distribution system. The deposition pattern of selected common bioaerosols is significantly affected by the size and ventilation rate. The airflow rate has been demonstrated to have an influence on the concentration homogeneity. The

experimental results for small-sized bioaerosols (Group 1) reveal that a small mixing fan inside the chamber prompted very effective mixing while non-homogeneity is observed even at a very high ventilation rate. Similar trends of spatial distribution pattern from the experimental and model results are found. In order to broaden our knowledge of deposition of bioaerosols, further investigation is needed to develop a model suitable for bioaerosols with different sizes and shapes. It was suggested that chamber experiment could be used to investigate the deposition pattern of more common indoor bacteria and fungi especially for those with health concerns (e.g. *Cladosporium* sp., *E. coli*, etc.). The results could be further validated through experiments in full scale chamber. When a model is fully established, modifications could be made for the adaptation to different indoor environment designs (e.g. hospital, transportation system, etc.); and a better control of the indoor bioaerosols could be achieved.

Chapter 6 Conclusions

Important findings on the exposure and control strategies of indoor bioaerosols were revealed through the assessment and evaluation of indoor airborne bacteria and fungi in Hong Kong, and the investigation of possible factors affecting the deposition of commonly isolated bioaerosols in a ventilated chamber.

The regional database of indoor airborne bacteria and fungi in residential (N=103) and commercial office buildings (N=239) was developed in the study, which was one of the most comprehensive investigations with the inclusion of other common IAQ parameters in subtropical city. It was revealed that there were (a) significant differences on the indoor airborne bacteria count (ABC) and airborne fungal count (AFC) in residential buildings among different sampling locations (i.e. living room, kitchen and bedroom) and different seasons (i.e. warm and cold); (b) relatively lower ABC and AFC recorded in the apartment of Hong Kong when compared with those in other countries; (c) lower ABC and AFC recorded in air-conditioned offices with 'Excellent Class' of IAQ; (d) significantly higher ABC in air-conditioned offices in Hong Kong when compared with some other countries, and similar ABC recorded in Hong Kong compared with countries with similar climatic conditions such as Taiwan; and (e) significantly lower AFC recorded in air-conditioned offices in Hong Kong when compared with other countries including Taiwan; and (f) dominant indoor fungal genera found, namely – *Aspergillus*, *Penicillium* and *Cladosporium*.

This was the first study to evaluate the contribution of airborne bacteria and fungi to an unsatisfactory IAQ. AFC and ABC were identified to be the 2nd and 3rd ranked contributors for the unsatisfactory rates of IAQ in the air-conditioned offices in Hong Kong, and the assessments of airborne fungi and bacteria levels in office environment also highlighted the importance and necessity for further investigations on the airborne fungi in the IAQ audits.

For the evaluation of exposure to bioaerosols, several indices and mathematical expressions were proposed in this study, with the feasibility tested with the data in the database: (a) a 'Relative Index of Exposure' to indoor bioaerosols was proposed as a quantitative measure of the influence due to exposure risk of indoor bioaerosols in these environments in addition to the I/O ratio which compared only the

abundance; (b) mathematical expressions were proposed to estimate the correlation between airborne bacteria and fungi levels correlated with temperature and relative humidity of the indoor environment, which was very useful for rapid estimation of the expected ABC and AFC under certain thermal environmental conditions; (c) an epistemic approach for assessing the acceptance of air-conditioned spaces against the indoor bioaerosols, which could provide policymakers with important information for making a fast response to the microbiological pollutant problems, while avoiding the inappropriate level of reliance on the results.

Positive influences of the existing IAQ policy of Hong Kong which implemented in the year 2003 were observed by reviewing the changes of the airborne bacteria and fungi exposure in air-conditioned offices in the past decade. It is believed that the improvements may be related to the implementation of GN and IAQ certification scheme by the HKEPD in 2003 (HKEPD 2003), in which recommendations for the improvement of the IAQ by controlling the indoor air pollutants through source control and dilution by ventilation were provided (IAQMG 1999).

Furthermore, several case studies were conducted in residential and commercials buildings in Hong Kong regarding different issues. These case studies included: (a) an investigation of the impact of indoor bioaerosols and some common air pollutants in the apartments on the quality of life (QOL) of patients with Chronic obstructive pulmonary disease (COPD), revealing the strong association between the QOL in patients with COPD and indoor environmental parameters; and indoor air pollutants were also suggested to be monitored for future related studies; and (b) an investigation of the effects of different ventilation conditions on the indoor bioaerosols levels of the unoccupied office areas and other area (i.e. washrooms), with a strong correlation between the ventilation condition and the levels, underscoring the importance of the control of indoor bioaerosols.

A ventilated chamber was constructed to investigate the deposition of five commonly isolated bioaerosols with sizes ranged from 1 μm to 10 μm. The deposition of bioaerosols in the chamber was found to be influenced by the ventilation rate, mixing conditions, and the size of the bioaerosols. In addition, an inclusion of drag with particle sphericity in an Eulerian-Lagrangian approach was proposed to improve the prediction of the deposition of the bioaerosols.

With the objectives achieved in the present study, further investigations could be

conducted for a better understanding of the deposition of the bioaerosols in the indoor environments in order to set up some useful controlling strategies. For examples, the shape effects of bioaerosols on their deposition in an indoor space are possible areas for further investigation for a more accurate mathematical model prediction. The well-developed model could then be applied to investigate the deposition and the distribution of bioaerosols in other environments (e.g. transportation system, classroom, hospital, etc.) to provide rapid assistance for the control of air-transmitted infectious diseases dispersal. Moreover, the model could also be used to investigate the efficiency of the controlling strategies of indoor bioaerosols such as ultraviolet germicidal irradiation system, etc. (Wong et al. 2011; Yang et al. 2012).

Appendices I

慢性呼吸疾病指標問卷

CHRONIC RESPIRATORY QUESTIONNAIRE

(CHINESE VERSION)

Name:	
HK ID:	
Ward/Bed:	/
□ Pre-PDP AX on	/ /
□ Post PDP Ax on	/ /

By

Pulmonary Rehabilitation Working Group,

Occupational Therapy

Central Coordinating Committee,

HA

慢性呼吸疾病指標問卷

第一次運作，七分制計分法，訪問用表

這份問卷是幫助你了解自己在過去兩星期的感覺。你會被問及你的氣促程度，你的疲倦程度及你的心情。

1) 在過去兩星期，請你回想哪些活動做起來會令你覺得氣促。這些活動必須是你日常生活中非常重要的，並且是常做的。請儘量列出使你過去兩星期內覺得氣促的活動。
[在答案表上，請在病人提及的活動號碼上加上圓圈。如果提及的活動是在原表中沒有，請在空欄處附加，並跟據病人的描述填寫。]
請你再想想在過去兩星期內，有沒有其他活動做起來令你覺得氣促?
[請記錄病人的回應]

2) 現在我會讀出一連串的活動，而這些活動一般會令肺病人覺得氣促。我會慢慢講，等你回應，如果在過去兩星期內做過這些活動而有覺得氣促，請你告訴我。如果你在過去兩星期內沒有做過這些活動，請說[無]。
[請讀出活動表，病人已自動提出的活動不需要重複讀。在讀出每個活動項目之後稍停片刻，讓病人有機會回應。在答案表上，請在病人提及的活動號碼上加上圓圈。]

1. 憤怒或情緒低落	14. 做運動
2. 沖涼或花洒浴	15. 舉手高過頭
3. 彎低腰	16. 跑步，例如追巴士
4. 手提物件，例如雜物或餸菜	17. 購物
5. 穿衫褲	18. 臨睡前，想睡覺的時候
6. 進食	19. 談話
7. 散步	20. 吸塵
8. 做家務	21. 在屋內行走
9. 心急	22. 行上斜坡
10. 收摺床被	23. 行上樓梯
11. 抹地或拖地	24. 與別人一同行平路
12. 搬動傢俬	25. 煮飯
13. 與小孩或孫兒玩耍	

3A) 你所選擇的活動中，哪一個在你日常生活中是最重要的?
我會讀一次你所選擇的活動，當我讀完，請你告訴我哪一個是最重要的?
[請讀出病人主動提出過的活動及剛才所選擇過的活動]
哪一個活動是你日常生活中最重要的?
[請在答案表中記錄]

3B) 剩下的活動中，哪一個是在你日常生活中是最重要的?
我會讀一次，當我讀完，請你告訴我哪一個是最重要的?
[請重複讀一次所剩下的活動項目]
哪一個活動是你日常生活中最重要的?
[請在答案表中記錄]

3C) 剩下的活動中，哪一個是在你日常生活中是最重要的?
[請在答案表中記錄]

3D) 剩下的活動中，哪一個是在你日常生活中是最重要的?
[請在答案表中記錄]

3E) 剩下的活動中，哪一個是在你日常生活中是最重要的?
[請在答案表中記錄]

4) 在過去兩星期內，當你做你所選擇的五過最重要的活動時，我想你形容你的氣促程度?

4A) 在過去兩星期內，請指出當你_____ *[訪問者請讀出活動 3A]* 時的氣促程度。請從你面前的咭選擇一個答案。*[綠咭]*

1. 極度氣促
2. 十分氣促
3. 頗氣促
4. 中度氣促
5. 少量氣促
6. 輕微氣促
7. 無氣促

4B) 在過去兩星期內，請指出當你_____ *[訪問者請讀出活動 3B]* 時的氣促程度。請從你面前的咭選擇一個答案。*[綠咭]*

1. 極度氣促
2. 十分氣促
3. 頗氣促
4. 中度氣促
5. 少量氣促
6. 輕微氣促
7. 無氣促

4C) 在過去兩星期內，請指出當你_____ *[訪問者請讀出活動 3C]* 時的氣促程度。請從你面前的咭選擇一個答案。*[綠咭]*

1. 極度氣促
2. 十分氣促
3. 頗氣促
4. 中度氣促
5. 少量氣促
6. 輕微氣促
7. 無氣促

4D) 在過去兩星期內，請指出當你_____ *[訪問者請讀出活動 3D]* 時的氣促程度。請從你面前的咭選擇一個答案。*[綠咭]*

1. 極度氣促
2. 十分氣促
3. 頗氣促
4. 中度氣促
5. 少量氣促
6. 輕微氣促
7. 無氣促

4E) 在過去兩星期內，請指出當你_____ *[訪問者請讀出活動 3E]* 時的氣促程度。請從你面前的咭選擇一個答案。*[綠咭]*

1. 極度氣促
2. 十分氣促
3. 頗氣促
4. 中度氣促
5. 少量氣促
6. 輕微氣促
7. 無氣促

5) 在過去兩星期內，你有多少時間覺得<u>失敗或不耐煩</u>? 請從你面前的咭選擇一個答案，指出過去兩星期內你有多少時間覺得失敗或不耐煩。*[藍咭]*

1 無論任何時間
2 大部份時間
3 頗多時間
4 間中
5 甚少
6 極少
7 無

6) 在過去兩星期內，當你呼吸困難時，有多少時間覺得害怕或驚慌? 請從你面前的咭選擇一個答案，指出過去兩星期內你有多少時間覺得害怕或驚慌。*[藍咭]*

1 無論任何時間
2 大部份時間
3 頗多時間
4 間中
5 甚少
6 極少
7 無

7) 在過去兩星期內，你是否覺得疲倦，程度又如何? 請從你面前的咭選擇一個答案，指出過去兩星期內你有多少時間覺得害怕或驚慌。*[橙咭]*

1 極度疲倦
2 十分疲倦
3 頗疲倦
4 中度疲倦
5 少量疲倦
6 輕微疲倦
7 無疲倦

8) 在過去兩星期內，你有多少時間因咳嗽或大力呼吸而覺得尷尬? 請從你面前的咭選擇一個答案，指出過去兩星期內你有多少時間因咳嗽或大力呼吸而覺得尷尬。*[藍咭]*

1 無論任何時間
2 大部份時間
3 頗多時間
4 間中
5 甚少
6 極少
7 無

9) 在過去兩星期內，你有多少時間覺得自己非常有信心及肯定可以應付自己的病? 請從你面前的咭選擇一個答案，指出過去兩星期內你有多少時間覺得自己非常有信心及肯定可以應付自己的病。*[黃咭]*

1 無
2 甚少
3 間中
4 頗多時間
5 大部份時間
6 差不多全部時間
7 無論任何時間

10) 在過去兩星期內，你覺得自己的活力如何? 請從你面前的咭選擇一個答案，指出你的活力程度。*[粉紅咭]*

1 完全無活力
2 輕微有活力
3 少量有活力
4 中度有活力
5 頗有活力
6 十分有活力
7 極度有活力

11) 在過去兩星期內，你有多少時間覺得情緒低落，擔心或不開心? 請從你面前的咭選擇一個答案，指出過去兩星期內你有多少時間覺得情緒低落，擔心或不開心。*[藍咭]*

1 無論任何時間
2 大部份時間
3 頗多時間
4 間中
5 甚少
6 極少
7 無

12) 在過去兩星期內，你有多少時間覺得自己能夠完全控制呼吸問題? 請從你面前的咭選擇一個答案，指出過去兩星期內你有多少時間覺得自己能夠完全控制呼吸問題。*[黃咭]*

1 無
2 甚少
3 間中
4 頗多時間
5 大部份時間
6 差不多全部時間
7 無論任何時間

13) 在過去兩星期內，你有多少時間覺得輕鬆及無壓力? 請從你面前的咭選擇一個答案，指出過去兩星期內你有多少時間覺得自己輕鬆及無壓力。*[黃咭]*

1 無
2 甚少
3 間中
4 頗多時間
5 大部份時間
6 差不多全部時間
7 無論任何時間

14) 在過去兩星期內，你有多少時間覺得缺少活力? 請從你面前的咭選擇一個答案，指出過去兩星期內你有多少時間覺得缺少活力。*[藍咭]*

1 無論任何時間
2 大部份時間
3 頗多時間
4 間中
5 甚少
6 極少
7 無

15) 在過去兩星期內，你有多少時間覺得氣餒或自己無用? 請從你面前的咭選擇一個答案，指出過去兩星期內你有多少時間覺得氣餒或自己無用。*[藍咭]*

1 無論任何時間
2 大部份時間
3 頗多時間
4 間中
5 甚少
6 極少
7 無

16) 在過去兩星期內，你有多少時間覺得勞累或遲鈍? 請從你面前的咭選擇一個答案，指出過去兩星期內你有多少時間覺得勞累或遲鈍。*[藍咭]*

1 無論任何時間
2 大部份時間
3 頗多時間
4 間中
5 甚少
6 極少
7 無

17) 在過去兩星期內，你覺得自己的生活有幾開心、滿意或滿足? 請從你面前的咭選擇一個答案，指出過去兩星期內你有多少時間覺得自己的生活有幾開心、滿意或滿足。*[灰咭]*

1 非常不滿意，大部份時間不開心
2 通常不滿意，不開心
3 有些不滿意，不開心
4 算是滿意，開心
5 大部份時間開心
6 大部份時間非常開心
7 極度開心，無比滿足

18) 在過去兩星期內，當你呼吸困難時，你有多少時間覺得情緒低落及害怕? 請從你面前的咭選擇一個答案，指出過去兩星期內你有多少時間因呼吸困難而覺得緒低落及害怕。*[藍咭]*

1 無論任何時間
2 大部份時間
3 頗多時間
4 間中
5 甚少
6 極少
7 無

19) 在過去兩星期內，有多少時間覺得坐立不安或緊張? 請從你面前的咭選擇一個答案，指出過去兩星期內你有多少時間覺得坐立不安或緊張。*[藍咭]*

1 無論任何時間
2 大部份時間
3 頗多時間
4 間中
5 甚少
6 極少
7 無

Appendices II

Department of Building Services Engineering & Department Rehabilitation Sciences

The impact of indoor air pollutants on people in Hong Kong Study Form

Subject information Subject No: _____

Name:	Diagnosis:
Age:	Location:
Gender:	Date: Time:
On LTOT: Yes/No if Yes: _____$Lmin^{-1}$	OT Compliance: 24hr/15hr/nocturnal/PRN
OT use: Indoor/Outdoor/both	Regular follow-up: Yes/No Frequency:
See Dr. due to respiratory problems within 1 month: Yes/No	
Frequency: Private/Public	
No. of admission due to respiratory problems within 6 months:	Onset till now:
Medication:	
Financial: self support/family support/CSSA/DA/HDA/compensation	
Role:	Occupation:
Live with: alone//family/other	Duration of living in present flat:
Direct lift landing/Stairs	B.P & pulse:
Moser ADL class:	

Subject responses Remarks: Time after taking puff: _____

Lung Functions (Forced)			
$FEV_{1:}$		FEV_1/ FVC:	
FVC :		PEF:	
MFTE			
Sub-test	At rest	Indoor mobility	Sit ←→ Stand
Time completed		Yes/No	Yes/No
RPE		/10	/10
RPD		/10	/10
RPT		/10	/10
Pace			
2 mins recovery		Yes/No	Yes/No
SaO_2			
Pulse rate			
Raw score			
Profile score			
Total score	RPD(Max) :	SaO_2 range:	

References

Abadie M, Limam K, Allard F. Indoor particle pollution: effect of wall textures on particle deposition. Building and Environment 2001; 36: 821–827.

Abdel Hameed AA, Khoder MI, Ibrahim YH, Saeed Y, Osman ME, Ghanem S. Study on some factors affecting survivability of airborne fungi. Science of the Total Environment 2012; 414: 696–700.

Adan OCG. On the fungal defacement of interior finishes. Eindhoven University of Technology, PHD thesis, 1994.

Agranovski V, Ristovski Z, Hargreaves M, Blackall PJ, Morawska L. Real-time measurement of bacterial aerosols with the UVAPS: performance evaluation. Journal of Aerosol Science 2003; 34(3): 301–317.

American Conference of Governmental Industrial Hygienists (ACGIH). Guidelines for the assessment about aerosols in the indoor environment. Cincinnati, Ohio, 1989.

American Conference of Governmental Industrial Hygienists (ACGIH). TLVs® and BEIs®: Threshold limit values for chemical substances and physical agents biological exposure indices. American Conference of Governmental Industrial Hygienists. Cincinnati, OH, 1997.

ANSI/ASHRAE Standard 62.1-2010. Ventilation for acceptable indoor air quality. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, 2010.

Araujo R, Cabral JP, Rodrigues AG. Air filtration systems and restrictive access conditions improve indoor air quality in clinical units: *Penicillium* as a general indicator of hospital indoor fungal levels. American Journal of Infection Control 2008; 36: 129–134.

ASTM PS40-95, 1995. Provisional standard guide for using indoor carbon dioxide concentrations to evaluate indoor air quality and ventilation. American Society for Testing and Materials, Philadelphia, 1995.

ASTM standard E741-00, 2000. Standard test method for determining air change in a single zone by means of trace gas dilution. American Society for Testing and Materials, Philadelphia, 2000.

Aydogdu H, Asan A, Otkun MT. Indoor and outdoor airborne bacteria in child day-care centers in Edirne City (Turkey), seasonal distribution and influence of meteorological factors. Environmental Monitoring and Assessment 2010; 164(1-4): 53–66.

The Brazilian Ministry of Health. Act 3523 Indoor air quality. Brazil, 1998.

Barker J, Bloomfield SF. Survival of Salmonella in bathrooms and toilets in domestics homes following salmonellosis. Journal of Applied Microbiology 2000; 89(1): 137–144.

Barker J, Jones MV. The potential spread of infection caused by aerosol contamination of surfaces after flushing a domestic toilet. Journal of Applied Microbiology 2005; 99(2): 339–347.

Barry TF, Meyer B, Chaisson WT, Smith JA, Culp JO, Bevirt WD. HVAC System Application, 5th ed. Chantilly, VA, Sheet Metal and Air Conditioning Contractor's National Association, Inc, 1995.

Bascilico MZ, Chiericatti C, Aringoli EE, Althaus RL, Basilico JC. Influence of environmental factors on airborne fungi in houses of Santa Fe City, Argentina Science of the Total Environment 2007; 376: 143–150.

Bearg DW. Indoor Air Quality and HVAC System, Boca Raton, FA, Lewis Publishers, 1993.

BGI Inc. A note on the output distribution of the collision nebulizer. BGI Inc. Waltham, MA, 2007.

Binder K. Monte Carlo simulation in statistical physics: an introduction, 4th Ed., Springer, Berlin, New York, 2002.

Blondeau P, Iordache V, Poupard O, Genin D, Allard F. Relationship between outdoor and indoor air quality in eight French schools. Indoor Air 2005; 15: 2–12.

Bluyssen PM, Cox C, Seppänen O, de Oliveira Fernandes E, Clausen G, Müller B, Roulet C-A: Why, when and how do HVAC-systems pollute the indoor environment and what to do about it? the European AIRLESS project. Building and Environment 2003; 38(2): 209–225.

Bornehag CG, Blomquist G, Gyntelberg F, Järvholm B, Malmberg P, Nordvall L, Nielsen A, Pershagen G, Sundell J. Dampness in buildings and health. Nordic interdisciplinary review of the scientific evidence on associations between exposure to ‘dampness in buildings and health effects (NORDDAMP). Indoor Air 2001; 11:72–86.

Bornehag CG, Sundell J, Hägerhed-Engman L, Sigsgaard T. Association between ventilation rates in 390 Swedish homes and allergic symptoms in children. Indoor Air 2005; 15: 275–280.

Bouilly J, Limam K, Béghein C, Allard F. Effect on ventilation strategies on particle decay rates indoors: an experimental and modeling study. Atmospheric Environment 2005; 39: 4885–4892.

Building Services Research and Information Association (BSRIA). Rules of Thumb - Guidelines for building services (3rd ed). BSRIA, 2001.

Burge HA. Bioaerosols: prevalence and health effects in the indoor environment. Journal of Allergy and Clinical Immunology 1990; 86(5): 687–701.

Burge HA, Pierson DL, Theron OG, Strawn KF, Mishra SK. Dynamics of airborne fungal populations in a large office buildings. Current Microbiology 2000; 40(1): 10–16.

Buttner MP, Stetzenbach LD. Monitoring airborne fungal spores in an experimental indoor environment to evaluate sampling methods and the effects of human activity on air sampling. Applied Environmental Microbiology 1993; 59: 219–226.

Byrne MA, Goddard AJH, Lange C, Roed J. Stable tracer aerosol deposition measurements in a test chamber. Journal of Aerosol Science 1995; 26: 645–653.

Cabral JPS. Can we use indoor fungi as bioindicators of indoor air quality? Historical perspectives and open questions. Science of the Total Environment 2010; 408: 4285–4295.

Calderon C, Ward E, Freeman J, McCartney A. Detection of airborne fungal spores sampled by rotating-arm and Hirst-type spore traps using polymerase chain reaction assays. Journal of Aerosol Science 2002; 33(2): 283–296.

Castón-Osorio JJ, Rivero A, Torre-Cisneros J. Epidemiology of invasive fungal infection. International Journal of Antimicrobial Agents 2008; 32(2): S103–S109.

Cavagna G, Foa V, Vigliani EC. Effects in man and rabbits of inhalation of cotton dust or extracts and purified endotoxins. British Journal of Industrial Medicine 1969; 26: 314–321.

Chan LLC, Tam K, Chan E, Ng B, So CT. Reliability and validity of the Chinese version of the chronic respiratory questionnaire (CCRQ) in patients with COPD. Hong Kong Journal of Occupational Therapy 2006; 16: 9–15.

Chan WY, Law KM, Vrijmoed LLP. A comparative study of qualitative sampling methods for the analysis of the indoor air molds. Proceedings of Healthy Buildings 2003 – The 7th International Conference, Singapore, 7-11 Dec 2003: 679–684.

Chan WY. The Eco-physiology of outdoor airborne fungi in Hong Kong. City University of Hong Kong, Hong Kong SAR, China, MPhil. Thesis, 2006.

Chao CY, Chan GY, Ho L. Feasibility study of an indoor air quality measurement protocol on 12 parameters in mechanically ventilation and air conditioned buildings. Indoor Built Environment 2001; 10(1): 3–19.

Chao CY, Wong KK. Residential indoor PM_{10} and $PM_{2.5}$ in Hong Kong and the elemental composition. Atmospheric Environment 2002; 36: 265–277.

Chao CYH, Wan MP, Sze To G.N. Transport and removal of expiratory droplets in hospital ward environment. Aerosol Science and Technology 2008; 42(5): 377–394.

Chartered Institution of Building Services Engineers (CIBSE). Guide B: Heating, Ventilating, Air Conditioning and Refrigeration, CIBSE, 2005.

Chow PK, Chan WY, Vrijmoed LLP. An investigation on the occurrence of fungi and bacteria in the MVAC system in an office premise. Proceedings of Indoor Air 2005 – The 10th International Conference on Indoor Air Quality and Climate, Beijing, China, 4–9 Sep 2005: 1096–1100.

Chow WK, Wong LT. Experimental studies on air diffusion of a linear diffuser and associated thermal comfort indices in an air-conditioned space, Building and Environment 1994; 29: 523–530.

Chow WK, Wong LT. Equations for a ventilation design derived from computational fluid dynamics. Indoor and Built Environment 1998a; 7: 276–288.

Chow WK, Wong LT. Survey on the air diffusion devices for air-conditioning systems in Hong Kong. Energy Engineering 1998b; 95(6): 50–79.

Chow WK, Wong LT. Air diffusion terminal devices: macroscopic numbers describing jet momentum. Building Services Engineering Research and Technology 1998c; 19: 49–54.

Commission of the European Communities (CEC). Indoor Air Quality and Its Impact on Man. Report No. 12: Biological Particles in Indoor Environment. Luxembourg, 1993.

Cox CS, Wathes CM. Bioaerosols in the Environment. In Cox CS, Wathes CM. (Eds.) Bioaerosols handbook. CRC Press. Inc. USA, 1995.

Dales RE, Miller D, McMullen E. Indoor air quality and health: validity and determinants of reported home dampness and moulds. International Journal of Epidemiology 1997; 26(1): 120–125.

Deloge-Abarkan M, Ha TL, Robine E, Zmirou-Navier D, Mathieu L. Detection of airborne *Legionella* while showering using liquid impingement and fluorescent in situ hybridization (FISH), Journal of Environmental Monitoring 2007; 9: 91–97.

Dionisi H, Harms G, Layton A, Gregory I, Parker J, Hawkins S. Power analysis for real-time PCR quantification of genes in activated sludge and analysis of the variability introduced by DNA extraction. Applied Environmental Microbiology 2003; 69: 6597–6604.

Donaldson GC, Seemungal TAR, Bhowmik A, Wedzicha JA. Relationship between exacerbation frequency and lung function decline in chronic obstructive pulmonary disease. Thorax 2002; 57: 847–852.

van Doorn R, Szemes M, Bonants P, Kowalchuk GA, Salles JF, Ortenberg E. Quantitative multiplex detection of plant pathogens using a novel ligation probe-based system coupled with universal, high-throughput real-time PCR on OpenArrays™. BMC Genomics 2007; 8: 276.

van Dijk EJ, Vermeer SE, de Groot JC, van de Minkelis J, Prins ND, Oudkerk M, Hofman A, Koudstaal PJ, Breteler MMB. Arterial oxygen saturation, COPD, and cerebral small vessel diseases. Journal of Neurology, Neurosurgery Psychiatry 2004; 75: 733–736.

Van Dingenen R, Raes F, Vanmarcke H. Molecule and aerosol particle wall losses in smog chamber made of glass. Journal of Aerosol Science 1989; 20: 113–122.

Eduard W. Fungal spores: A critical review of the toxicological and epidemiological evidence as a basis for occupational exposure limit setting. Critical Reviews in Toxicology 2009; 39(10): 799–864.

Emenius G, Svartengren M, Korsgaard J, Nordvall L, Pershagen G, Wickman M. Building characteristics, indoor air quality and recurrent wheezing in very young children (BAMSE). Indoor Air 2004; 14: 34–42.

Environment Australia. State of knowledge report: air toxics and indoor air quality in Australia. Department of the Environment and Heritage, Australian Government, 2001.

Erkara IP, Asan A, Yilmaz V, Pehlivan S, Qkten SS. Airborne *Alternaria* and *Cladosporium* species and relationship with meteorological conditions in Eskischir City, Turkey. Environmental Monitoring and Assessment 2008; 144: 31–41.

Fanger PO, Melikov AK, Hanzawa H, Ring J. Air turbulence and sensation of draught. Energy and Buildings 1988; 12: 21–39.

Filion G, Laflamme C, Turgeon N, Ho J, Duchaine C. Permeabilization and hybridization protocols for rapid detection of Bacillus spores using fluorescence *in situ* hybridization. Journal of Microbiological Methods 2009; 77(1): 29–36.

Finnish Society of Indoor Air Quality and Climate (FiSIAQ). Classification of Indoor Climate 2000: Target values, Design guidance and product requirements, FiSIAQ Publications 5E, Espoo: FiSIAQ, 2001.

Flannigan B, Samson RA, Miller JD. Microorganisms in home and indoor work environments (Eds). New York, Taylor & Francis, 2001.

Fletcher CM, Peto R. The natural history of chronic airflow limitation. British Medical Journal 1977; 1: 1645–1648.

FLUENT. FLUENT 6.3 User's Guide. Fluent Inc, Lebanon, 2006.

Gandara A, Mota LC, Flores C, Perez HR, Green CF, Gibbs SG. Isolation of *Staphylococcus aureus* and anitbiotic-resistant *Staphylococcus aureus* from residential indoor bioaerosols. Environmental Health Perspectives 2006; 114(12): 1859–1864.

Gao NP, Niu JL. Modeling particle dispersion and deposition in indoor environments. Atmospheric Environment 2007; 41: 3862–3876.

Garrett MH, Hooper, BM, Cole FM, Hopper MA. Airborne fungal spores in 80 homes in the Latrobe Vally, Australia: levels, seasonality and indoor-outdoor relationship. Aerobiologia 1997; 13(2): 121–126.

Gerba CP, Wallis C, Melnick JL. Microbiological hazards of household toilets: droplet production and the fate of residual organisms. Applied Environmental Microbiology 1975; 30(2): 229–237.

Gots RE, Layton NJ, Pirages SW. Indoor health: Background levels of fungi. AIHA Journal 2003; 64(4): 427–438.

Górny RL, Dutkiewicz J. Bacterial and fungal aerosols in indoor environment in Central and Eastern European countries. Annals of Agricultural and Environmental Medicine 2002; 9: 17–23.

Górny RL, Reponen T, Willeke K, Schmeechel D, Robine E, Boissier M. Fungal fragments as indoor air biocontaminants. Applied Environmental Microbiology 2002; 68: 3522–3531.

Górny RL. Filamentous microorganisms and their fragments in indoor air—a review. Annals of Agricultural and Environmental Medicine 2004; 11: 185–197.

Guo H, Kwok NH, Cheng HR, Lee SC, Hung WT, Li YS. Formaldehyde and volatile organic compounds in Hong Kong homes: concentrations and impact factors. Indoor Air 2009; 19: 206–217.

Guyatt GH, Berman LB, Townsend M, Pugsley SO, Chambers LW. A measure of quality of life for clinical trials in chronic lung diseases. Thorax 1987; 42: 773–778.

Haas D, Habib J, Gallwe H, Buzina W, Schlacher R, Marth E, Reinthaler FF. Assessment of indoor air in Austrian apartments with and without visible mold growth. Atmospheric Environment 2007; 41(25): 5192–5201.

Haider A, Levenspiel O. Drag coefficient and terminal velocity of spherical and non-spherical particles. Powder Technology 1989; 58(1): 63–70

Hargreaves M, Parappukkaran S, Morawska L, Hitchins CH, Gilbert D. A pilot investigation into associations between indoor airborne fungal and non-biological particle concentrations in residential houses in Brisbane, Australia. The Science of the Total Environment 2003; 312(1-3): 89–101.

Harrison J, Pickering CA, Faragher EB, Austwick PK, Little SA, Lawton L. An investigation of the relationship between microbial and particulate indoor air pollution and the sick building syndrome. Respiratory Medicine 1992; 86: 225–235.

Health Canada. Exposure Guidelines for Residential Indoor Air Quality. A report of the federal-provincial advisory committee on environmental and occupational health. Health Canada, 1987.

Health Canada. Indoor air quality in office buildings: A technical guide. Minister of Health, Canada, 1993.

Health Canada. Fungal contamination in public buildings: a guide to recognition and management. Minister of Health, Canada, 1995.

Health Canada. Fungal contamination in public buildings: health effects and investigation methods. Minister of Health, Canada, 2004.

Hinds WC. Aerosol technology: properties, behavior, and measurement of airborne particles (2nd Ed.). Canada, John Wiley & Sons Inc, 1999.

Holt JG, Krieg NR, Sneath PHA, Staley JT, Williams ST. Bergey's manual ® of determinative bacteriology (9th Ed.) Williams & Wilkins, Baltimore, USA 1994.

Hong Kong Observatory (HKO). Summary of meteorological observations in Hong Kong. Hong Kong Observatory, The Government of the Hong Kong Special Administration Region, China, 1997–2011.

Hong Kong Environmental Protection Department (HKEPD). Final report – Consultancy study of indoor air pollution in offices and public places in Hong Kong. Agreement No. CE 14/95. Hong Kong Government, Environmental Protection Department, Air Services Group. The Government of the Hong Kong Special Administrative Region, China, 1997.

Hong Kong Environmental Protection Department (HKEPD). Indoor Air Quality Information Centre. Indoor air quality certification scheme for offices and public places. Hong Kong Environmental Protection Department. The Government of the Hong Kong Special Administrative Region, China, 2003.

Horner WE, Worthan AG Morey PR. Air-and dustborne mycoflora in houses free of water damage and fungal growth. Applied and Environmental Microbiology 2004; 70(11); 6394–6400.

Hui PS, Wong LT, Mui KW. Feasibility study of an express assessment protocol for the indoor air quality of air-conditioned offices. Indoor and Built Environment 2006; 15(4): 373–378.

Hui PS, Wong LT, Mui KW. Evaluation of professional choice of sampling locations for indoor air quality assessment. Building Environ 2007a; 42(8): 2900–2907.

Hui PS, Wong LT Mui, KW, Law KY. Survey of unsatisfactory airborne bacteria levels in air-conditioned offices. Indoor Built Environment 2007b; 16(2): 139–149.

Indoor Air Quality Management Group (IAQMG). Hong Kong Special Administrative Region: Guidance notes for the management of indoor air quality in offices and public plates. Hong Kong Environmental Protection Department. The Government of the Hong Kong Special Administrative Region, China, 1999.

Indoor Air Quality Management Group (IAQMG). Hong Kong Special Administrative Region: Guidance notes for the management of indoor air quality in offices and public plates. Hong Kong Environmental Protection Department. The Government of the Hong Kong Special Administrative Region, China, 2003.

Jaffal AA, Banat IM, El Mogheth AA, Nsanze H, Bener A, Ameen AS. Residential indoor airborne microbial populations in the United Arab Emirates. Environmental International 1997; 23(4): 529–533.

Jarvis BB, Miller JD. Mycotoxins as harmful indoor air contaminants: Applied Microbiology and Biotechnology 2005; 66(4): 367–372.

Jia C, Batterman S, Godwin C, VOCs in industrial, urban and suburban neighborhoods, part 1: indoor and outdoor concentrations, variation, and risk drivers. Atmospheric Environment 2008; 42: 2083–2100.

Johansson P, Samuelson I, Ekstrand-Tobin A, Mjörnell K, Sandberg PI, Sikander E Microbiological growth on building materials – critical moisture levels. State of the art. Borås, SP Swedish National Testing and Research Institute, 2005.

Kalogerakis N, Paschali D, Lekaditis V, Pantidou A, Eleftheriadis K Lazaridis M. Indoor air quality – bioaerosol measurements in domestic and office premises. Journal of Aerosol Science 2005; 36: 751–761.

Kanaani H, Hargreaves M, Ristovski Z, Morawska L. Deposition rates of fungal spores in indoor environments, factors effecting them and comparison with non-biological aerosols. Atmospheric Environment 2008a; 42: 7141–7154.

Kanaani H, Hargreaves M, Smith J, Ristovski Z, Agranovski V, Morawska L. Performance of UVAPS with respect to detection of airborne fungi. Journal of Aerosol Science 2008b; 39: 175–189.

Kembel SW, Jones E, Kline J, Northcutt D, Stenson J, Womack AM, Bohannan BJM, Brown GZ, Green JL. Architectural design influences the diversity and structure of the built environment microbiome. The Journal of International Society for Microbial Ecology 2012, Article in press.

Kemp PC, Neumeister-Kemp HG, Esposito B, Lysek G, Murray F. Changes in airborne fungi from the outdoors to indoor air; large HVAC systems in nonproblem buildings in two different climates. American Industrial Hygiene Association Journal 2003; 64: 269–275.

Kim KY, Kim CN. Airborne microbiological characteristics in public buildings of Korea. Building and Environment 2007; 42(5): 2188–2196.

Kim SY, Kim ZY, Lee S, Ko G. Comparison of molecular and total ATP-based analytical methods with culture for the analysis of bioaerosols. Science of the Total Environment 2011; 409: 1732–1737.

Klappenbach JA, Saxman PR, Cole JR, Schmidt TM. rrndb: the ribosomal RNA operon copy number database. Nucleic Acid Research 2001; 29: 181–184.

Kleinheinz GT, Langolf BM, Engleber E. Characterization of airborne fungal levels after mold remediation. Microbiology Research 2006; 161(4): 316–376.

Knoke D, Bohrnstedt GW, Mee AP. Statistics for social data analysis, 4th Ed. Australia: Thomson Wadsworth, 2002.

Ko WSF, Tam W, Wong TW, Chan PSD, Tung HA, Lai KWC, Hui SCD. Temporal relationship between air pollutions and hospital admissions for chronic obstructive pulmonary disease in Hong Kong. Thorax 2007; 62: 780–785.

Kosonen R, Tan F. The effect of perceived indoor air quality on productivity loss. Energy and Buildings 2004; 36(10): 981–986.

Kurup V, Shen HD, Vijay H. Immunobiology of fungal allergens: International Achieve of Allergy Immunology 2002; 129: 181–188.

Lacasse Y, Brosseau L, Milne S, Martin S, Wong E, Guyatt GH, Goldstein RS. Pulmonary rehabilitation for chronic obstructive pulmonary disease. Cochrane Database of Systematic Reviews 2002; 3: CD003793.

Lacey CJ, Dutkiewicz J. Bioaerosols and occupational lung disease, Journal of Aerosol Sciences 1994; 25(8): 1371–1404.

Laflamme A, Miller JD. Collection of spores of various fungi by a Reuter centrifugal sampler. International Biodeterioration 1992; 29(2) 101–110.

Lai ACK, Byrne MA, Goddard AJH. Aerosol deposition in turbulent channel flow on a regular array of three dimensional roughness elements. Journal of Aerosol Science 2001; 32: 121–137.

Lai ACK. Particle deposition indoors: a review. Indoor Air 2002; 12: 211–214.

Lai ACK, Byrne MA, Goddard AJH. Particle deposition in ventilation duct onto three-dimensional roughness elements Building and Environment 2002; 37: 939 – 945.

Lai ACK. Supermicron particle deposition from turbulent chamber flow onto smooth and rough vertical surfaces. Atmospheric Environment 2005; 39(27): 4893–4900.

Lai ACK, Nazaroff WW. Supermicron particle deposition from turbulent chamber flow onto smooth and rough vertical surfaces. Atmospheric Environment 2005; 39: 4893–4900.

Lai ACK, Chen FZ. Modeling particle deposition and distribution in a chamber with two-equation Reynolds-averaged Navier-Stokes model. Journal of Aerosol Science 2006; 37: 1770–1780.

Lai ACK, Cheng YC. Study of expiratory droplet dispersion and transport using a new Eulerian modeling approach, Atmospheric Environment 2007; 41: 7473–7484.

Langer V, Hartmann G, Niessner R, Seidel M. Rapid quantification of bioaerosols containing *L. pneumophila* by Coriolis® μ air sampler and chemiluminescence antibody microarrays. Journal of Aerosol Science 2012; 48: 46–55.

Law AKY, Chau CK, Chan GYS. Characteristics of bioaerosol profile in office buildings in Hong Kong. Building and Environment 2001; 36(4): 527–541.

Lee HP. Microbial contamination of indoor air. MEng Thesis. Hong Kong, China: The City University of Hong Kong, 2002.

Lee SC, Chang M. Indoor and outdoor air quality investigation at schools in Hong Kong. Chemosphere 2000; 41(1–2): 109–113.

Lee IM, Tsai SS, Chang CC, Ho CK, Yang CY. Air pollution and hospital admissions for chronic obstructive pulmonary disease in a tropical city: Kaohsiung, Taiwan. Inhalation Toxicology 2007; 19: 393–398.

Lee JH, Jo WK. Characteristics of indoor and outdoor bioaerosols at Korean high-rise apartment buildings. Environmental Research 2006; 101(1): 11−17.

Lee SH, Lee HJ, Kim SJ, Lee HM, Kang H, Kim YP. Identification of airborne bacterial and fungal community structures in an urban area by T-RFLP analysis and quantitative real-time PCR. Science of The Total Environment 2010; 408(6): 1349−1357.

Lee SC, Chang M, Chan KY. Indoor and outdoor air quality investigation at six residential buildings in Hong Kong. Environmental International 1999; 25(4): 489−496.

Lee SC, Guo H, Li WM, Chan LY. Inter-comparison of air pollutant concentrations in different indoor environments in Hong Kong. Atmospheric Environment 2002a; 36(12): 1929–1940.

Lee SC, Li WM, Ao CH. Investigation of indoor air quality at residential homes in Hong Kong-case study. Atmospheric Environment 2002b; 36(2): 225–237.

Lee YH. Air hygiene in washroom-study on indoor microbiological air quality. The World Toilet Expo and Forum 2006. Bangkok, Thailand, 2006.

Leung WH, Lai HY, Vrijmoed LLP. A comparison of indoor microbes in two old folks home with different ventilation systems. Proceedings of Indoor Air 2005 – The 10th International Conference on Indoor Air Quality and Climate, Beijing, China, 4–9 Sep 2005: 618–622.

Lehtonen M, Reponen T, Nevalainen A. Everyday activities and variation of fungal spore concentration in indoor air. Journal of Biodeterioration and Biodegradation 1993; 31(1): 25–39.

Li A, Ahmadi G. Dispersion and Deposition of Spherical Particles from Point Sources in a Turbulent Channel Flow. Aerosol Science and Technology 1992; 16: 209–226.

Li CS, Kuo YM. Characteristics of airborne microfungi in subtropical homes. The Science of Total Environment 1994; 155(3): 267–271.

Li K. Molecular comparison of the sampling efficiency of four types of airborne bacterial samplers. Science of the Total Environment 2011; 409: 5493–5498.

Li X, Qiu Y, Yu A, Chai T, Zhang X, Liu J, Wang D, Wang H, Wang Z, Song C. Degenerate primers based RT-PCR for rapid detection and differentiation of airborne chicken Newcastle disease virus in chicken houses. Journal of Virological Methods 2009; 158(1-2): 1–5.

Li Y, Leung GM, Tang JW, Yang X, Chao CYH, Lin JZ, Lu JW, Nielsen PV, Niu J, Qian H, Sleigh AC, Su H-J.J, Sundell J, Wong TW, Yuen PL. Role of ventilation in airborne transmission of infectious agents in the built environment — a multidisciplinary systematic review, Indoor Air 2007; 17: 2–18.

Liao C-M, Luo W-C, Chen S-C, Chen J-W, Liang H-M. Temporal/seasonal variations of size-dependent airborne fungi indoor/outdoor relationships for a wind-induced naturally ventilated airspace. Atmospheric Environment 2004; 38: 4415–4419

Loth E. Drag of non-spherical solid particles of regular and irregular shape. Powder Technology 2008; 182(3): 342–353.

Luo R, Niu JL. Determining diffusion and partition coefficients of VOCs in cement using one FLEC. Building and Environment 2006; 41(9): 1148–1160.

Madelin TM, Madelin MF. Biological analysis of fungi and associated molds. In Cox CS, Wathes CM. (Eds.) Bioaerosols handbook. CRC Press. Inc. USA, 1995.

Mehta SK, Mishra SK, Pierson DL. Evaluation of three portable samplers for monitoring airborne fungi. Applied and Environmental Microbiology 1996; 62: 1835–1838.

Metzker ML. Emerging technologies in DNA sequencing. Genome Research 2005; 15: 1767–1776.

Moser KM, Bokinsky GE, Savage RT, Archibald CJ, Hansen PR. Results of a comprehensive rehabilitation program: Physiologic and functional effects on patients with chronic obstructive pulmonary disease. Archives Internal Medicine 1980; 140: 1596–1601.

Ministry of the Environment (ENV). Singapore guidelines for good indoor air quality in office premises. Singapore, 1996.

Mui KW. Building environmental performance model for variable air volume systems in air-conditioned high rise buildings in sub-tropical climates. The Hong Kong Polytechnic University, PhD thesis, 2002.

Mui KW, Wong LT. Evaluation of neutral criterion of indoor air quality for air-conditioned offices in subtropical climates. Building Services Engineering Research and Technology 2007a; 28(1): 23–33.

Mui KW, Wong LT. Neutral temperature in subtropical climates – a field survey in air-conditioned offices. Building Environment 2007b; 42(2): 699–706.

Mui KW, Wong LT, Law LY. Domestic water consumption benchmark development for Hong Kong. Building Services Engineering Research and Technology 2007; 28: 329–335.

Mui KW, Wong LT, Hui PS. Risk of unsatisfactory airborne bacteria levels in air-conditioned offices of subtropical climates. Building and Environment 2008; 43(4): 475–479.

Mui KW, Wong LT, Wu CL, Lai ACK. Numerical modeling of exhaled droplet nuclei dispersion and mixing in indoor environments. Journal of Hazardous Material 2009a; 167: 736–744.

Mui KW, Wong LT, Hui PS. Screening strategies of an indoor air quality express assessment protocol (EAP) for air-conditioned offices. Indoor and Built Environment 2009b; 18: 77–82.

National Institute for Occupational Safety and Health (NIOSH): NIOSH Health hazard evaluation report: NIOSH Publications Office, Cincinnati, Ohio, 2003.

Nazaroff WW. Indoor particle dynamics. Indoor Air 2004; 14(S7): 175–183.

Nelson NA, Kaufman JD, Burt J, Karr C. Health symptoms and the work environment in four nonproblem United States office buildings. Scandinavian Journal of Work, Environment & Health 1995; 21(1): 51–59.

Nevalainen A. Bacterial Aerosols in Indoor Air. University of Kuopio, Finland, 1989.

Nevalainen A, Pasanen AL, Niininen M, Reponen T, Kalliokoski P, Jantunen M.J. The indoor air quality in Finnish homes with mold problems. Environment International 1991; 17(4): 299–302.

The New York City Department of Health and Mental Hygiene. Guidelines on assessment and remediation of fungi in indoor environments. New York City Department of Health, Bureau of Environmental & Occupational Disease Epidemiology, 2000.

Nomura Y, Hopke PK, Fitzgerald B, Mesbah B. Deposition of particles in a chamber as a function of ventilation rate. Aerosol Science and Technology 1997; 27: 62–72.

Occupational Safety and Health Administration (OSHA). A brief guide to mold in the workplace. U.S. Department of Labor, OSHA, 2003.

Occupational Safety and Health Administration (OSHA). Preventing mold-related problems in the indoor workplace – A guide for building owners, managers and occupants. U.S. Department of Labor, OSHA, 2006.

Øie L, Nafstad P, Botten G, Magnus P, Jaakkola JJK. Ventilation in homes and bronchial obstruction in young children. Epidemiology 1999; 10: 294–299.

Ojima M, Toshima Y, Koya E, Ara K, Tokuda H, Kawai S, Kasuga F, Ueda N. Hygiene measures considering actual distributions of microorganisms in Japanese households. Journal of Applied Microbiology 2002; 93(5): 800–809.

Okuyam K, Kousaka Y, Yamamoto S, Hosokawa T. Particle loss of aerosols with particle diameters between 6 and 200 nm in stirred tank. Journal of Colloid and Interface Science 1986; 110: 214–223.Otten JA, Burge H.A. Bacteria. In Macher JM, Ammann HM, Burge HA, Milton DK, Morey PM (eds.) Bioaerosols: Assessment and Control, Cincinnati, OH, American Conference of Governmental Industrial Hygienists 1999.

Orosa JA, Oliveira AC. An indoor air perception method to detect fungi growth in flats. Expert Systems with Applications 2012; 39(3): 3740–3746.

Otten JA, Burge HA. Bacteria, in Macher JM, Ammann HM, Burge HA, Milton DK, Morey PM (eds). Bioaerosols: assessment and control. American Conference of Governmental Industrial Hygienists Cincinnati, OH, 1999.

Pace NR. A molecular view of microbial diversity and the biosphere. Science 1997; 276: 734–740.

Parat S, Perdrix A, Fricker-Hidalgo H, Saude I, Grillot R, Baconnier P. Multivariate analysis comparing microbial air content of an air-conditioned building and a naturally ventilation building over one year. Atmospheric Environment 1997; 31(3): 441–449.

Pastuszka JS, Kyaw Tha Paw U, Lis DO, Wlazlo A, Ulfig K. Bacterial and fungal aerosol in indoor environment in Upper Silesia, Poland. Atmospheric Environment, 2000; 34(22): 3833–3842.

Peccia J, Hernandez M. Incorporating polymerase chain reaction-based identification, population characterization, and quantification of microorganisms into aerosol science: A review. Atmospheric Environment 2006; 40: 3941–3961.

Pernis B, Vigliani EC, Cavagna G, Finulli M. The role of bacterial endotoxins in occupational diseases caused by inhaling vegetable dusts. British Journal of Industrial Medicine 1961; 18: 120–129.

Peters TM, Leith D Measurement of particle deposition in industrial ducts. Journal of Aerosol Science 2004; 35(4): 529–540.

Qian H, Li Y, Nielsen PV, Huang X. Spatial distribution of infection risk of SARS transmission in a hospital ward. Building and Environment 2009; 44: 1651–1658.

Queensland Department of Public Works. Indoor air quality – A report on health impacts and management options. Commonwealth of Australia 2000.

Quintero E, Rivera-Mariani F, Bolanos-Rosero B. Analysis of environmental factors and their effects on fungal spores in the atmosphere of a tropical urban area (San Juan, Puerto Rico). Aerobiologia 2010; 26: 113–124.

Rajasekar A, Balasubramanian R. Assessment of airborne bacteria and fungi in food courts. Building and Environment 2011; 46: 2081–2087.

Rating and Valuation Department (RVD). Hong Kong Property Review 2012. RVD, The Government of the Hong Kong Special Administrative Region, China, 2012.

Reck M, Larsen PS, Ullum U. Particle deposition in low-speed, high-turbulence flows. Atmospheric Environment 2002; 36: 4801–4809.

Ren P, Jankun TM, Belanger K, Bracken MB, Leaderer BP. The relation between fungal propagules in indoor air and home characteristics. Allergy 2001; 56(5): 419–424.

Reponen T, Grinshpun SA, Conwell KL, Wiest J, Anderson M. Aerodynamic versus physical size of spores: measurement and implication for respiratory deposition. Grana 2001; 40(3): 119–125.

Rinsoz T, Duquenne, P, Greff-Mirguet G, Oppliger A. Application of real-time PCR for total airborne bacterial assessment: Comparison with epifluroescene microscopy and culture-dependent methods. Atmospheric Environment 2008; 42: 6767–6774.

Roache PJ. Verification of codes and calculation. AIAA Journal 1998; 36: 696–702.

Robbins CA, Swenson LJ, Nealley ML, Gots RE, Kelman BJ. Health effects of mycotoxins in indoor air: a critical review. Applied Occupational and Environmental Hygiene 2000; 15: 773–784.

Rowan NJ, Johnstone CM, McLean RC, Anderson JG, Clarke JA. Prediction of toxigenic fungal growth in buildings by using a novel modelling system. Applied and Environmental Microbiology 1999; 65(11): 4814–4821.

Salonen H, Lappalainene S, Lindroos O, Harju R, Reijula K. Fungi and bacteria in mould-damaged and non-damaged office environments in a subarctic climate. Atmospheric Environment 2007; 41(32): 6797–6807.

Samson RA, Hoekstra ES, Frisvad JC, Filtenborg O. Introduction to food- and airborne fungi 6th Ed. The Netherlands, 2002.

Seemungal TAR, Donaldson GC, Paul EA, Bestall JC, Jeffries DJ, Wedzicha JA. Effect of exacerbation on quality of life in patients with chronic obstructive pulmonary disease. American Journal of Respiratory and Critical Care Medicine 1998; 157: 1418–1422.

Seino K, Takano T, Nakamura K, Watanabe M. An evidential example of airborne bacteria in a crowded, underground public concourse in Tokyo. Atmospheric Environment 2005; 39(2): 337–341.

Sen B, Asan A. Fungal flora in indoor and outdoor air of different residential houses in Tekirdag City (Turkey): Seasonal distribution and relationship with climatic factors. Environmental Monitoring and Assessment 2009; 151: 209–219.

Shelton BG, Kirkland KH, Flanders WD, Morris GK. Profiles of airborne fungi in buildings and outdoor environments in the United States. Applied Environmental Microbiology 2002; 68: 1743–1753.

Siafaka NM, Vermeire P, Pride NB, Paoletti P, Gibson J, Howard P, Yernault JC, Decramer M, Higenbottam T, Postma DS, Rees J. Optimal assessment and management of chronic obstructive pulmonary diseases (COPD). European Respiratory Journal 1995; 8: 1398–1420.

Simpson A, Martinez FD. The role of lipopolysaccharide in the development of atopy in humans. Clinical and Experimental Allergy 2010; 40: 209–223.

Singh SJ, Sodergren SC, Hyland ME, Williams J, Morgan MDL. A comparison of three diseases-specific and two generic health-status measures to evaluate the outcome of pulmonary rehabilitation in COPD. Respiratory Medicine 2001; 95: 71–77.

Springorum AC, Clauβ M, Hartung J. A temperature-controlled AGI-30 impinger for sampling of bioaerosols. Aerosol Science and Technology 2011; 45(10): 1231–1239.

Standardization Administration of the People's Republic of China. Chinese indoor air quality guidelines GB/T 18883-2002, PCR, 2002.

Standards Australia/ Standards New Zealand. AS/NZS 3666.1:2002 Air-handling and water systems of buildings - Microbial control. AS/NZS, 2002.

Straja S, Leonard RT. Statistical analysis of indoor bacterial air concentration and comparison of four RCS biotest samplers. Environment International 1996; 22(4): 389–404.

Su HJ, Wu PC, Chen HL, Lee FC, Lin LL. Exposure assessment of indoor allergens, endotoxin, and airborne fungi for homes in Southern Taiwan. Environmental Research Section 2001; A85: 135–144.

Su HJ, Chen HL, Huang CF, Lin CY, Li FC, Milton DK. Airborne fungi and endotoxin concentrations in different areas within textile plants in Taiwan: a 3-year study. Environmental Research 2002; 89(1): 58–65.

Su HJ, Wu PC, Chien HP. Levels of Indoor Airborne Microbes Associated with Ventilation Efficiency in Naturally-Ventilated Residences. International Journal of Ventilation 2006; 5(3): 313–322.

Sundell J, Levin H, Nazaroff WW, Cain WS, Fisk WJ, Grimsrud DT, Gyntelberg F, Li Y, Persily AK, Pickering AC, Samet JM, Spengler JD, Taylor ST, Weschler CJ. Ventilation rates and health: multidisciplinary review of the scientific literature. Indoor Air 2011; 21(3):191–204.

Sunyer J. Urban air pollution and chronic obstructive pulmonary disease: A review, European Respiratory Journal 2001; 17:1024–1033.

Sze To GN, Wan MP, Chao CYH, Wei F, Yu SCT, Kwan JKC. A methodology for estimating airborne virus exposures in indoor environments using the spatial distribution of expiratory aerosols and virus viability characteristics. Indoor Air 2008; 18(5): 425–438.

Tang JW. The effect of environmental parameters on the survival of airborne infectious agent. Journal of The Royal Society Interface 2009; 6: S737–S746.

Taylor JH, Brown KL, Toivenen J, Holah JT. A microbiological evaluation of warm air hand driers with respect to hand hygiene and the washroom environment. Journal of Applied Microbiology 2000; 89(6): 910–919.

Thatcher TL, Lai ACK, Moreno-Jackson R, Sextro RG, Nazaroff WW. Effects of room furnishings and air speed on particle deposition rates indoors. Atmospheric Environment 2002; 36: 1811–1819.

de Torres JP, Pinto-Plata V, Ingenito E, Bagley P, Gray A, Berger R, Celli B. Power of outcome measurements to detect clinically significant changes in pulmonary rehabilitation of patients with COPD. Chest 2002; 121(4): 1092–1098.

Tsai FC, Macher JM. Concentrations of airborne culturable bacteria in 100 large US office buildings from the BASE study. Indoor Air 2005; 15(S9): 71–81.

Tsai FC, Macher JM, Hung YY. Biodiversity and concentrations of airborne fungi in large US office buildings from the BASE study. Atmospheric Environment 2007; 41(25): 5181–5191.

Tseng CH, Wang HC, Xiao NY, Chang YM. Examining the feasibility of prediction models by monitoring data and management data for bioaerosols inside office buildings. Building and Environment 2011; 46(12): 2578–2589.

Tu YE. Time budget study and total exposure assessment to air pollutants of Hong Kong population. The Hong Kong Polytechnic University, PhD thesis, 2005.

Tung TCW, Chao CYH, Burnett J. A methodology to investigate the particulate penetration coefficient through building shell. Atmospheric Environment 1999; 33: 881–893.

Turner JR, Hering SV. Greased and oiled substrates as bounce-free impaction surfaces. Journal of Aerosol Science 1987; 18(2): 215–224.

US Department of Defense (USDD). System safety program requirements. Military Standard 882C, Washington, DC, 1993.

The United States Environmental Protection Agency (USEPA). Mold remediation in schools and commercial buildings. USEPA, Office of Air and Radiation, Indoor Environments Division, 1991.

US Environmental Protection Agency (USEPA). Mold remediation in schools and commercial buildings. USEPA, Office of Air and Radiation, Indoor Environments Division, 2001.

US Environmental Protection Agency (USEPA). A standardized EPA protocol for characterizing indoor air quality in large office buildings. USEPA, Washington, DC, 2003.

Vanhee LME, Nelis HJ, Coenye T. Enumeration of airborne bacteria and fungi using solid phase cytometry. Journal of Microbiology Methods 2008; 72(1): 12–19.

Viitanen H, Ritschkoff AC. Mould growth in pine and spruce sapwood in relation to air humidity and temperature. Report No 221. Uppsala, Sweden: Swedish University of Agricultural Sciences, Department of Forest Products, 1991.

Wadell H. The coefficient of resistance as a function of Reynolds number for solids of various shapes. Journal of the Franklin Institute 1934; 217(4): 459–490.

Wan MP, Chao CYH. Transport characteristics of expiratory droplets and droplet nuclei in indoor environments with different ventilation airflow patterns. Journal of Biomechanical Engineering 2007; 129(3): 341–353.

Wang S, Jin X. Model-based optimal control of VAV air-conditioning system using genetic algorithm. Building and Environment 2000; 35: 471–487.

West JS, Atkins SD, Emberlin J, Fitt BDL. PCR to predict risk of airborne disease. Trends in Microbiology 2008; 16(8): 380–387.

Wolkoff P. How to measure and evaluate volatile organic compound emissions from building products. A perspective. The Science of the Total Environment 1999; 227(2–3): 197–213.

Wong LT. Occupant load assessment for old residential high-rise buildings. Architectural Science Review 2003; 46: 273–278.

Wong LT, Mui KW. Modelling transient occupant loads for offices. Architectural Science Review 2006; 49(1): 53–58.

Wong LT, Mui KW. Modeling water consumption and flow rates for flushing water system in high-rise residential buildings in Hong Kong. Building and Environment 2007; 42(5): 2024–2034.

Wong LT, Mui KW, Law KY, Hui PS. Epistemic assessment of radon levels of offices in Hong Kong. Atmospheric Environment 2006a; 40(8): 1441–1451.

Wong LT, Mui KW, Hui PS. A statistical model for characterizing common air pollutants in air-conditioned offices. Atmospheric Environment 2006b; 40(23): 4246–4257.

Wong MC. Indoor airborne fungi of Hong Kong: biodiversity, physiology and ecology. Mphil thesis, City University of Hong Kong, 1997.

Wong SL, Chan WY, Lai ACK. A new mathematical and experimental study for prediction irradiance field of upper-room ultraviolet germicidal system. Indoor Air 2011. The 12th International Conference on Indoor Air Quality and Climate, 5-10 Jun, Austin, Texas, Paper A468_2.

World Health Organization (WHO). Indoor air quality: organic pollutants. EURO Report and Studies 111, 1987.

World Health Organization (WHO). Indoor air quality: biological contaminants. WHO regional publications, European Series No. 31, Copenhagen, 1999.

World Health Organization (WHO). Regional Offices for the Western Pacific, Environmental health team reports on Amoy Gardens, 2003.

World Health Organization. WHO air quality guidelines global update 2005 – report on a working group meeting, Bonn, Germany, 18–20 October 2005.

World Health Organization (WHO). WHO guidelines for indoor air quality: dampness and mould. Copenhagen: WHO Europe, 2009.

Wu PC, Su HJ, Lin CY. Characteristics of indoor and outdoor airborne fungi at suburban and urban homes in two seasons. The Science of the Total environment 2000; 253(1-3): 111–118.

Wu PC, Li YY, Chiang CM, Huang CY, Lee CC, Li FC, Su HJ. Changing microbial concentrations are associated with ventilation performance in Taiwan's air-conditioned office buildings. Indoor Air 2005; 15: 19–26.

Wu Y, Shen F, Yao M. Use of gelatin filter and BioSampler in detecting airborne H5N1 nucleotides, bacteria and allergens. Journal of Aerosol Science 2010; 41(9): 869–879.

Wyon D P. The effects of indoor air quality on performance and productivity. Indoor Air 2004; 14(S7): 92–101.

Xu MD, Nematollahi M, Sextro RG, Gadgil AJ, Nazaroff WW. Deposition of tobacco smoke particles in a low ventilation room. Aerosol Science and Technology 1994; 20: 194–206.

Yang Y, Chan WY, Wu CL, Kong RYC, Lai ACK. Experimental and numerical study of airborne bacteria inactivation by an upper-room ultraviolet germicidal irradiation (UVGI) system. International Royal Society of Interface 2012, paper accepted.

Yau D, Pun WM. Air quality in Hong Kong 2008. Hong Kong Environmental Protection Department, 2008.

Yu ITS, Li Y, Wong TS, Tam W, Chan AT, Lee JHW, Leung DYC, Ho T. Evidence of airborne transmission of the severe acute respiratory syndrome virus. The New England Journal of Medicine 2004; 350: 1731–1739.

Zhao B, Wu J. Effect of particle spatial distribution on particle deposition in ventilation rooms. Journal of Hazardous Material 2009; 170(1): 449–456.

Zhao B, Zhang Z, Li X. Numerical study of the transport of droplets or particles generated by respiratory system indoors. Building and Environment 2005; 40: 1032–1039.

Zeng QY, Rasmuson-Lestander, A, Wang XR. Extensive set of mitochondrial LSU rDNA-based oligonucleotide probes for the detection of common airborne fungi. FEMS Microbiology Letters 2004; 273: 79–87.

Zhu H, Phelan PE, Duan T, Raupp GB, Fernando HJS, Che F. Experimental study of indoor and outdoor airborne bacterial concentrations in Tempe, Arizona, USA. Aerobiologia 2003; 19(3/4): 201–211.