THE CONCEPT OF SAFE INDOOR AIR QUALITY FOR THE MANAGEMENT OF INDOOR ENVIRONMENT IN IMMUNE BUILDINGS

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The Concept of Safe Indoor Air Quality for the Management of Indoor Environment in Immune Buildings

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DECLARATION

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

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ABSTRACT

When Hong Kong picked up its economy after World War II, acceptable indoor built environment has been the challenge to many of the building services engineers. In 1990s “Healthy Building” was put on the agenda in Hong Kong. Unfortunately, the outbreak of SARS and its high infectious rates in buildings shatters the arrogance of the engineers.

Professor Daniel W.T. Chan hypothesized the SARS virus was propagating through the drainage systems in high rise buildings and caused the vertical cluster infection in Block E of the Amoy Garden. The hypothesis was accepted in the report by World Health Organization after the investigation panel meeting on 30th April 2003.

This study identifies a bottle neck of the usual notion of “Healthy Building”. The invulnerability of “healthy building” lies in its incapability of protection against infection. This thesis adds an important complement for the sake of optimizing the design of acceptable indoor built environment. The classic notion of ‘healthy building’ is first enhanced by a novel concept of ‘Sustainable Immunized Building’. One of the features of this innovative approach is to provide a model for evaluation

of relative protection against indoor cross infection in terms of reduction in probability through the enhancement of building and services system designs and operation.

After a comprehensive review of the available models describing probability of indoor airborne infection, the Wells-Riley model, in a modified form, is used as a base. Firstly, the hypothesis of SARS virus propagation through the drainage system was demonstrated by tracer gas investigation in a 37 storey high rise residential buildings. The relative risk of cross-infection via drainage system was estimated. Secondly, a comprehensive field investigation and computational fluid dynamic analysis was conducted on the natural ventilation performance of typical high rise apartments. Thirdly, a comprehensive model is developed to explain the filtration mechanism of window type air-conditioned units typically found in residential buildings in Hong Kong. Fourthly, a new protocol is proposed for household air cleaner performance evaluation.

The new “sustainable immunized building” concept perfects the notion of “healthy building” and provides a more valuable and pragmatic solution to protect building users.

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CHAPTER 1: INTRODUCTION

At the beginning of the twenty-first century we have encountered several epidemic outbreaks, such as the life-threatening outbreaks of Severe Acute Respiratory Syndrome (SARS) in both nosocomial settings and in residential buildings in 2003, and the outbreaks of Upper Respiratory Tract Infection (URTI) and influenza in several primary schools in March 2008, leading to a suspension of school classes for several weeks. These disease outbreaks occurred in buildings and imposed new challenges to building engineering professions who are under the quest of lessening the risk of disease spread via the building services systems. Particularly, the SARS outbreaks in the residential estates, including the Amoy Gardens, reinstate the important role of sanitary engineering systems in buildings on safeguarding our community health. This draws our attention on a long-forgotten building quality demand – a safe indoor environment that ideally contains no pathogenic or infective micro-organisms such as fungi, bacteria or virus that can trigger infection or impose adverse health effect among the occupants. Kowalski [2004] proposed a concept of immune building after the bioterrorism attack in the United States in September 11th 2001. His main focus is to provide technical information on building management and attempting to protect buildings against the growing threat of bioterrorism. This

thesis does not consider the disease outbreaks caused by intentional release of biological warfare in a building, but consider the cases if an infected person, who is unknown of his severity of the disease that he/she is carrying, enters and stays in a building and unintentionally release the pathogen inside a building. In response to this new building quality demand, a new concept named as “Sustainable Immunized Building” is proposed; aiming for the sake of the sustainable use of resources to create the highest level of service to building occupants, i.e. an immune indoor environment that, if properly managed, the risk of airborne disease transmission inside can be minimized. This is an advanced requirement as compared with the nominal healthy building concept in 1990s. As the main concern of creating an immune indoor environment is to deal with airborne pathogens in indoor air, this also creates a new level of indoor air quality management, named as “safe indoor air quality”. The aim of this research study is to address the key attributes of immune buildings. The understanding on the anatomy of building systems and the identification of the possible routes for disease transmission within a building is needed. During the SARS outbreak in 2003, several hypothetic routes of disease transmission were proposed. This research is concerned with (1) the possible mechanisms of disease transmission within a building when an epidemic outbreak like SARS occurs, (2) how an epidemic outbreak in building can be modeled as

reported in the literature and (3) the effect of immune defense measures, namely the operation of ventilation, air filtration and air cleaning inside the building, on the risk of epidemic outbreak.

The issue of safe indoor environment and the health effect induced by the exposure of indoor environment was actually discussed early in more than a hundred of years before. Early in 1850, a surgeon a New York named John Griscom had already pointed out the concern on the deficient ventilation in bedrooms and dormitories, and its relation to the outbreak of tuberculosis and other diseases that were known to be contracted in crowded places [Sundell 2004]. In the late 1890s the Bubonic Plague (Black Death) epidemic in Hong Kong triggered the legislation on ventilation requirement in residential buildings, as stated in the Public Health and Buildings Ordinance enacted in 1903 [McInnis 2003]. In the post war era the economical development is flourishing worldwide and more high-rise air-conditioned office building appears, while after the energy crisis in 1970s, epidemic illness of “sick building syndrome” was reported in the 1980s among the various developed countries like the United Kingdom, the United States and Scandinavian Europe. Sick building syndrome refers to a situation in which reported sick symptoms among a population of building occupants can be temporally associated with their presence in

that building [United States Environmental Protection Agency 1994]. Unlike the epidemic outbreak of respiratory disease, for sick building syndrome the etiology of such an epidemic illness is unknown. The health of occupants inside a sick building deteriorates. An immune building should not trigger sick symptoms among the occupants staying inside. In view of this, the investigation of possible factors associated with sick-symptoms is also included in this thesis.

The following sections provide a review on the world-wide evolution of the quality and healthiness of the indoor built environment, which begins from the history of public health and building developments in the nineteenth century United Kingdom and Hong Kong, and continues to review the phenomenon of building-related illnesses which has been reported since the post war period world-wide. Also discussed are infectious disease outbreaks that can be occurred inside buildings.

1.1 Building Quality and Community Health in the Victorian Period of the UK

Healthy buildings has long been recognized as a necessity of human living, early since humans sought caves for protection against wild animals and external climatic stress. The relationship between health and housing has long been recognized; in

England the Victorians clearly recognized an association between poor housing and ill-health [Ranson 1991]. Domestic sanitary facilities were believed to be an important vehicle for the transmission of infection [Hardy 1993]. In particular, the public health and medical professions demonstrated the connection between the prevalence of typhoid fever epidemic, a fatal disease at that period, with the conservancy of sewerage disposal [Boobyer 1896, Parkes 1892]. It was identified that when the old pail system or privies were replaced by Water Closets within a city in the United Kingdom, the death-rate from typhoid fever of that particular city dropped significantly [Daunton 1983]. Another case of disease outbreaks among buildings was reported from Derby states in the United Kingdom that between October 1837 and March 1838, among a row of houses along the Litchurch Street, six houses were attacked by Typhus fever. 16 persons were attacked by severe fever in Derby, UK, of whom 5 died. The ill-fated houses were investigated and the cesspools overflow and the ditch connected to these houses were obstructed and filled-up as a foul and stinking pool. The wilful inattention to house drainage was suspected to be the cause of the fatal fever outbreak [Chadwick 1842].

1.2 Building Regulations and Public Health at the late Nineteenth Century in Hong Kong

In Hong Kong, one of the most threatening events on the city's public health is the outbreak of Bubonic Plague (Black Death) in the late nineteenth century. After that, a revision of Building Ordinances in Hong Kong was enacted as the Public Health and Buildings Ordinance in 1903, exactly 100 years before the outbreak of SARS. It is an important milestone for the evolution of the Building Ordinances in Hong Kong. The life-threatening Black Death Bubonic Plague outbreaks in 1890s aroused the consciousness of the association of degraded building environment quality and human health, and manifested the need of more legislative clout to deal with the disease outbreaks in buildings. The clout came in the form of the Closed Houses and Insanitary Dwelling Ordinance in 1894 [McInnis 2003]. Before that the earliest legislative provision can be dated back to the Ordinance No. 5 in year 1844 that the Preservation of Order and Cleanliness was passed to deal with dilapidated buildings [McInnis 2003], while rudimentary building control was introduced in Hong Kong in the Buildings and Nuisances Ordinance in 1856 [Buildings Department 1999], which set out basic sanitary requirements in buildings. The 1856 Ordinance was replaced by the 1889 Buildings Ordinance, which addressed many measures on the sanitary condition of a building; however, no specific requirements for securing proper ventilation and lighting for the occupants was enforced in the Ordinances before 1894. The link between health and soundly built and properly maintained buildings

was manifested in 1903 that the Government combined two separated Ordinances, the previous 1887 Public Health Ordinance, and the 1889 Buildings Ordinance, into one, named the Public Health and Buildings Ordinance. At the same time a new statutory agent named “Authorized Architect” was introduced to supervise building works. In the 1903 Ordinance amendments was made for still better ventilation that was intended to safeguard public health [McInnis 2003]. In addition, requirements on house cleaning and prevention of diseases were specified, in particular the “Tai Ping Tei” cleansing practice was implemented to offer rights to the government health inspectors to check the cleanliness of indoor living space and implement compulsory disinfection in unsatisfied buildings, which aims at preventing disease outbreaks in unsanitary indoor living environment. While after several decades, the Urban Council was established in 1935 and at the same time the Public Health and Buildings Ordinance was repealed and replaced by two separate Ordinances, the 1935 Buildings Ordinance did stipulated higher standards of lighting and ventilation.

1.3 Building Development in Hong Kong after World War II

In spite of the separation between public health control and building control into two Ordinances since 1935, after World War II the impact of communicable disease

outbreaks on legislative building control can still be observed in a Cholera outbreak incident in 1960s. In May 1964, the days that Hong Kong was suffered the worst water shortage, 14 Cholera infected cases (with 4 patients died) were reported and found to be associated with illegal water piping connection in a restaurant [Lee 1994]. The water supply pipework was connected with a well, which was polluted by WC discharge from the same restaurant. After the incident, a more stringent requirement on the water supply connection to buildings was added to the post-war 1955 Buildings Ordinance, as stated in Section 21(6)(e) since 1966. The evolution of Buildings Ordinance, before and after the World War II, is summarized in table 1.

Table 1.1 Evolution of Buildings Ordinance

Year	Ordinance	Note
1844	Ordinance No. 5	• "An Ordinance for the Preservation of Order and Cleanliness", mainly deals with dilapidated buildings.
1856	Buildings and Nuisances Ordinance	• Response to the overcrowding and poor standards of health and hygiene.
1899	Buildings Ordinance	• Based on the Metropolitan Building Act of 1855 in UK. • Surveyor General to inspect building works and to certify new buildings for occupation.
1903	Public Health and Buildings Ordinance	• After the outbreak of Bubonic Plague in the late nineteenth century. • "Authorized Architect" introduced. • Requirements on house cleaning and

		prevention of diseases were specified. • "Tai Ping Tei" cleansing: government health inspectors to check the cleanliness of indoor living space.
1935	Buildings Ordinance	• The Ordinance in 1903 was repealed and replaced by "Building Ordinance" and "Public Health Ordinance".
1955	Buildings Ordinance	• The post-war Building Ordinance. • "Tai Ping Tei" cleansing practice suspended.
1960	Buildings Ordinance	• New buildings from 1960 onward to be equipped with water flushing facilities and drainage pipes for wastes, toilets and flushing cisterns for hygienic sanitation.
1963	Buildings Ordinance	• Water shortage: water supply restriction. • Severe outbreak of Cholera in 1963-1964. • Today's Building Ordinance Section 21 (6)(e), related to water supply to buildings, was firstly included in the Ordinance in 1966.
1974	Buildings Ordinance	• "Authorized Architect" was re-titled as "Authorized Person". • A new statutory agent "Registered Structural Engineer" was introduced.

1.4 Manifestation of Sick Building Syndrome and Building Related Illnesses

After World War II the economy of Hong Kong becomes flourishing. High-rise buildings with deeper floor plan appear, with the use of reinforced concrete as building material and the elevators for vertical transport. In these buildings, ventilation solely by windows is not adequate for the interior area, making the

mechanical ventilation becomes the solution for ventilation and thermal comfort control. This blooming trend can be observed among offices and hotel buildings since 1960s. While air-conditioning system contributes on sustaining the productivity among the white collar citizens in our warm and humid city during the summer period, the fully sealed façade design and the sole reliance on mechanical ventilation and air-conditioning system do impose problems. The first is that the Chinese translation for “air-conditioning” is commonly known as “cold air”, and the expectation of the cool feeling on air-conditioned environment imposes influences years after. Chan et al. conducted a survey on the thermal environment of over 1000 air-conditioned workstations; the study found that over 60% of them fall into the colder side of the comfort zone as recommended in the ASHRAE Standard 55-1992 [Chan et al. 2000]. The second problem is, the oil embargo in 1973 triggered a demand for energy conservation. Buildings became more air tight to reduce the infiltration of outdoor hot and humid air, and to reduce the exfiltration of indoor conditioned air. The design fresh air quantity was reduced to a barely acceptable level of 2.5 litres per second per person. The reduction of fresh air flow rate, increased tightness of air-conditioned building, and the extensive use of synthetic material in building fabrication, results in more complaints of sick symptoms among building occupants; such a degradation of well-being and health was regarded as

“sick building syndrome” (SBS), the term adopted by the World Health Organization since the early 1980s [World Health Organization 1983]. Sick building syndrome describe a medical condition where people inside a building suffer from a certain entity of symptoms of illness or feel unwell for no apparent reason, while the condition improves or even disappear when people are away from a building [World Health Organization 1995]. These buildings are non-industrial buildings, while the symptoms include irritation of the eyes, nose, throat or skin plus general symptoms such as lethargy and headache. The same entity of illness is labelled “sick office syndrome”, “tight building syndrome” or “stuffy office syndrome” in some publications [Norback 1990]. For health complaints among building occupants that a specific cause or etiology can be identified, the problem is referred as “building-related illness” (BRI). Building-related illnesses are usually characterized by a unique set of symptoms which may be accompanied by clinic signs, laboratory findings and identifiable pollutants. The building or the system inside is the site of microbial growth or pollutant emission. Examples of building-related illnesses includes hypersensitivity diseases (such as hypersensitivity pneumonitis, humidifier fever, asthma, allergic rhinitis), legionnaires’ disease, fiberglass dermatitis, and the direct toxic effects from exposures to contaminants such as carbon monoxide, ammonia, formaldehyde, pathogenic micro-organisms [Godish 1995]. While in

1990s the building industry and the government authority have initiated notional discussions on healthy building in 1990s, the nominal ‘healthy buildings’ is not able to reduce risk of spread of communicable diseases at the beginning of the twenty-first century.

1.5 Outbreak of SARS in Hong Kong

In 2003 the Severe Acute Respiratory Syndrome (SARS) outbreak occurred in Hong Kong, with several cases reported from hotels, hospitals and high-rise residential buildings. At that time the property management sector was under increasing pressure to lessen the risk of spreading of the disease via the building services systems. Building executives were bewildering on what to do to reduce the risk of spread of the fatal virus, and many of the measures were “allergic” and over-response. The outbreak casts doubts on the standards and practices of contemporary comfortable and healthy environment. After the incident, the society has been continuously under threats of spread of Avian Flu and Influenza. The incidents prompt us the vital need of a vigorous review of the current engineering practice in building system design and management. A new request of the provision of a “safe” indoor environment that can reduce the risk of disease spread becomes a new indoor environment quality demand of buildings.

1.6 Diseases Outbreaks in Buildings

The danger of airborne spread of infectious disease, either in outdoor environment or inside buildings, has attracted attention among academia early since more than a hundred of years before. In earlier centuries the scientists and laymen were convinced of the concept of disease transmission by miasmas or clouds of noxious vapors [Goldmann 2000]. In the nineteenth century, belief in the importance of miasmas in transmitting infection succumbed slowly to advances in science and epidemiology [Goldmann 2000]. At that period, close confinement and the re-breathing of expired air were presumed to be the generating causes of fever, and assumption seemingly supported by the greater disease rates in the lower classes with higher housing density than the rich [Pickstone 1992, Addington 2000]. Air in crowded, confined space was assumed to have an abnormally strong carbonic gas content [Corbin 1986], as a product of respiration, emerged with constituent of miasmic contamination; and ventilation with outside air was seen as the only solution to prevent dullness, dementia and perhaps death from human contaminated interior air [Addington 2000]. While assumption of airborne miasmic spread of infectious disease was rejected after the discovery of bacteria at the late nineteenth century, and it was discovered that some micro-organisms are fragile and incapable

of surviving long when airborne [Krajick 1997]; in the twentieth century a certain few diseases had been verified as airborne [Langmuir 1961]. While the old myth that outdoor air carries diseases was abandoned [Krajick 1997] as outdoor air is self-sterilizing due to the sunlight and temperature changes, it is the indoor air where the respiratory diseases tend to spread [Kowalski 2006]. Examples of micro-organisms that are known to be transmitted by an airborne route include measles virus [Riley et al. 1978], influenza virus [Wells and Henle 1936, Loosli et al. 1943, Blachere et al. 2009], rhinovirus (responsible for common cold) [Myatt 2004, Couch et al. 1966, Dick et al. 1987] and mycobacterium tuberculosis [Fennelly et al. 2004, Riley et al. 1959]. It is also suspected that airborne transmission would be possible for Norwalk-like virus (NLV), which causes the outbreak of gastroenteritis [Marks et al. 2000, 2003]. Airborne transmission has also been implicated in nosocomial outbreaks of *Staphylococcus aureus*, including methicillin-resistant strains (MRSA) [Rutala et al. 1983, Farrington et al. 1990, Kumari et al. 1998], *Acinetobacter* spp. [Allen and Green 1987, Bernards et al. 1998] and *Serratia marcescens* [Uduman et al. 2002]. While for Tuberculosis the discovery of streptomycin in 1946 offered a cure for the disease, and immunization was thought to be capable to eradicate or control the important viral infections such as measles, smallpox and influenza; the recent resurgence of tuberculosis in industrialized

countries, with outbreaks of multidrug resistant strains, shows the importance of cost-effective, preventive infection control through building ventilation, filtration and disinfection to reduce the risk of airborne disease spread in indoor. More importantly, the outbreak of Atypical Pneumonia in Hong Kong, named by the World Health Organization (WHO) as Severe Acute Respiratory Syndrome (SARS), a newly mutated virus to which no one appears to be immune at the time of outbreak in 2003, aerobiological engineering of indoor environment would be the only measure to control such a disease with no vaccines available.

The outbreak of Severe Acute Respiratory Syndrome (SARS) in 2003 in a high-rise residential housing estate, named Amoy Gardens, triggered numerous researches on several hypothetic routes of transmission. Li et al. [2004] proposed the re-entrant route, while another hypothetic route - the study of possibility of drainage stack contamination as a route for SARS transmission is part of the research work described in this thesis. To characterize the risk of disease infection in buildings, a review on epidemiological models is performed and to be described in the following section.

1.7 Review on Models to Describe the Propagation of Epidemics

Epidemiological models for general disease transmission in populations have been used to describe the progression of infection from susceptible to infectious individuals. One of the classical deterministic models is regarded as the Susceptible – Infected – Recovered (SIR) model based on the work of Kermack and McKendrick [1927]. Fraser et al. [2004] have derived a Von Foerster equation-based criteria for outbreak control, adopting the basic reproductive number (R_0) and the proportion of asymptomatic infections that arise prior to the on set of symptoms (θ) to analyze the general properties of directly transmitted agents that determine the likely success of certain measures for containing early-stage outbreak. Both R_0 and θ are strong predictors to describe the impact of simple public health control measures against the infectious disease [Fraser et al. 2004, Chen et al. 2006].

For the management of safe indoor environment, the assessment of airborne infection risk with respect to the possible dose released by infector, together with the exposure by susceptible person (under environmental control geared towards decreasing the concentration of infectious micro-organisms in room air by dilution ventilation, by passing room air through filters, or by other removal or inactivation

mechanisms) is necessary. While for indoor air pollution risk assessment, dose-response assessment for chemicals and particulate matter has been reported [Anderson and Albert 1999], the dose-response assessment for infectious micro-organisms in quantitative microbial risk assessment differs from chemicals and particulate matter that the infectious micro-organisms can propagate once entered a susceptible human body host [Haas et al. 1999]. For waterborne bacteria and virus, dose-response modeling for quantitative microbial risk assessment has been reported [Haas 1983, Haas et al. 1993]. For airborne pathogens, there is a lack of information in the literature concerning infectious dose and viability of pathogens emitted from infected person for typical airborne transmissible disease such as measles and tuberculosis [Szeto et al. 2008] for dose-response modeling and quantitative microbial risk assessment. In view of this, the method of estimating the quantum of infection [Wells 1955, Riley and O'Grady 1961{p.76}] as airborne infectious units by the use of the Wells-Riley equation is referred for to quantify the source of infectious agent released from patients in previously occurred airborne infectious disease outbreak cases.

In 1978, Riley, Murphy and Riley published a model [Riley et al. 1978] which incorporated Wells' concept of the quanta of infection, reflecting an exponential

behaviour of airborne infections in confined spaces. This model is referred to as the Wells- Riley model (see equation 1.1), and deals with the probability of a susceptible person becoming infected by inhaling a quanta of infection. The Wells-Riley equation adopts the Reed-Frost modification {equation 1.1} as the conceptual model for the spread of contagious disease [Riley 1980].

$$C = S(1 - e^{-Ir}) \qquad \{\text{equation 1.1}\}$$

Where C is the number of new infected cases, S is the number of susceptible persons, I is the number of infective persons, r is the contact rate between infective persons and the susceptible persons. The paper published by Wilson and Burke [1942] provides a full account on the derivation of equation 1.1. Riley [1980] defined the factors relating to the contact rate between infective and susceptible persons as (1) the number of infectious organisms dispersed into a closed system which remain airborne long enough to be breathed by the susceptible persons, (2) the volume of air into which these organisms are dispersed to, (3) the number of infectious organisms breathed by the susceptible persons during (4) the time that the infective persons and susceptibles share a closed system during one generation of epidemic spread. Mathematically the contact rate r is defined in equation 1.2.

$$r = \frac{pqt}{Q} \qquad \{\text{equation 1.2}\}$$

Where p is the pulmonary inhalation rate of susceptibles, q is the dissemination rate of infectious particles from one infective person, t is the time that infectors and susceptibles share a confined space or ventilating system during one generation, and Q is the dilution rate due to germ-free air (the assumption is that the ventilation system provide good mixing under steady state conditions). Substitute equation 1.2 into equation 1.1 gives the mathematical equation named as "Wells-Riley model for airborne infection" {equation 1.3}.

$$P = \frac{C}{S} = (1 - e^{-\frac{Iqpt}{Q}}) \qquad \{\text{equation 1.3}\}$$

where P is the probability of infection, C is the number of new infections, S is the number of susceptible persons, I is the number of infected persons in the index case, q is the number of infectious quanta per hour generated from an infected person and Q is the room ventilation rate (in m^3/hour). The term $\frac{Iq}{Q}$ represents the steady state concentration of infectious quanta in a single zone under well-mix condition.

By adopting the Wells-Riley equation, several assumptions are made [Gammaitoni and Lucci 1997], including (1) difference in susceptibility among the susceptible persons are ignored. (2) The number of infectives in the room is assumed to be constant. (3) The generation rate of quanta of infection from the infectious person is considered constant. (4) Droplet nuclei inside the room is evenly distributed and well-mixed inside the room. (5) The rate of change for the number of infected persons is proportional to the number of encounters between susceptibles and quanta of infection. This term is modeled with the lass of mass action.

According to Riley [1980], the model was tested by using the measles outbreak data from a case in the Mexico Central School in 1945, reported by the New York State Health Department [Perkins et al. 1947] and Riley [1980] commented that “our model simulated the observed pattern quite well”. The model was further tested with the data observed in measles outbreaks in other elementary schools [Linneman et al. 1972, New York State Department of Health 1973]. The Wells-Riley equation was used widely for the evaluation of the effect of ventilation, filtration and other physical processes on the transmission of airborne diseases [Fennelly and Nardell 1998, Nardell et al. 1991] such as measles outbreak [Riley 1978] and tuberculosis

[Beggs et al. 2003].

For the contact rate defined by equation 1.2 and the Wells-Riley equation presented in equation 1.3, the deposition fraction of inhaled viable infectious particles at the site of infection was not considered. To determine the effective contact rate at the target site of infection within the human body, two factors should also be considered. The first is to consider the fraction that can deposit inside the body; and the second is the immunity defense in human body that can resist the invasion of pathogen. If the immunity defense is strong enough the effective contact rate should be reduced. In the studies by Nazaroff et al. [1998] and Ko et al. [2004], a factor *f*, the deposition fraction is added such that the equation for the risk of infection becomes equation 1.4.

$$P = (1 - e^{-\frac{Iqpft}{Q}}) \qquad \text{\{equation 1.4\}}$$

In this study, when the Wells-Riley equation is used to study the change in relative risk of infection due to the change of infectious quanta concentration in the indoor environment (under enhanced ventilation or air cleaning), it is assumed that the whole fraction the infectious particle inhaled by the susceptible can deposit in the alveoli region in the lung and successfully trigger an infection, i.e., considering $f = 1$

in equation 1.4. If the immune defense of a susceptible person is capable to protect the alveoli, then some of the infectious particles inhaled by the person will be unsuccessful to trigger an infection, such that the fraction f is reduced in this situation. Assuming f =1 implies the infectious particles inhaled are capable to overcome the immune defense of the susceptible person to trigger an infection.

On the dissemination rate of infectious particles from one infective person (q) the concept of quanta of infection proposed by Wells [1934, 1955] was adopted. The model was then applied to investigate a measles outbreak case in an elementary school in the United States in 1978. The quanta generation rate in the outbreak was estimated based on epidemiological record, the airflow of outdoor air ventilation system, and the equivalent airflow rate of germ-free air produced through air filtration of re-circulated air. The concept of infectious quanta will be discussed in section 1.8. While the Wells-Riley equation has also been adopted by other researchers [Nardell et al. 1991, Rudnick and Milton 2003] for the estimation of quanta generated in airborne disease outbreaks, the effect of pathogen removal due to air filtration is usually not considered in these later studies, except for the measles outbreak investigated by Riley et al. [1978]. Section 1.9 in this chapter will discuss the typical size of infectious particles to facilitate the estimation the reduction on

concentration of infectious particles by typical filters.

1.8 The Concept of Infectious Quanta

1.8.1 Wells' concept of quantum of infection

William F. Wells [1934] proposed that infectious organisms could be transmitted through the airborne route by the dried residues of human expiratory droplets. He defined residues as 'droplet nuclei', suggested that the size of human expiratory droplets were large but they would shrink quickly by evaporation once they were exposed into the air. The shrinking aerosols would ultimately form droplet nuclei, which are small enough to suspend in air for substantial time. Wells and Stone [1934] experimentally demonstrated the possibility of airborne transmission of infectious materials by taking air samples in a test chamber. On the concept of quantum of infection, Wells published his book "Airborne Contagion and Air Hygiene" [1955], in which he presented a method for quantifying the infectiousness of airborne agents. He defined a unit of infection termed a "quantum" (q) as the amount of infectious material to infect $1 - e^{-1}$ of the people in an enclosed space. His ninth postulate states that "the response to inhaled droplet nuclei contagium is quantal; the Poisson equation expresses reasonably well the relation between dosage and initial response, a quantum infecting 63.2% of homogeneously exposed hosts by definition. He

explained, “When on the average one animal breathes one quantum, 36.8% of the animal will survive, since this is the fraction whose negative natural logarithm is 1. Thus 1 quantum of contagium has been breathed per animal when 63.2% of the animals become infected.” This number of quanta in a room is generally considered to be a physical measure indicating both the quantity and the pathogenicity of the infectious material present in the air. Wells published equations based on the quanta unit, showing a dependence of the number of new cases on the size of the space, the number of infectors, and susceptibles. While it is impossible directly measure the number of droplet nuclei present in a particular case of outbreak [Nardell et al. 1991], nor the number of quanta [Beggs et al. 2003] can be directly estimated as the overall infectivity of airborne pathogen is as much depends on the immunological state of susceptible individuals as the physical and biological characteristics of the agent; it is possible to indirectly measure the quanta production rate in an outbreak if various physical parameters associated with the outbreak are known [Beggs et al. 2003].

1.8.2 Review of quanta generation rate of airborne infections

The quanta generation rate serves as an indirect measurement of the quantity and the infectivity of the pathogens generated in a disease outbreak case. This approach has been adopted by several researchers for the analysis of airborne disease outbreaks.

The quanta generation rate for a same disease can be different for different cases since the quantity of infectious particle released from patient and the infectivity in one outbreak case would not necessary be the same to another patient in another case. Table 1.2 summaries the findings from the literature review on outbreak cases. Knowing the quanta generation rate enables the evaluation of relative risk under various scenarios for the management of safeness of indoor air.

Table 1.2 Quanta generation rate for various airborne infectious diseases

Disease	Reported quanta per hour	Reported in	Original source
Measles	480	Riley et al. 1978	Riley et al. 1978
Measles (Taiwan)	107	Liao et al. 2008	Lee et al. 1992
Tuberculosis (office)	12.7	Nardell et al. 1991	Nardell et al. 1991
Tuberculosis (bronchoscopy case)	250	Nardell et al. 1991	Catanzaro 1982
Influenza	15	Rudnick and Milton 2003	Moser et al. 1979
Rhinovirus (type 16)	10	Rudnick and Milton 2003	Dick et al. 1987
SARS (Taiwan)	28.77	Liao et al. 2005	Liao et al. 2005

1.9 Review of the Studies Reporting Size of Infectious Particles

One of the assumptions made, on the use of Wells-Riley equation, was that the settling rate for the tiny airborne infectious particles is so slow relative to the room air currents that the effect is neligible [Riley 1980]. The validity of this assumption is discussed in this section. On the size of airborne infectious particles, research studies were reported early as in 1940s. Duguid [1946] used collection media (glass slides and filters) with subsequent microscopic analysis of the expiratory droplets collected on the media, and concluded that 95% of particles were smaller than 100 μm, and the majority were in the range from 4 to 8 μm. More recent study reported by Papineni and Rosenthal [1997] suggested that 80 – 90% of particles from human expiratory activities are smaller than 1 μm, by the use of optical particle counters (with particle detection range from 0.3 to 10 μm) and also electron microscopy as droplet detection methods. Another recent study reported by Yang et al. [2007] used an aerodynamic particle sizer to examine the captured samples from subjects coughed into bag, and the measurement suggested a mode at 1 – 2 μm for dried aerosol and at 8.35 μm for coughed droplets which had not dried [Morawska et al. 2009]. Chao et al. [2009] reported a study using the interferometric Mie imaging (IMI) technique to measure the size of expiratory droplets immediately at the mouth

opening, and found that the geometric mean diameter of droplets from coughing was 13.5 μm, while it was 16.0 μm for speaking. Chao et al. [2009] noted that the lower size detection limit of IMI system was about 2 μm, which might not cover the entire size range of expiratory droplets. Another recent study by Morawska et al. [2009] employs an expiratory droplet investigation system with aerodynamic particle sizer, which measures the aerodynamic diameter of particles in the diameter range of 0.5 – 20 μm, and suggested the majority of particles generated from expiratory activities was below 1.8 μm in diameter. Different instruments of measurement provide different result on the size range for the majority of droplets generated from expiratory activities.

1.9.1 Literature review on the size of infective tuberculosis particles

On the measurement size distribution of infectious aerosols in indoor environment, two studies were reported in the literature, one concerning tuberculosis and the other concerning influenza virus. Fennelly et al. [2004] developed a cough aerosol sampling system (CASS), based on Andersen six-stage cascade impactor for viable air sampling. In their experiment, the impactor was loaded with six plastic plates containing selective 7H-11 agar for cultivation of M. tuberculosis. Tuberculosis

patients inside a hospital were asked to cough to the CASS. The researchers found that the stages between 1 to 5 (corresponding to 1.1 μm to above 7 μm) were culturable for cough-generated aerosol of M tuberculosis from voluntary coughing patient (without induction), with a mode in stage 4, corresponding to 2.1 – 3.3 μm in aerodynamic diameter, at which the largest colony of forming unit was identified. With reference to their result, in this thesis the size of 2.7 μm is defined as a representative size of the infectious tuberculosis particles.

1.9.2 Literature review on the size of infective influenza particles

Blachere et al. [2009] conducted a study on the size of airborne particles containing influenza virus in a hospital emergency department during February 2008 influenza season. They employed 2-stage cyclone aerosol sampler which conforms to the American Conference of Governmental Industrial Hygienists / International Organization for Standardization criteria for respirable particle sampling. The first stage collects particles with a diameter > 4 μm, the second stage collects particles with a diameter of 1 – 4 μm, and a back-up filter was used to collect particles with a diameter <1 μm. Sampling tubes filled with Lysis/Binding Solution (Ambion) were

installed in all the stages inside the sampler. The collected samples were spiked with a control RNA, complementary DNA (cDNA) was generated by reverse transcription of the isolated RNA, and Real-time PCR detection was conducted. The researchers reported that 49% of the isolates were collected in the second stage of particle sampling, corresponding to 1 – 4 μm diameter, and 4% of the isolates were collected at the backup filter corresponding to particle size <1 μm diameter. Their findings indicate that > 50% of the total viral particles were found in the respirable aerosol fraction. With reference to this literature review, in this thesis the size of 2.7 μm is defined as a representative size of the infectious influenza particles.

1.9.3 Terminal velocity for typical infective particles

Based on the literature review findings in sections 1.9.1 and 1.9.2, the particle size range for majority of tuberculosis (bacteria) infectious particles, reported in study by Fennelly et al. [2004], is ranged between 2.1 to 3.3 μm, and the majority of infectious influenza particles, reported in study by Blachere et al. [2009], is ranged between 1 to 4 μm. For the calculation of terminal velocity of these infective particles, a size of 2.7 μm is selected as a reference value. According to the Center for Disease Control and Prevention [1994], the estimated size of the droplet nuclei carrying the tuberculosis bacilli is ranged between 1 to 5 μm, the upper limit of 5 μ

m is also selected for the calculation of settling velocity. The settling velocity can be calculated by equation 1.5.

$$V_{TS} = \frac{\rho_p d_p{}^2 g C_c}{18\eta} \qquad \{\text{equation 1.5}\}$$

Where V_{TS} is the settling velocity, ρ_p is the density of infectious particle (1100 kg/m^3 [Porter 1946]), d_p is the diameter of droplet nuclei, g is the gravity (9.81 Nm^{-2}), C_c is the slip factor (equation 1.6), and η is the viscosity of air (1.81×10^{-5} Pa・s)

$$C_c = 1 + 0.8715 \times \frac{\lambda_o}{d_p} \times \frac{T}{P} \qquad \{\text{equation 1.6}\}$$

Where λ_o is 0.066 μm for air, T is air temperature (293 K) and P is atmospheric pressure (101.325 kPa). The calculation result is shown in table 1.3.

Table 1.3 Settling velocity for infectious particle

Particle diameter	2.7 μm	5 μm
Slip factor, C_c	1.0616	1.0333
Settling velocity, V_{TS}	0.00026 m/s	0.00086 m/s

When comparing the settling velocity with the room air velocity in typical mechanically ventilated indoor environment, the settling velocity of 0.00026 to 0.00086 m/s is much slower, compare with room air velocity ranged between 0.017 m/s when fan coil unit in the room was switched OFF and window closed, to 0.402 m/s when fan coil unit in the room was at high speed measured in the survey reported in chapter 3, using the omni-directional air velocity sensor. Thus the assumption taken by Riley [1980] that "the settling rate for the tiny airborne infectious particles is so slow relative to the room air currents that the effect is neligible", is considered to be valid.

1.10 Chapter summary

In this chapter, a historical review on the theme of indoor environmental quality demand at various eras is conducted. The "new" theme to immunize the buildings for a safe indoor air quality appears after the SARS outbreak in 2003. The use of airborne infection risk model, known as the Wells-Riley equation for risk estimation is also reviewed. In the following chapters, the engineering control methods that can change the variables in the risk model, as shown in equation 1.4, will be discussed.

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CHAPTER 2: OBJECTIVES AND METHODOLOGY

2.1 Objective of This Research

As mentioned in Chapter 1, the occurrence of Sick Building Syndrome since 1980s and the outbreaks of diseases in buildings in the twenty-first century prompt us the vital need to integrate appropriate engineering and management strategies to immunize the buildings and maintain a safe and healthy conditions in indoor environment. The objective of this research is the enhancement of our knowledge and understanding on:

- the concept of safe indoor air quality, defined as the indoor air with minimal amount of pathogenic or infective micro-organisms, to minimize the risk of disease infection and the manifestation of sick symptoms among the occupants in a building;
- the engineering methods for building immunization for the improvement on the safeness and healthiness of indoor air;
- the anticipation and evaluation on the risk of disease spread in indoor space;
- the diagnosis of sick-symptoms complaint among building occupants and the maintenance of comfortable indoor environment to minimize the “antagonists” that triggers the sick-symptoms.

2.2 Scope of This Research

To fulfill the objectives stated in section 2.1, several factors that are related to the risk of infection among the susceptible persons are addressed. When an infected person enters the building and generating infectious matters, engineering methods that can reduce the concentration of infectious matter include outdoor air ventilation for dilution, recirculating filtration and air cleaning. This study proposes a method for evaluation of the available quantity of natural ventilation in a typical high-rise residential building. For air filters and air cleaners used in household setting, performance evaluation on the equivalent clean air delivery rate would be investigated. On the study of the possibility of pathogen transmission inside a building, the spread of pathogen in hospitals resulting nosocomial disease outbreak was studied by Li et al. [2004b], while for high-rise residential buildings, the computation simulation study on contaminant transport in the semi-open light-well, named as “re-entrant”, was also reported [Li et al. 2004a, Yu et al. 2004]. This study will focus on the effect of air ventilation system operation on the airflow in drainage system, and the possibility of contaminant transport from one flat to another via the vertical drainage stack. For the sick building syndrome and indoor environmental comfort study, this research will focus on sick-symptoms prevalence study and

indoor environmental quality satisfaction among building users in educational institution buildings with central air-conditioning system.

2.3 Structure of This Thesis

This thesis is presented in eight chapters. ***Chapter 1*** gives a brief introduction and review of the revolution of indoor environmental safety and health in buildings, starting with the record of disease outbreak cases and the legislative aspects on regulating public health, and presents the background information for the understanding on the theory and mathematical models for indoor epidemics.

Chapter 2 lays down the objectives and the scope of the research study, and also the structure of thesis. The methodology of study is briefly introduced, while further elaboration would be provided in the individual chapters. The remaining chapters in this thesis cover several aspects for the management of safe indoor air quality, to achieve an immune state of indoor environment, such that the risk of epidemic outbreak of disease and illness are maintained at a minimal, and the level of microbiological contamination, including bacteria and virus, should also be kept at a minimal. The building-associated epidemic of sickness, namely sick building syndrome, is discussed in chapter 3. On the management of safe indoor air quality,

the use of air cleaners and filters to reduce microbial and particulates contamination is discussed in chapter 4 and 5. The possible routes for transmission of airborne infection inside a building are discussed in chapter 6 and 7. The assessment of airborne infection epidemic risk is discussed in chapter 8.

Chapter 3 deals with the health and comfort factors of indoor environmental quality management. The maintenance of a healthy and comfortable indoor environment is viewed as an indirect mean to sustain of the immunity level among building occupants by ensuring no antagonistic factors to the human immune system is present in the built environment. Study on sick building syndrome prevalence in mechanically ventilated and air-conditioned buildings is reported in this chapter.

Chapter 4 and 5 cover the engineering solution to reduce biological contamination through air cleaning. The use of air cleaners adopting various technologies for air disinfection is covered in chapter 4, and the testing of air filter performance is reported in chapter 5. Method for performance testing is demonstrated in both chapters, and the equivalent air cleaning rates contributed by different air cleaners and filters are estimated. As airborne microbes are particles that obey the laws that govern particle dynamics [Kowalski 2006], the filtration rate obtained from the

performance test is adopted to predict the removal rates of airborne pathogens. This enables the assessment on infection risk reduction contributed by the production of germ-free air by air filtration.

Chapter 6 describes the investigation on the possibility of cross-contamination from flats to flats in a high-rise residential building through the drainage system with a loss of water trap seal. The effect of different operating modes of room ventilation system on the airflow inside the drainage system would be compared, and the relative risk of airborne infection would be evaluated.

Chapter 7 discusses the contemporary practice on the ventilation of residential buildings, including the local legislative requirement and its impact of building layout design, in particular the formation of cruciform layout with semi-closed light-wells in typical private residential buildings. It also includes the study of ventilation performance of building. The airborne infection risk under different ventilation modes in residential flat is evaluated.

Chapter 8 presents the study of the likelihood of airborne transmission of infection indoors in mechanically ventilated and air-conditioned buildings based parameters

including the outdoor air supply flow rate and the efficiency of air filters on the removal of pathogenic particles. The reported quantity of infectious quanta in the literature for various kinds of disease in previous outbreak cases is referred in the analysis, with the use of Susceptible-Infectious-Removal (SIR) epidemic model to predict the epidemic potential in a building when an infected person is presence in an indoor environment.

Chapter 9 is the concluding chapter which summarizes the research findings as described in the previous chapters. Recommendation is made for future research.

2.4 Research Methodology

2.4.1 Sick Building Syndrome prevalence and indoor environmental quality performance investigation in buildings

Sick Building Syndrome is commonly assessed with the aid of questionnaires. Occupants were asked to complete a questionnaire asking the occurrence of sick symptoms when working in the office. Questions on occupants' satisfaction on the indoor environment, ranking of indoor environmental qualifiers (i.e. thermal comfort, visual comfort, indoor air quality, aural comfort and ergonomics) were also included

in the questionnaire. In addition to the subjective response from the building occupants, physical parameters on indoor environment quality were also measured during the survey. An instrument named as “Environmental Health and Comfort Analyzer” was developed in this study for the purpose of measuring representative physical parameters. More details would be discussed in Chapter 3.

2.4.2 Study on air cleaner performance

On the test of performance of air cleaners, standard for chamber test for particulate air cleaners is available from the Association of Home Appliances Manufacturers (AHAM) in United States. For testing the removal ability of other gaseous pollutant or pathogens, the Electrical and Mechanical Services Department in Hong Kong has proposed a testing method similar to the AHAM, which also outlines method of performance testing inside experimental chambers. This study adopts a different approach, and focuses on the evaluation the bacteria removal effectiveness of the air cleaners in a real indoor environment setting, rather than a chamber test. Subject to availability of building site, the experiments were conducted inside a flat of a high-rise residential building with centralized fresh air supply system. Human and environmental bacteria source was adopted as the performance index. Airborne bacteria samples were collected by Burkard Air Sampler and are allowed to grow on

a suitable agar inside an incubator at a constant temperature. Identification of species of bacteria was conducted on selected samples. The number of colonies formed on the surface of agar was counted. Performance of air cleaner was evaluated by comparing the number of bacteria counts in air with and without using the air cleaner.

2.4.3 Study on particle deposition characteristics and air filtration

A bedroom of a residential flat at low floor (1/F), installed with typical window-type household air-conditioner was selected for the experiment. Light-scattering particle counter capable to measure particles from 0.3 μm size was employed in this study. The air filters used in our test were typical filters for household use; one is the air filter provided by the manufacturer of the window type air-conditioner, while another electrostatic filter labeled “high-efficiency” (although no specific performance testing data is provided), available from typical household appliances store, was also tested.

2.4.4 Study on the likelihood of airborne transmission of infection indoors

The likelihood of airborne transmission of infection inside an office building was

assessed based on the outdoor air ventilation rate and the efficiency rating of air filters used inside. A 75-storeys high-rise office building was selected for the assessment. Outdoor air ventilation rate delivered to each floor of the office was evaluated by measuring the air velocity at the outdoor air supply louver inside the room housing the Air Handling Unit (AHU room). The classic deterministic SIR model based on the work of Kermack and McKendrick [1927] and the Wells-Riley equation for airborne infection were referred to derive an expression for the estimation of basic reproductive ratio (R_0), serving as an index for epidemic potential in case of airborne disease outbreak inside a building.

2.4.5 Study on contaminant transfer in high-rise residential buildings

Field study was conducted in existing residential buildings to verify if the building drainage system could be a route for the transportation of contaminant from one flat to another. Tracer gas experiment was adopted as a method of testing. However, in typical building design in Hong Kong, the lack of space allowance for maintenance imposes safety concern and difficulty on accessing the drainage stack and the water trap; in occupied buildings the access points of the drainage system may also be blocked by the appliances installed by the occupier, which results in difficulty when

selecting a building for our test. Eventually, an existing, unoccupied 37 storeys residential building was available, with sufficient access points to the drainage system inside each flat such that it is feasible to conduct the tracer gas test. More details on the testing procedures and building description would be provided in Chapter 7.

2.4.6 Study on the natural ventilation in residential building

Tracer gas experiment approach was also adopted to study the air change rate inside the rooms of residential flat. An existing, unoccupied 41 storeys residential building with cruciform layout was selected for the investigation. In typical private sectors residential buildings the windows in kitchens and bathrooms are open to the semi-enclosed light-well named as the re-entrant and this is the case for our selected building. The ventilation rate under natural ventilation mode is compared with the mechanical ventilation mode (using window-type air-conditioner for ventilation through the outdoor air louver). To account for the ventilation rate achieved at different wind speed and direction, Computational Fluid Dynamics (CFD) coupled with multi-zone modeling is applied on the analysis of the wind driven natural ventilation rate.

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CHAPTER 3: SICK BUILDING SYNDROME AND INDOOR ENVIRONMENTAL QUALITY

On the health problems in buildings, the illnesses ascribed specifically to building, Marks and Banks [1994] defined the term building associated illness to describe three types of problems, including the building-related illnesses, sick building syndrome and long-latency diseases caused by exposures of physical and chemical contaminants. Building-related illnesses refers to illness among single persons that the illness can be specifically diagnosed [ACGIH 1999], and a known cause can be identified; examples for building-related illness include Legionnaire's disease, Pontiac fever, humidifier fever and allergic alveolitis [Hodgson 1989, Kreiss 1989, Berglund et al. 1992]. For long-latency diseases caused by exposures of contaminants, examples include lung cancer due to radon exposure [Samet 2000] and hypersensitivity diseases resulting from an abnormal or maladaptive response of immune system to a substance recognized as foreign to the body [Brightman and Moss 2000]. In this chapter the main focus is the study of sick building syndrome (SBS), which describes a constellation of symptoms that have no clear etiology, and are attributable to exposure to a particular building environment.

3.1 Definition of Sick Building Syndrome

The first “sick” buildings were recognized prior to 1960 [WHO 1983], and adverse indoor environmental conditions were formally noticed by researchers as early as in the 1960s [Black and Milroy 1966]. In 1970s a high prevalence of symptom complaints among the occupants of many buildings were reported in several countries, at which a strong correlation with the attendance time in the building was identified. This has been termed “Sick Building Syndrome” (SBS) by a Working Group of the World Health Organization in 1980s. A building where there are a substantial number of occupants with SBS symptoms is referred to as a “sick building”.

3.1.1 Definition from World Health Organization

The World Health Organization [1983] recognized sick building syndrome to exist in all types of non-occupational buildings and non-industrial occupational buildings. The symptoms identified were (1) eye, nose and throat irritation, (2) sensation of dry mucous membranes and skin, (3) erythema, (4) mental fatigue, (5) headaches, high frequency of airway infections and cough, (6) hoarseness, wheezing, itching and unspecific hypersensitivity, (7) nausea, dizziness. World Health Organization defined two categories sick buildings included “temporarily sick buildings” that were newly

constructed or newly remodelled buildings, where the symptoms decrease in time and mostly disappear after approximately half a year. The second category was named as “permanently sick buildings” at which the symptoms persist for years and were sometimes resistant even to extensive remedial action and no obvious cause was evident. In 1986, World Health Organization presented a modified list of Sick Building Syndrome symptoms, classified in four main groups: (1) sensory irritation of skin and upper airways, (2) general symptoms e.g. fatigue and dizziness, (3) odour and (4) lower airway and gastrointestinal symptoms. However, many researchers considered symptoms from the lower airway and gastrointestinal systems were not related to sick building syndrome.

3.1.2 Definition from ASHRAE

A vague definition is introduced by the American Society of Heating, Air-conditioning, and Refrigerating Engineers (ASHRAE), “If more than 20% of the occupants in a building complain about one or more sickness symptoms; if these symptoms persist for more than two weeks; if the cause of the complaints is not readily recognizable; and if those persons affected recover from such symptoms on leaving the building, SBS is said to occur”. While this definition does define the number of occupants suffered (in percentage) as a criteria to differentiate which

building suffers from SBS and which does not; there is still a lack of authorized list on which symptom is associated with SBS among the studies in literature.

3.1.3 Definition from other researchers

Berglund et al. [2002] reviewed the definitions of Sick Building Syndrome, as proposed by various researchers. The building is diagnosed as "sick" usually because a large enough number of occupants have reported constellation of symptoms. Finnegan et al. [1984] defined sick building syndrome as "generally taken to describe a building in which complaints of ill health are more common than might reasonably be expected". The definition from Burge et al. [1987] is "a term used to describe common symptoms associated with the occupation of predominantly sealed office buildings". Berglund et al. [1996] defined sick building syndrome as "a phenomenon whereby people experience a group of symptoms while working in, living in or otherwise occupying specific buildings; these symptoms are present in the population at large, but are distinguished by being more prevalent, as a group, in some buildings in comparison with others; the symptoms disappear or are reduced in intensity when the affected persons are away from the suspected building". These definitions demonstrate extensive variation, and showing a lack of widely agreed precise definition on symptoms that should be included and the methodology to

measure.

3.2 Sick Symptoms Adopted in the Literature

As discussed in section 3.1, the symptom list suggested by the World Health Organization in 1986 cannot provide an authorized and widely accepted list of symptoms. To determine which sick symptoms should be included in the assessment of sick building syndrome prevalence in buildings, the symptom list proposed in the literature is reviewed. The list and number of sick symptoms varies among different SBS surveys. Jaakkola [1986] suggested a quantitative index ranging from 0 to 6, in according to the presence of symptoms from six symptom groups including skin, eye, nasal, pharyngeal symptoms, lethargy and headache. Whorton et al. [1987] presented five general symptoms which are associated with Sick Building Syndrome (Table 3.1). Molhave [1987] defined 18 sick symptoms, and grouped them into five criteria (Table 3.2). The sick symptoms adopted in this study will be discussed in section 3.5.2.1.

Table 3.1 Sick symptoms defined by Whorton et al. [1987]

Type	Examples
Mucus membrane irritation	• Eyes • Nose • Throat symptoms
Neuropsychiatric disturbances	• Fatigue • Headache • Confusion • Dizziness
Skin disorders	• Itchiness • Dryness • Rash
Asthma-like symptoms	• Tight chest • Difficulties in breathing
Unpleasant odour and taste sensations	• Odour

Table 3.2 Sick symptoms defined by Molhave [1987].

Group	Sick symptoms
Sensoric irritation in eye, nose or throat	• Dryness • Stinging, smarting, irritating sensation • Hoarseness, changed voice
Skin irritation	• Reddening of skin

	• Stinging, smarting, itching sensation • Dry skin
Neurotoxic symptoms	• Mental fatigue • Reduced memory • Lethargy, drowsiness • Reduced power of concentration • Headache • Dizziness, intoxication nausea • Tiredness
Unspecific hyper-reactions	• Running nose and eye • Asthma-like symptoms in non-asthmatic persons • Respiratory sounds
Odour and taste complaints	• Changed sensitivity • Unpleasant odour or taste

3.3 Factors Associated with Sick Building Syndrome

On the risk factors associated with sick building syndrome, Hedge et al. [1989, 1992] suggested a multiple risks model that several groups of risk factors interact with each other, impose a total stress load on building occupants and mediate complaints of sick symptoms. The risk factors include (1) direct environmental risk (e.g. exposure to pollutants), (2) indirect environmental risks (e.g. workers' satisfaction with

thermal conditions), (3) occupational risks (e.g. job stress, use of video display units), and (4) individual risks (e.g. gender, age, personality). Lahtinen et al. [1998] suggested that sick building syndrome most likely is of multi-factorial origin related to chemical, physical, biological and psychosocial factors that interact or coincide with one another. Psychosocial factors may serve as moderators or mediators in the process, either increasing or decreasing the vulnerability of the individual to environmental exposures, or as outcomes in a situation where the subject is compelled to work in a “contaminated” environment.

On the environmental factors that are related to symptom prevalence, Mendell [1993] reviewed the findings of 32 studies of 37 factors that are potentially related to office worker symptoms, and found that air-conditioning, carpets, more workers in a space, use of video display terminals, and a ventilation rate at or below 10 litres per second per person are generally consistently found among SBS studies to have an association of increased symptoms. For job and personal factors, job stress or dissatisfaction, female gender and allergies or asthma are consistently found to have an association of increased sick symptoms. Consistent or mostly consistent findings of no association with altered symptom prevalence were reported for total viable fungi, total viable bacteria, total particles, air velocity, carbon monoxide,

formaldhyde and noise. Mendell [1993] reported that for some of the factors the findings were too inconsistent or sparse for simple interpretation. These factors are listed in table 3.3. Findings for four factors, including humidity, noise, humidification and ionization, were so inconsistent as to include associations with both higher and lower symptom prevalence.

Table 3.3 Summary of reported associations between work-related symptoms and various environmental factors and measurements from studies conducted between 1984 to 1992. [Data: Mendell 1993]

Environmental measures	
Low ventilation rate	↑
Carbon monoxide	◯
Total VOCs	?
Formaldehyde	◯
Total particles	◯
Respirable particles	?
Floor dust (all or protein)	?
Total viable bacteria	◯
Total viable fungi	○
Endotoxins	?
Beta-1,3-glucan	?
Low negative ions	?

High temperature	?
Low humidity	?
Air velocity	◯
Light intensity or glare	?
Noise	◯
Building factors	
Air-conditioning	↑ ↑
Humidification	?
Mechanical ventilation without air-conditioning	?
Newer building	?
Poor ventilation maintenance	?
Workspace factors	
Ionization	?
Improved office cleaning	?
Carpets	↑
Fleecy materials / open shelves	?
Photocopier in room or near	?
Environmental tobacco smoke	?
More workers in the space	↑
Job and personal factors	
Clerical job	?
Carbonless copy use	?
Photocopier use	?
Use of video display terminal	↑
Job stress / dissatisfaction	↑ ↑

Female gender	↑
Smoker	?
Allergies / asthma	↑ ↑

↑ ↑ = consistent higher symptom reports; ↑ = mostly consistent higher symptom reports; ◯ = consistent lack of association; ◯ = mostly consistent lack of association; ? = sparse or inconsistent findings.

It can be observed that a number of possible causes of sick building syndrome were suggested in the literature, but many of them were so inconsistent among various studies, such that the causes for SBS were still not clearly established, and no conclusion can be drawn on any definite correlation of the sick symptoms and the potential causative factors.

3.4 The Sick Building Syndrome Model

Jones et al. [1995] proposed an operational model of occupant health relating to SBS. The model proposes that SBS is the outcome of the dynamic interaction between the occupants and their surrounding environment and that symptoms occur when the response of the immune system is lowered below a certain threshold. The threshold is negatively affected by ‘antagonists’ and positively affected by ‘alleviators’.

Antagonists are anything that places a load upon the occupant's physical and psychological resources, whilst alleviators are anything that reduces or alleviates the level of load. Personal characteristics and private life play an important role in this overall resource-load equation.

Based on this model, several aspects can be noted. Firstly, the term 'sick building syndrome' can be considered as a misnomer that, it is not the building that is sick; it is the interaction of the sensation of the occupant with the indoor built environment, activities and his/her social relationship which gives rise to one's response manifested as sickness symptoms, not illness. Secondly, whether sick building syndrome occurs is not assessed by any building expert, but rather, by the individual occupant. Any acute response is normalised by taking an ensemble response in that space. In addition, whether a building is sick or healthy can be indexed by some SBS indices over a period of time. Thirdly, people who have a lower level of immunity, for any reason, would be more susceptible to SBS. Finally, despite the intricate causal factors, if a relationship between sick building syndrome and indoor environmental quality (IEQ) components can be identified, the adverse effect of the "antagonists", which lead to manifestation of sick symptoms, can be mitigated.

3.5 Method of Study of SBS

3.5.1 Objectives

From the above review of Sick Building Syndrome, the objectives of this study are set as follow:

- Develop an investigation protocol suitable for buildings in Hong Kong;
- Investigate the SBS situation in the campus buildings in the University, and in office buildings.
- Develop a monitoring instrument, allowing simultaneous monitoring of the indoor environmental condition and the survey of sick building syndrome and indoor environmental quality perception among the occupants.

3.5.2 Questionnaire Design

To determine the perception of indoor environmental quality and the presence of sick symptoms among the occupants inside a building, questionnaire survey is necessary. For the survey on the prevalence of sick building syndrome among the occupants, survey on to the sick syndromes is a major part. Description of sick syndromes can be numerous, while the degree of 'how sick' is usually expressed as 'prevalence' which is the percentage of admitting the occurrence of a symptom by the investigated subject, and 'SBS index' which is the average number of admitting the occurrence of number of symptoms per person; thus the description of symptoms

and the symptoms listed in any questionnaire are important. While the use of a standard questionnaire was promoted by Building Research Establishment which has published a questionnaire [Raw 1995] and tried to promote it as a standard questionnaire; however, it is not widely taken as a 'standard'. To achieve the research objective of this study, a questionnaire specific for this project was designed, rather than adopting published "standard" form.

3.5.2.1 Sick symptoms

To define the symptom list to be used in the questionnaire, several SBS questionnaires used in other studies were compared. Burge PS et al. [1993] consider five symptoms, namely (1) dry eyes, (2) stuffy or blocked nose, (3) dry, sore throat, (4) headache and (5) lethargy to be the fundamental components of SBS, for the calculation of personal sick symptom index (PSI, five-symptom). Burge S et al. [1987] studied the symptoms of building sickness by considering ten symptoms, including the above-mentioned five symptoms plus (6) itchy/watering eyes, (7) running nose, (8) flu-like symptom, (9) breathing tightness and (10) chest tightness. The above mentioned ten symptoms were also adopted in the study conducted by Wilson and Hedge [1987]. These basic ten symptoms are included in the survey questionnaire for this study, such that the result can be compared to other studies

reported in the literature. In addition, the skin symptoms “skin itching” and “rash” are also added to the symptom list of this study, since the skin symptoms were described in the World Health Organization’s definition of SBS in 1983, and also commonly included on European SBS questionnaires such as the MM questionnaire or that used by Zweers et al. [1990]. The symptom “ear rings” is also used to test if the IEQ aural discomfort factor may cause aliment or discomfort on the ears. Three other symptoms "nausea", "dizziness", and "asthma" which are thought to be more related to medical symptoms are also used in order to find out if the IEQ risk factors may cause any ailments pertaining to health problems which are harder or slower to recover even if the risk factor is eliminated. The symptom “muscle aching” was adopted in the study on USEPA Headquarter complaint building [USEPA 1990], for this study a similar symptom “muscle pain” is included in the list. Finally, the symptom “Other uneasiness” is also used, to represent the feeling of discomfort which is caused by 'no reason' (do not know) and is a term of feeling easily understood and generally expressed by Chinese. As a result there are all together 18 symptoms in the list in this study, as shown in table 3.4.

Table 3.4 Symptoms used in this study

Symptoms used in this study	Type	Basic 5 symptoms	Basic 10 symptoms	Adopted in study…
Dry eyes	Ocular	✓	✓	Burge S et al. [1987]; Wilson and Hedge [1987]
Watering eyes			✓	
Stuffy / blocked nose	Nasal	✓	✓	
Running nose			✓	
Dry, sore throat	Oropharyngeal	✓	✓	
Breathing tightness	Respiratory		✓	
Chest tightness			✓	
Skin itching	Cutaneous			Molina et al. [1989]; Zweers et al. [1990]
Rash				
Ear ring	Ear			
Headache	General	✓	✓	Burge S et al. [1987]
Lethargy		✓	✓	
Muscle pain				USEPA [1990]
Flu like symptoms	Sickness		✓	Burge S et al. [1987]
Nausea				
Dizziness				
Asthma				
Other uneasiness				

3.5.2.2 Level of Experiencing Sick Symptoms

The usual SBS studies aimed to find the prevalence and SBS indices in terms of the percentage of surveyed subjects experiencing the sick symptoms and average number of symptoms per person respectively. The list of symptoms put in a questionnaire nevertheless could be ‘inviting’, having the effect of reminding the surveyed subject such symptoms may likely occur. A positive feedback could merely mean ‘it does have occurred’ or ‘causing slight discomfort’ rather than a ‘complaint’. Therefore, instead of asking the question of ‘have you had’ [Raw 1995], the approach [Jones and O'Sullivan 1995] of asking the surveyed subject to select a level was used. Indeed, Raw [1995] requested the subjects to vote ‘yes’ when they had two episodes in the past year and that had an effect of eliminating over responses. It is doubtful that the memory of the surveyed subject is able to be so precise. Also, it is important that at what level of experience to any of the sick building symptoms may constitute a ‘complaint’. In the U.K. project, if the question tends to have a ‘neutral’ vote, the number of levels is 7 making 4 as the middle road - neutral. It conforms to the seven-point scale of the thermal comfort vote used by ASHRAE [ASHRAE S55-1992]. For questions with votes from ‘strongly agree’ to ‘strongly disagree’, the number of levels is 5 making 3 as neutral.

In this study, in terms of sick symptom experience, the five-point scale is used for the experience of sick symptoms indicating ‘not at all’ to ‘very much’ as there is no ‘neutral’ tendency for SBS. Part of the analysis would be to set at what level that the vote to any sick symptoms would likely constitute a ‘complaint’.

3.5.2.3 Survey of Indoor Environmental Quality Satisfaction

For the indoor environmental quality (IEQ) survey, responses from occupants on the four basic IEQ components, namely, thermal comfort, indoor air quality (IAQ), visual comfort and aural comfort were included. The technique for studying thermal comfort is well developed and covered in various standards and international studies [ASHRAE 1992, de Dear et al. 1993]. Beranek started his survey on questionnaire rating subjective acceptability to derive the Noise Criteria curves back in 1956 [Beranek 1956]. The aural comfort questionnaire was developed according to recent studies in landscape (open-plan) offices [Tang and Chan 1998]. The visual comfort questionnaire was designed to measure the subjective responses in the use of video display unit [Bean and Bell, 1991]. Survey on indoor air quality perception was devised in this study. It included the response on comfort vote on Indoor Air Quality, nominal description on feeling, acceptability to odour, acceptability to air movement,

preference of air movement. For the sensation on each of the indoor environmental qualifier, the respondent was requested to make a judgement by marking a score on a continuous line between 0% to 100%. In addition to the perception on the individual indoor environment quality factors, a ranking of various acceptability of the IEQ components, to distinguish their relative merit or demerit, was requested.

3.5.2.4 Other Questions

In addition to the survey on sick syndrome prevalence and the acceptance on indoor environmental quality, the hypothesis of ‘reducing antagonists and enhancing alleviators’ was another focus when formulating the questionnaire. The objectives of the SBS were no longer to identify causes, but to identify antagonists and alleviators and ways for their reduction and enhancement appropriately. The level of stress experienced ‘in work’ and ‘at home’ is asked in the questionnaire. Other types of questions in the questionnaire included: (1) impressions on external environmental pollution; (2) space, repetitive action in work and muscle strain; and (3) number of sick days in the past month and in the past year.

On the whole, a bilingual (in both Chinese and English) questionnaire for this study was finalized, pertaining demographic data, the presence of sick symptoms and

personal and environmental stress, and questions on the four indoor environmental qualifiers (thermal comfort, indoor air quality comfort, visual comfort and aural comfort). Types of questions in the questionnaire included comfort vote, direct and indirect acceptability, comfort preference, level of subjective response and the prevalence of any abnormalities.

3.5.3 Survey method

The survey was in two parts, comprising of a physical measurement of the key parameters and a survey of the subjective responses to the indoor environmental quality. Eight (8) offices were available for the survey during the period of study, and details are listed in section 3.7.1. At each time an occupant (the subject) in an office was randomly selected and requested if the time are convenient to participate a survey, and presented the questionnaires if agreed. While the subject was answering the questionnaire the physical measurements by the Indoor Environmental Health and Comfort Analyzer were commenced at the same time. Sound pressure level (measured by Tenma sound pressure level meter) was also measured. It took about ten minutes to complete the survey at one work station, to allow warm-up time for the instruments. The choice of locations was at random within an office. The success of each chosen location depended on the availability of the subject.

3.6 Development of the Indoor Environmental Health & Comfort Analyzer

On the causes of sick building syndrome, air quality in buildings, as well as noise and artificial lighting are suggested to be the possible to have an implication [Raw 1992]. In view of this, a monitoring device for indoor environmental quality measurement is developed in this study. Millet (1994) reported a small instrument that measures the basic physical parameters of air temperature, radiant temperature, relative humidity, carbon dioxide, horizontal illumination and noise level in a box shaped like a pyramid. This instrument does not record the subjective responses for IEQ from building occupants. Chan et al. (1999) reported the development of an Indoor Environmental Quality Logger for the measurement of subjective response and physical parameters. However, the IEQ logger cannot record the sick symptoms reported from the occupant, and does not record the information on occupants' clothing and activity level for thermal comfort assessment. In this study, a third generation "Indoor Environmental Health and Comfort Analyzer" has been developed to incorporates records of physical measurement, subjective response, sick symptoms reported and the clothing and activity level among building occupants. An English version of the questionnaire developed in section 3.5.2 has

been incorporated in the analyzer.

The Indoor Environmental Health and Comfort Analyzer was designed to achieve the following characteristics:

- Compact size
- Record of essential physical parameters
- Record of subjective responses on indoor environmental quality from occupants
- Record of sick symptoms, information on clothing and activity level reported by building occupants.
- Recorded information can be used to derive useful comfort indices
- Readings of acceptable accuracy

3.6.1 Responses to Indoor Environmental Quality

3.6.1.1 Thermal Comfort

For thermal comfort sensation, the usual study is taking the operative temperature or effective temperature for a linear regression with the Predicted Mean Vote (PMV) or Observed Mean Vote (OMV). Neutral temperature is taken as the x-intercept of the linear regression line, which is the temperature at which the occupants in the indoor space tend to fell neutral and would not vote on either the warm or the cool side. The

ASHRAE seven-point scale is used in the Indoor Environmental Health and Comfort Analyzer.

3.6.1.2 Indoor Air Quality

For indoor air quality comfort, carbon dioxide can be used as a surrogate indicator [Fanger et al. 1992]. A sensation scale similar to the one used in thermal comfort can be constructed for indoor air quality except that only five-point scale are used (Table 3.5).

Table 3.5 Sensation vote for indoor air quality sensation

Sensation	Very bad	Bad	Neutral	Good	Very good
Vote	- 2	- 1	0	1	2

3.6.1.3 Visual Comfort

Visual comfort and performance are generally described in terms of horizontal illuminance and cylindrical illuminance. In terms of sensation on visual comfort, the judgement is usually made on a continuous line at two ends with 0% to 100%. The sensation response is given with a mark on the line. The length of the mark from 0% is interpreted as the linear correspondence of the subjective sensation to the lighting condition. The continuous scale is used in the Indoor Environmental Health and

Comfort Analyzer.

3.6.1.4 Aural comfort

The sensation of aural comfort is based on judgement of the aural environment. Similar to the visual comfort, the judgement is usually made on a continuous line at two ends with 0% to 100%.

3.6.1.5 Acceptability of Indoor Environmental Quality

The subjective acceptability of the four indoor environmental qualifiers follows the subjective thermal acceptability as set out by McIntyre [1980]. The building occupant is asked to indicate “accept” or “not accept” on each of the individual indoor environmental qualifier, and the overall indoor environmental quality.

3.6.2 Measurements of Physical Parameters

Air temperature, globe temperature, relative humidity and air velocity were measured at the desktop level where the sensor base was placed. These sensors were mounted on the top of the sensor base box. For indoor air quality measurement a carbon dioxide sensor was used and placed on the top of the sensor base box. A photocell type lighting sensor was used to measure the horizontal illuminance. The

noise level was measured separately at the same time. The dimension of sensor base box is 290 mm × 210 mm × 132 mm. The air velocity sensor had a rod making the height of the logger to be 390 mm (figure 3.1). A firmware-driven data acquisition system is integrated in the analyzer, such that an interface between the sensor base box and a console is possible through a communication cable. The console displays the readings from sensor, and performs data-logging. The sensors were calibrated in the laboratory before taken to the field measurement. The specification of sensors is shown in table 3.6.

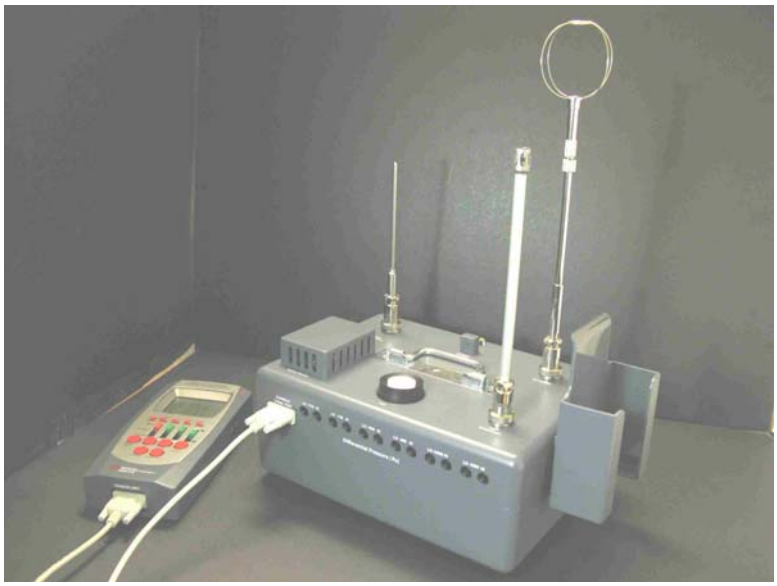

Figure 3.1 Console and sensor base of the Indoor Environmental Comfort and Health Analyzer

Table 3.6 Specification of sensors used in the analyzer

Parameter	Sensor Description	Sensor Accuracy	Recommendation from standards	Response time
Air temperature	Thermistor	± 0.1°C (-50°C to 50°C)	± 0.1°C [ASHRAE Standard 113]	5 seconds (90%)
Globe temperature	Thermistor inside 40mm diameter grey table tennis ball	± 0.1°C (-50°C to 50°C)	± 0.2°C [ISO 7726]	3.8 seconds (90%)
Omindirectional Air velocity	Omindirectional anemometer	± (0.02 m/s + 1% of reading)	± (0.05 m/s + 5% reading) [ISO 7726]	0.3 seconds (95%)
Relative humidity	Polymer sensing element	± 1.8 %	± 2% to ± 3% [ASHRAE Std. 111]	4 seconds (63%)
Carbon dioxide	Non-dispersive infrared sensor	± (30 ppm + 5% of reading)	N/A	3 minutes (90%)
Illuminance	Cosine-corrected photocell	± 3%	± 3% [BS 667]	Instantaneous
Sound Pressure Level	Microphone	IEC/ANSI Type II		1 micro seconds

3.6.3 Questionnaire

In addition to the function of logging the subjective responses on IEQ by the buttons on the console, as described in section 3.6.1, the electronic version of the comprehensive indoor environmental quality survey questionnaire, as described in section 3.5.2 (in English language), was also incorporated in the device. The whole questionnaire was divided into 6 parts, including (1) survey of the experience of 18

sick-symptoms for the sick building syndrome survey, (2) survey of activity level and the details of clothing of the occupant, for the derivation of metabolic rate and the clothing value for thermal comfort analysis, (3) survey of indoor environmental comfort and air quality perception, (4) survey of the type(s) of odour experienced by the occupant, (5) survey of visual comfort and the use of video display unit, and (6) survey of the type(s) of noise as experienced by the occupant. The questions asked are the same as the questionnaire in paper format. The available choices of answers are displayed on the LCD display screen and the occupant select among the choices by the “up” or “down” button, and confirm the answer by pressing the “set” button on the console (figure 3.2a and 3.2b). After completing the sick building syndrome questions, the personal sick symptom index (i.e. no. of symptoms experienced by the occupant), and the normalized personal sick symptoms index, based on 10 basic symptoms, are counted.

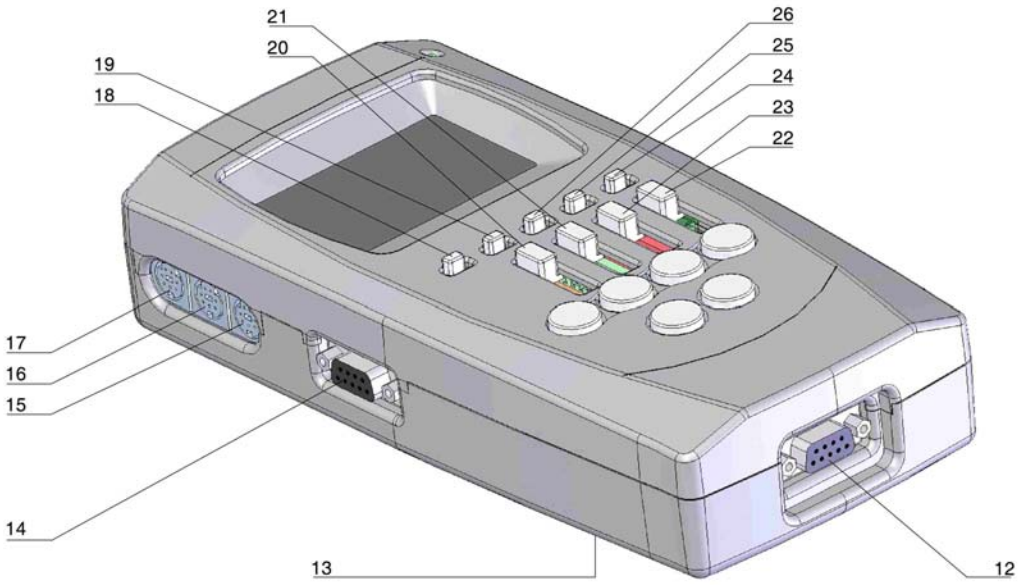

Figure 3.2a Construction of console unit

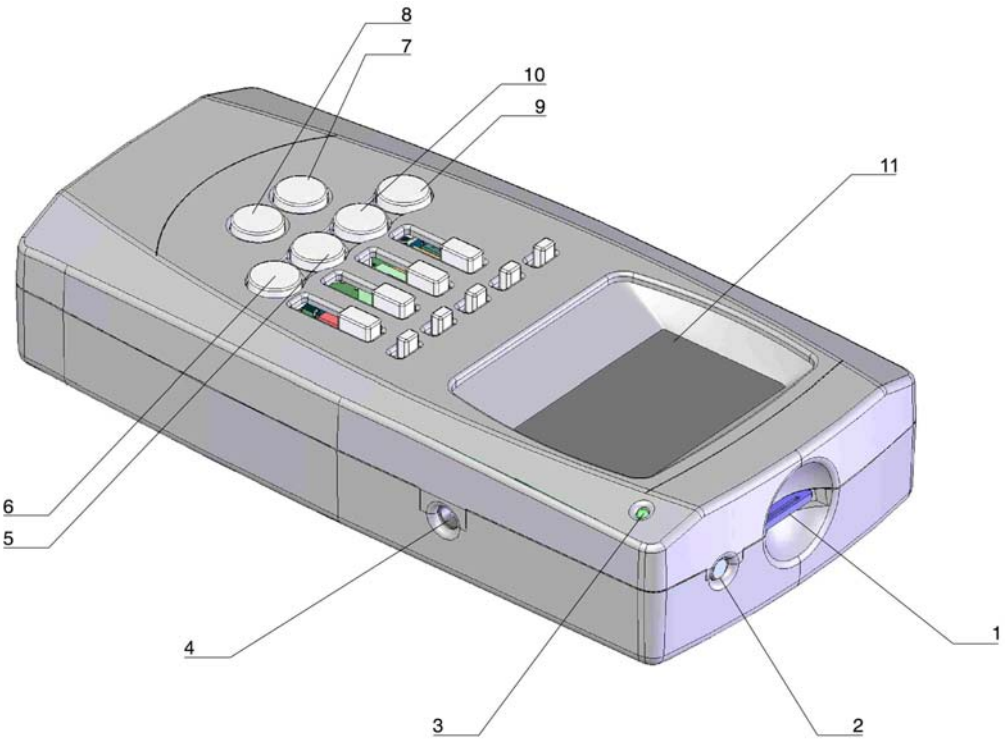

Figure 3.2b Construction of console unit

Table 3.7 Legend for figure 3.2a and figure 3.2b

No.	Parts	No.	Parts
1	SD card slot	14	Sound level meter connector
2	Infra-red temperature sensor	15	Luminance sensor socket
3	Vote alert LED	16	Uni-directional air velocity sensor socket
4	DC power socket	17	Air temp. & RH sensor probe Socket
5	Down button	18	Overall comfort acceptance switch
6	Set/Enter button	19	Thermal comfort acceptance switch
7	ON/OFF button	20	Thermal comfort level selector
8	Start/Stop button	21	Air quality level selector
9	Mode/Vote button	22	Visual comfort level selector
10	Up button	23	Aural comfort level selector
11	LCD display	24	Aural comfort acceptance switch
12	Sensor unit connector	25	Visual comfort acceptance switch
13	Battery compartment	26	Air quality acceptance switch

3.6.4 Computer Program for Data Analysis

A software tool was developed to visualize and analyze the measurement data and the answers of questionnaires stored by the console on the SD memory card. In addition, the following indices can be calculated by the software based on the measurement data and the survey result:

- Sick Building Syndrome indices:
    - Building Sickness Score (based on 18-symptoms)
    - Normalized Building Sickness Score (based on 10 basic symptoms)

    - Personal Sick Symptom Index
    - Normalized Personal Sick Symptom Index (based on 10 basic symptoms)
- Thermal comfort indices:
    - Turbulence intensity
    - Mean radiant temperature
    - Operative temperature
    - Draught rating
    - Thermal sensation vote
    - Equivalent temperature
    - Predicted Mean Vote
    - Predicted Percentage of Dissatisfaction
    - New effective temperature (ET*)
    - Predicted thermal sensation (TSEN)
    - Predicted thermal discomfort (DISC)
    - Standard effective temperature (SET*)
    - Neutral temperature defined by Auliciems' [1983] relation
    - Neutral temperature defined by Humphreys' [1981] relation

The thermal comfort indices are calculated by the computer program based on the physiological data of a human body defined in the ASHRAE thermal comfort tool [1997] and its source code of the related prediction equations. Details of the thermal comfort prediction tool can be referred in Fountain and Huizenga [1996].

3.7 Results and Discussion

3.7.1 Offices Surveyed

In this study, 8 offices in 3 buildings were surveyed in summer month (August). Each office is served by individual primary air handling unit. The characteristics are summarized in Table 3.8. The number of respondents for each office depends on the availability of the occupants.

Table 3.8 Summary data of the Offices Surveyed.

Office number	Building	No. of respondent	Type of building	Air-side system
1	A	14	Tertiary education	PAU + FCU
2	A	18	Tertiary education	PAU + FCU
3	A	15	Tertiary education	PAU + FCU
4	B	40	Office in University	PAU + FCU
5	B	32	Office in University	PAU + FCU
6	B	30	Office in University	PAU + FCU
7	B	11	Office in University	PAU + FCU
8	C	10	Commercial	FAF + VAV

PAU: Primary Air-handling Unit, FCU = Fan Coil Unit, FAF = Fresh Air Fan, VAV = Variable Air Volume system

3.7.2 Sick Building Syndrome Indices

3.7.2.1 Terminology

In Sick Building Syndrome studies, the most common SBS index is the sick-symptom prevalence percentage (SPP). All the data are lumped together for the calculation purpose and for comparison among studies. Another common SBS index to use is the building sick-symptom score (BSS). It refers to the average number of sick symptoms experienced per respondent, which was firstly named by Wilson and Hedge [1987]. Jones & O'Sullivan [1995, 1998] used the same name in their studies. It was called 'Symptom Prevalence Index' in Godish [1995]. In this study the approach of building sick-symptom score is adopted. The term “Average Building Sick-symptom Score (ABSS)” is defined as the average number of sick symptoms per person per office or buildings; it is the average BSS over the number of offices or buildings in a study. In addition, due to the variety and different numbers of sick symptoms used in different studies, it is very difficult to make comparisons and to set a threshold of BSS to distinguish sick buildings. A normalisation process is used to normalise the BSS on a common platform.

3.7.2.2 Analysis of the Sick-symptom Prevalence Percentage (SPP) and Building Sick-symptom Score (BSS)

In this study, grouping all 170 respondents together, the sick-symptom prevalence percentages of each of the 18 symptoms investigated are shown in figure 3.3 in descending order. The sick-symptom prevalence percentage obtained in this study is presented with four other studies in table 3.9a and 3.9b. The other studies include the USEPA headquarter study [1990], the Swedish sick buildings study by Stenberg et al. [1990], the study conducted by the Hong Kong Environmental Protection Department HKEPD [Ng et al. 1997] and the sick buildings study in London by Wilson and Hedge [1987].

The sick-symptom prevalence percentages in this study are lower than those found in the HKEPD by Ng et al. [1997] for all symptoms. Compared with the Swedish sick buildings study [Stenberg et al. 1990], the SPPs found in this study are also lower except for the symptom “skin itching” (16.5% in this study vs. 12% in Stenberg et al.). The SPPs found in this study are also lower compared with the study by Wilson and Hedge [1987] in London (except for the sick symptom “breathing tightness”), while the SPPs found in this study are higher than those obtained from the USEPA headquarter study, even those the latter is notorious of being a sick building.

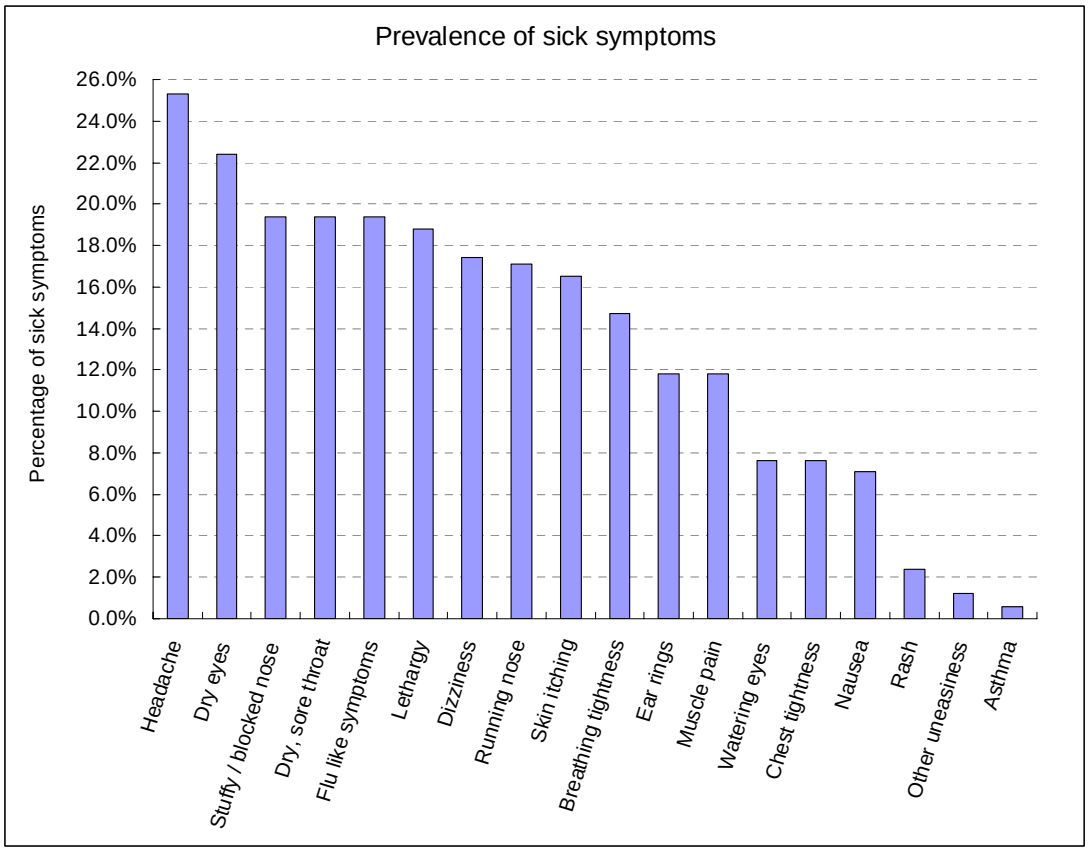

Figure 3.3 Prevalence of sick symptoms

Table 3.9a Sick-symptom prevalence percentage in five studies

Symptom no.	This study		USEPA Headquarter (1990)		Stenberg et al. (1990)	
	Symptom	SSP(%)	Symptom	SSP(%)	Symptom	SSP(%)
1	Headache	**25.3**	Headache	14	Headache	36
2	Dry eyes	**22.4**	Dry eyes	15	Eye irritation	36
3	Watering eyes	**7.6**				
4			Burning eyes	10	Swollen eyelids	13
5	Stuffy / blocked nose	**19.4**	Stuffy nose	16	Nasal congestion	33
6	Running nose	**17.1**	Runny nose	8	Nasal catarrh	21
7	Dry / sore throat	**19.4**	Dry throat	9	Throat dryness	38
8					Sore throat	18
9	Flu-like symptom	**19.4**			Sensation of getting cold	
10	Lethargy	**18.8**	Fatigue/sleepiness	13	Abnormal tiredness	49
11	Dizziness	**17.4**				
12	Skin itching	**16.5**			Facial itching	12
13					Itching on hands	12
14	Breathing tightness	**14.7**	Short of breath	2		
15	Chest tightness	**7.6**	Chest tightness	1		
16	Ear rings	**11.8**				
17	Muscle pain	**11.8**	Aching muscles / joints	3		
18	Nausea	**7.1**			Nausea	8
19	Rash	**2.4**			Facial rash	14
20					Rashes on hands	8
21	Other uneasiness	**1.2**				
22	Asthma	**0.6**				
23						
24			Cough	4	Irritative cough	15
25			Wheezing	1		
26			Fever	1		
27					Eczema	15
BSS		**1.94**		1.12		3.70

Table 3.9b Sick-symptom prevalence percentage in five studies

Symptom no.	This study		HKEPD (Ng et al. 1997)		Wilson & Hedge (1987)	
	Symptom	SSP(%)	Symptom	SSP(%)	Symptom	SSP(%)
1	Headache	**25.3**	Headache	30	Headache	43
2	Dry eyes	**22.4**	Eye discomfort	34	Dry eyes	27
3	Watering eyes	**7.6**			Itching eyes	28
4						
5	Stuffy / blocked nose	**19.4**	Block nose	22	Stuffy nose	47
6	Running nose	**17.1**	Runny nose	27	Runny nose	23
7	Dry / sore throat	**19.4**	Dry / sore throat	28	Dry throat	46
8						
9	Flu-like symptom	**19.4**			Flu-like symptom	23
10	Lethargy	**18.8**	Fatigue	33	Lethargy	57
11	Dizziness	**17.4**				
12	Skin itching	**16.5**	Dry/itching skin	20		
13						
14	Breathing tightness	**14.7**			Difficulty in breathing	9
15	Chest tightness	**7.6**			Chest tightness	9
16	Ear rings	**11.8**				
17	Muscle pain	**11.8**				
18	Nausea	**7.1**				
19	Rash	**2.4**				
20						
21	Other uneasiness	**1.2**				
22	Asthma	**0.6**				
23			Sinusitis	7		
24						
25						
26						
27						
BSS		**1.94**		1.77		3.11

3.7.2.3 Normalized 5-symptom average building sickness score ($ABSS_{N5}$)

An initial comparison on the building sickness score (BSS) among five studies shows that the BSS for this study is higher than the USEPA study (despite the notorious situation) and the HKEPD study, while lower than the Swedish study (study initiated by complaints) and the London study by Wilson and Hedge [1987]. However, as the number of sick symptoms adopted varies for different study, in order to make a comparison with more significance, the building sickness score should be normalized, using a same set of basic symptoms. When five basic symptoms, viz. lethargy (fatigue or tiredness), eye, headache, throat and nasal (nose) symptoms are selected in the normalization process, the 5-symptom average building sickness score per person ($ABSS_{N5}$) is calculated and presented in table 3.10. The normalized five-symptom $ABSS_{N5}$ for this study is 0.80, which is much lower than the building sickness score (without normalization) of 1.94. It is expected as the sick-symptom prevalence for the basic five symptoms are within the range of only 18 to 25% in this study, and 18 symptoms are used in the questionnaire, which is slightly more than other SBS studies.

Table 3.10 Normalised SSP and $ABSS_{N5}$ in six studies.

	Normalised Sick-symptoms Prevalence Percentage (NSSP)					$ABSS_{N5}$
Symptom no.	1	2, 3, 4	5, 6	7, 8	10	
Symptom	headache	eye	nasal	throat	lethargy	
This study	**25.3%**	**24.1%**	**25.3%**	**19.4%**	**18.8%**	**0.80**
Wilson and Hedge 1987 (overall)	43%	27%	35%	46%	57%	2.08
Wilson and Hedge 1987 (Non air cond)	36%	18%	33%	34%	46%	1.68
Wilson and Hedge 1987 (Air cond.)	45%	29%	49%	49%	59%	2.33
HKEPD Ng et al. 1997	30%	34%	25%	28%	33%	1.50
USEPA 1990	14%	15%	12%	9%	15%	0.65
Stenberg et al. 1990	36%	36%	27%	28%	49%	1.76

The $ABSS_{N5}$ in this study is slightly higher than the USEPA headquarter study (0.65), while much lower when compared with the other four studies. The $ABSS_{N5}$ for the study in Stenberg [1990] Swedish sick buildings (initiated by complaints) is 1.76, and this level may be considered as above the threshold of sick buildings. The $ABSS_{N5}$ for each of the individual building in this study is listed in table 3.11. For all the eight zones in three buildings the $ABSS_{N5}$ are lower than the threshold.

Table 3.11 $ABSS_{N5}$ of different buildings in this study.

Office	Building	BSS	$ABSS_{N5}$
1	A	0.71	0.21
2	A	2.22	0.78
3	A	2.21	1
4	B	2.82	0.82
5	B	2	0.92
6	B	1.71	0.71
7	B	2.75	1.18
8	C	1.1	0.8
Overall (This study)		1.94	0.8
Stenberg 1990	Swedish buildings	3.7	1.76

3.7.3 Relationship between Stress at Work and SBS

Two types of stress were investigated in this study, 'stress at work' and 'stress in home'. In the questionnaire the respondents were requested to indicate the stress level (at work and in home) on a five-point scale, where 1 refers to 'not at all' and 5 refers to 'very much so'. A vote of 4 or 5 in the five-point scale is regarded as a higher level of stress. The percentage of occupants voting 4 or 5 on 'stress at work' in each building zone is regressed against the building sickness score (figure 3.4) and the normalized five-symptom $ABSS_{N5}$ (figure 3.5). The correlation between stress at work and the building sick-symptom score is good ($R^2 = 0.85$) while the correlation is fair ($R^2 = 0.54$) between the stress at work and the normalized five-symptom $ABSS_{N5}$. This suggests 'stress at work' is likely a factor contributes to SBS.

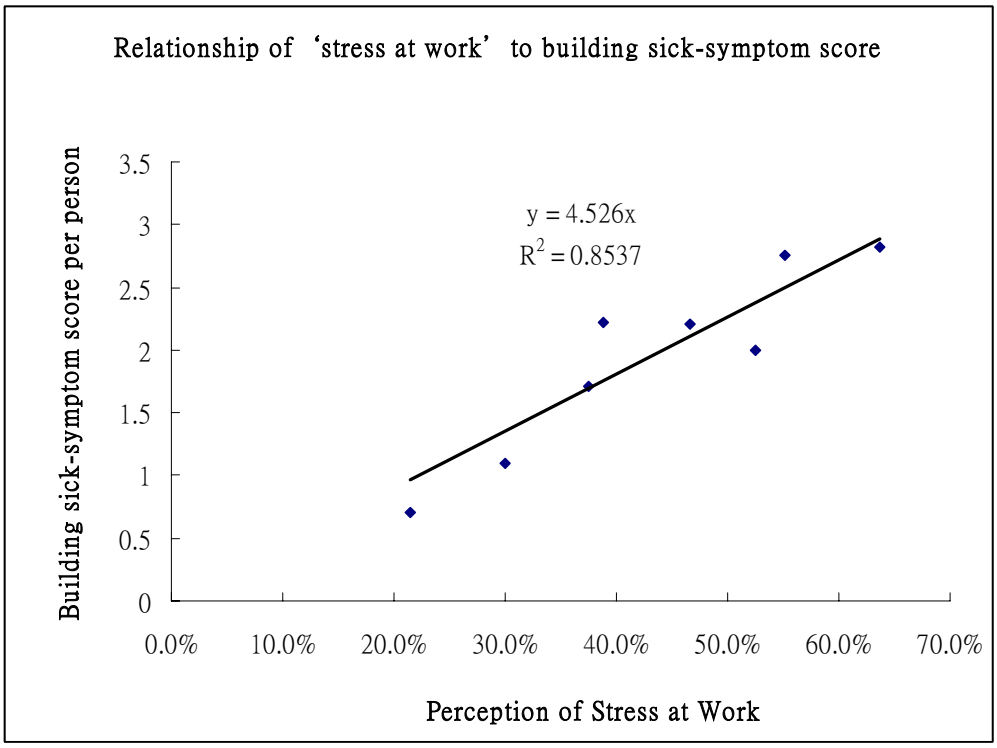

Figure 3.4 Stress at work vs. building sick-symptom score

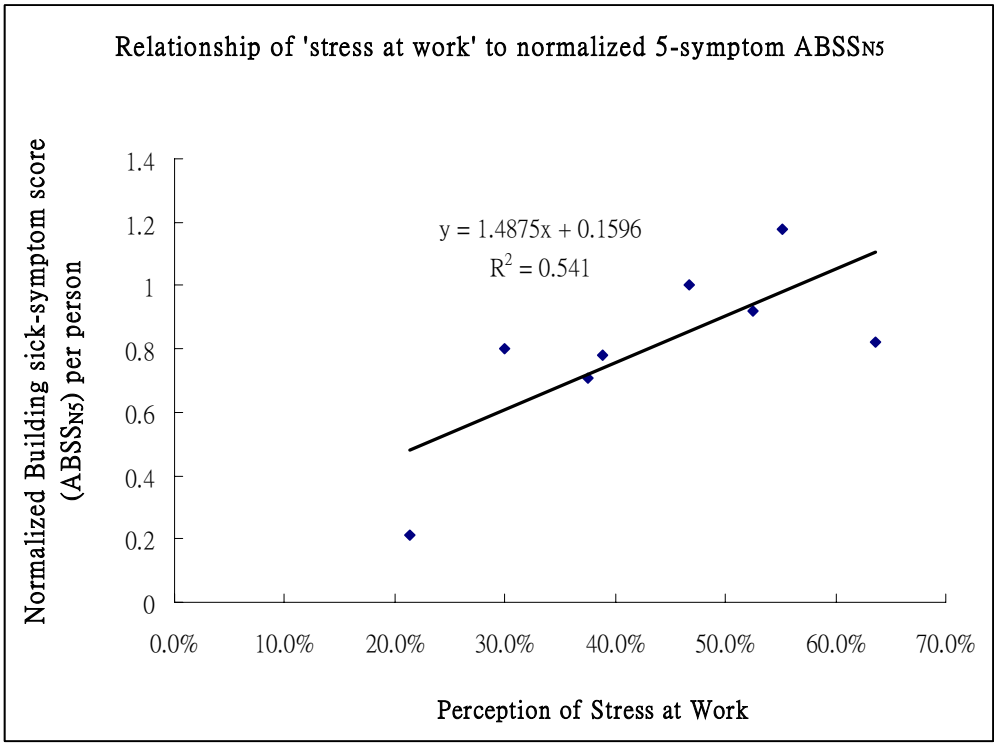

Figure 3.5 Stress at work vs. normalized five-symptom $ABSS_{N5}$.

The perception of stress at work for building zones 1 to 7 is correlated against individual symptoms as shown in table 3.12. Symptoms with prevalence percentage below 12% are not included in the analysis. Figure 3.6 shows the correlation relationships of perception of stress at work (%) to the symptom ‘dry eye’.

Table 3.12 Summary of the Correlation Relationships of Perception of Stress at Work (%) to the SPP of Selected Symptoms (%).

Symptom	Slope	y - Intercept	Correlation coefficient R^2
Dry eye	0.5597	-0.0484	0.5648
Stuffy / blocked nose	0.1457	0.103	0.1061
Dry / sore throat	0.2617	0.056	0.2236
Headache	0.4932	0.0028	0.4752
Lethargy	0.3004	0.0617	0.2791
Running nose	0.3803	-0.0033	0.6882
Flu-like symptom	0.207	0.1007	0.0988
Breathing tightness	0.1877	0.0656	0.116
Skin itching	0.4045	-0.0104	0.7546
Dizziness	-0.039	0.1851	0.0096

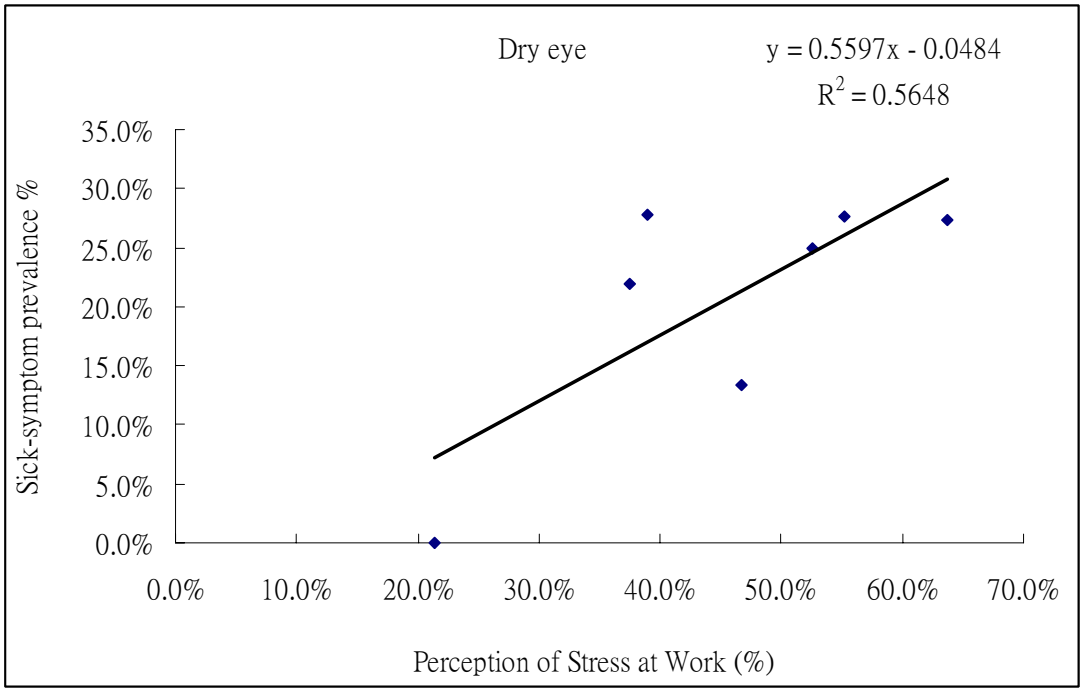

Figure 3.6 Correlation relationships of perception of stress at work (%) to the SPP (%) of symptom 'dry eye'.

According to the correlation coefficient identified in table 3.12, the symptoms can be catergorized into four groups, as shown in table 3.13. This suggests symptoms 'skin itching', 'headache', 'running nose' and 'dry eye' would be more likely to be induced by stress at work.

Table 3.13 Symptoms grouped according to the correlation coefficient

Group	R^2	Symptoms
1	$R^2 > 0.4$	Dry eye, headache, running nose, skin itching
2	$0.4 > R^2 > 0.2$	Dry / sore throat, lethargy
3	$0.2 > R^2 > 0.1$	Stuffy / blocked nose, breathing tightness
4	$0.1 > R^2$	Flu-like symptom, dizziness

Overall speaking, ‘stress at work’ may be an important casual factor for sick building syndrome. This finding agrees with the review study conducted by Mendell [1993] (summarized in table 3.3) that an association between job stress and sick building syndrome prevalence is positive. Stress at work can be regarded an antagonist (see section 3.4) in the working environment. Reducing the level of stress at work may be effective to reduce the sick-symptom prevalence.

3.7.4 Relationship between Outdoor Air Ventilation and SBS

For the manifestation of sick building syndrome, it has long been hypothesized that reduced outdoor air ventilation rate can be associated as sick symptoms complaints were begun to flood public health agencies during the late 1970s [Kreiss 1993], and in the 1970s the ventilation standards had been lowered to 5 cubic feet per minute (or 2.4 L/s per person). Building-related symptoms were assumed to be attributable to lower rate of ventilation [Kreiss 1993]. In the review study conducted by Mendell [1993], there were higher symptoms reported for the factor “low ventilation rate” (as shown in table 6.3). Despite this, different findings were reported on the association between outdoor air flow rate and sick symptoms prevalence. Sundell et al. [1991] suggested that low outdoor air flow rates correlate strongly with high prevalence of general symptoms (but not so strongly with mucous membrane and skin symptoms)

as observed in the Office Illness Project of Northern Sweden. In addition, Jaakola et al. [1988] also found a significant correlation between the outdoor air flow rate and the incidence of sick symptoms when the outdoor air flow was less than 5 L/s per person. In another study in Norway, Hanssen [1993] conducted measurements of ventilation conditions in seven schools with ventilation rate between 1 to 8 L/s per person. In one of the schools the ventilation system was adjusted to provide 8 L/s per person outdoor air with no recirculation. In that particular school, general or central nervous system symptom among the occupants were significant reduced, while mucous membrane symptoms were not. In contrast, in an American study Salisbury [1984] reported that the symptom prevalence rates were paradoxically the highest on the floor with the highest outdoor air flow rate of 39 L/s per person, while the lowest symptom prevalence was observed at the floor with the lowest outdoor air flow rate of 8.5 L/s per person. In some studies, investigators cannot find consistent association between SBS symptoms prevalence and ventilation rate. Jaakkola et al. [1991] failed to observe any relationships between ventilation rate, within a range of 7 to 70 L/s per person, and the symptom prevalence rate. In another study, Ruotsalainen et al. [1993] reported no association between the magnitude of air flows or air exchange rates and the occurrence of SBS symptoms reported by staff in mechanically ventilated day-care centres in Finland. As carbon dioxide may be used

as a surrogate indicator on ventilation adequacy, several studies in the literature investigated if relation exists between carbon dioxide concentration and symptom prevalence; however, no significant relationship between CO_2 levels and the prevalence of SBS symptoms has been observed in the Danish Town Hall study [Skov and Valbjorn 1987] and 11 office buildings [Norback et al. 1990a] and in 6 sick schools [Norback et al. 1990b] in Sweden. With different findings on the association between ventilation rate and sick symptoms prevalence reported in different studies in the literature, this study attempts to investigation if a higher outdoor air ventilation rate can alleviate sick symptoms among building occupants.

3.7.4.1 Outdoor Air Supply and CO_2 Level among the Investigated Buildings

For building zones 1 to 7 the outdoor air supply flow rate was estimated by conducting a measurement of 9-point or 12-point average air velocity at the primary air duct from the primary air handling units (PAU), which delivers pre-conditioned outdoor fresh air from the outdoor air intake to the occupied zone. All the primary air handling units are variable speed. For Building B and office 1 of Building A, the actual outdoor air flow rate measured at the ductwork was very close to the maximum rated outdoor air supply flow of the PAU. Table 3.14 shows the measurement results. Table 3.15 shows the outdoor air flow rate supplied to the

office in L/s per person, and Table 3.16 shows the mean CO_2 concentration in the office area, measured by the Environmental Health and Comfort Analyzer.

Table 3.14 Measured outdoor air flow rate for investigated offices

Office	Building	Average air velocity (m/s)	Duct area (m^2)	Measured air flow rate (m^3/s)	PAU rated max. airflow (m^3/s)
1	A	7.61	0.18	1.37	1.4
2	A	5.71	0.18	1.03	1.4
3	A	2.38	0.18	0.43	1.4
4	B	4.11	0.396	1.63	1.65
5	B	3.40	0.468	1.59	1.65
6	B	3.63	0.455	1.65	1.65
7	B	3.43	0.468	1.60	1.65

Table 3.15 Average outdoor air supply in L/s per person

Office	Building	PAU rated max. airflow (m^3/s)	Actual outdoor airflow (m^3/s)	Observed no. of persons	L/s per person
1	A	1.4	1.37	25	54.8
2	A	1.4	1.03	28	36.8
3	A	1.4	0.43	30	14.3
4	B	1.65	1.63	75	23.3
5	B	1.65	1.59	85	18.7
6	B	1.65	1.65	80	20.6
7	B	1.65	1.60	70	22.9

Table 3.16 CO_2 level in the investigated offices

Office	Building	No. of persons	Outdoor Airflow (L/s/p)	**CO_2 concentration in office area**			
				Minimum	Maximum	Average	S.D.
1	A	25	54.8	574	885	690	93.5
2	A	28	36.8	557	1002	695	104.7
3	A	30	14.3	925	1314	1063	108.9
4	B	75	23.3	852	1042	918	57.8
5	B	85	18.7	1000	1927	1313	234.7
6	B	80	20.6	775	1085	940	66.7
7	B	70	22.9	766	1304	920	119.5

3.7.4.2 Outdoor Air Supply and Building Sick-symptom Score

As observed from table 3.15, the outdoor air supply flow rate is ranged between 14.3 L/s per person to 54.3 L/s person. The building sick-symptom score per person is plotted against the outdoor air supply flow rate as shown in figure 3.7. The normalized building sick-symptom score ($ABSS_{N5}$) is also plotted against outdoor air supply flow rate as shown in figure 3.8. Some correlation (R^2=0.4659) between BSS and outdoor air flow rate can be observed, and for the normalized $ABSS_{N5}$ the correlation is higher (R^2=0.6912). The office 1 in building A has the lowest percentage of people claiming a serious stress at work, and also supplied with a surplus outdoor air flow rate of 54.3 L/s per person, and the building sick-symptom

score and $ABSS_{N5}$ for this office is the lowest. The two factors, namely (1) the lower stress level among occupants, and (2) the surplus outdoor air flow rate, may alleviate the occurrence of sick symptoms.

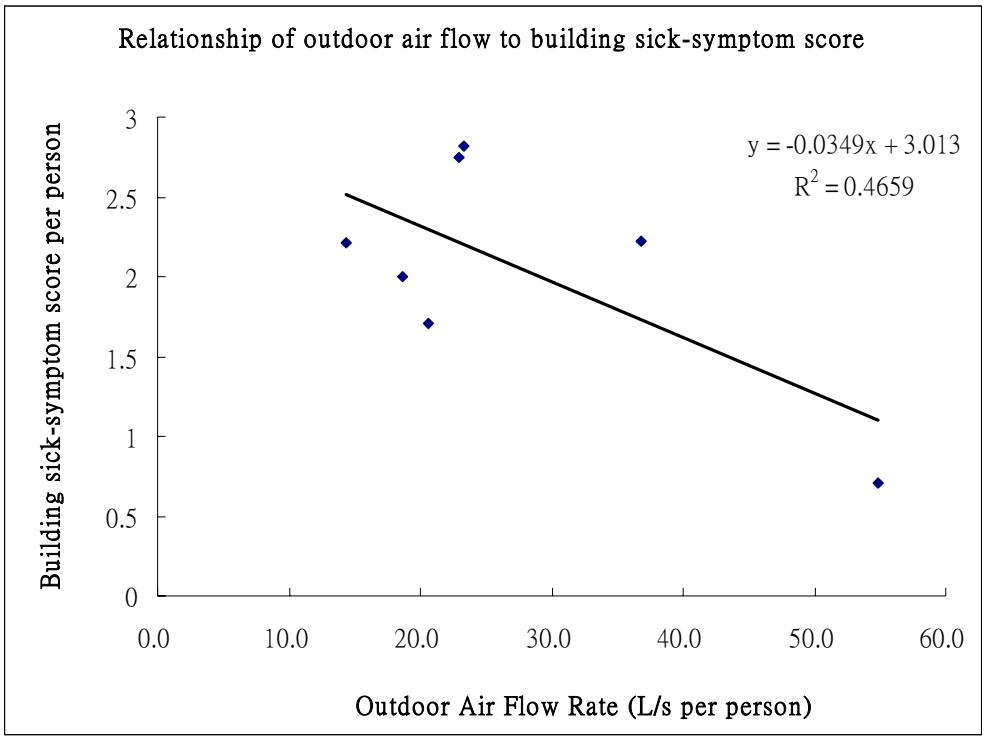

Figure 3.7 Outdoor air supply vs. building sick-symptom score

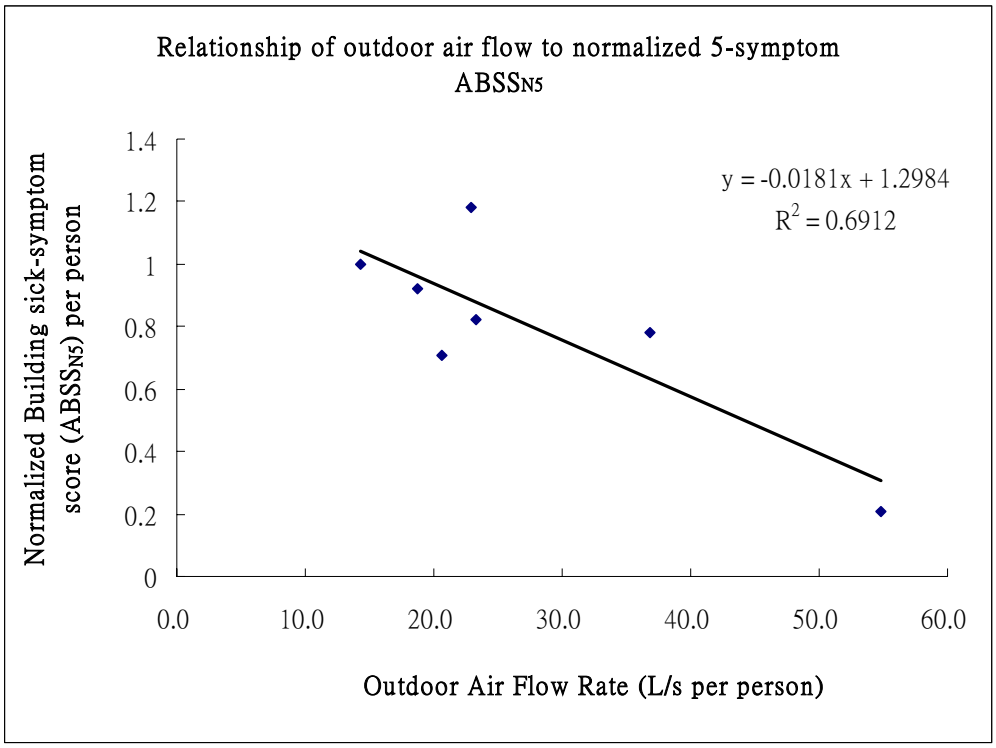

Figure 3.8 Outdoor air supply vs. normalized $ABSS_{N5}$

3.7.4.3 CO_2 Concentration and Symptom Prevalence Percentage in offices

As shown in table 3.16, the carbon dioxide concentration can still be as high as 1002 ppm at the floor with an average of 36.8 L/s per person, showing that uneven distribution or short-circuiting of outdoor air supply may occur. As a result, CO_2 concentration is used as an index to provide some indication on the adequacy of outdoor air received in the occupant space in the office. Table 3.17 compares the sick symptom prevalence percentages (SPP) among different groups of work stations in offices 1 to 7, categorized according to the measured CO_2 concentration.

Table 3.17 Sick symptom prevalence percentage (SPP) for different CO_2 level

Symptom	SPP (%) for workstations with CO_2 concentration……				SPP (%)
	< 800 ppm	800 - 925	926 - 1100	> 1100 ppm	All data
Dry eyes	20.5%	15.9%	24.0%	26.3%	22.4%
Stuffy / blocked nose	20.5%	11.4%	26.0%	15.8%	19.4%
Dry, sore throat	15.4%	25.0%	12.0%	23.7%	19.4%
Headache	12.8%	29.5%	24.0%	34.2%	25.3%
Lethargy	12.8%	18.2%	18.0%	26.3%	18.8%
Watering eyes	7.7%	11.4%	6.0%	5.3%	7.6%
Running nose	5.1%	9.6%	26.0%	26.3%	17.1%
Flu like symptoms	12.8%	20.5%	24.0%	18.4%	19.4%
Breathing tightness	10.3%	18.2%	10.0%	21.1%	14.7%
Chest tightness	0.0%	4.5%	12.0%	13.2%	7.6%
Skin itching	7.7%	18.2%	22.0%	15.8%	16.5%
Ear rings	15.4%	20.5%	6.0%	5.3%	11.8%
Nausea	10.3%	11.4%	4.0%	2.6%	7.1%
Dizziness	10.3%	22.7%	22.0%	13.2%	17.4%
Muscle pain	10.3%	11.4%	8.0%	15.8%	11.8%

The sick building prevalence percentage is at least 4% lower than the average among workstations with CO_2 level lower than 800 ppm, for symptoms including dry/sore throat, headache, lethargy, running nose, flu-like symptom, breathing tightness, chest tightness, skin itching and dizziness. Among these symptoms, for dry/sore throat, headache, lethargy, running nose, breathing tightness and chest tightness, the SPP is

at least 4% higher than the average, among workstations with CO_2 level higher than 1100 ppm. For symptoms like headache, running nose and chest tightness, the SPP increases more significantly with CO_2 level. Table 3.18 only considers the occupants that reported a level of 4 or 5 on stress at work, and presents the sick symptom prevalence among these occupants for different CO_2 level in the workstation.

Table 3.18 Sick symptom prevalence percentage (SPP) for level 4 or 5 stress at work

Symptom	SPP (%) for workstations with CO_2 concentration……				SPP (%)
	< 800 ppm	800 - 925	926 - 1100	> 1100 ppm	All data
Dry eyes	23.1%	26.1%	12.0%	35.3%	23.1%
Stuffy / blocked nose	46.2%	13.0%	20.0%	17.6%	21.8%
Dry, sore throat	23.1%	30.4%	16.0%	35.3%	24.4%
Headache	23.1%	34.8%	24.0%	47.1%	32.1%
Lethargy	7.7%	26.1%	20.0%	29.4%	20.5%
Watering eyes	23.1%	17.4%	8.0%	5.9%	12.8%
Running nose	7.7%	8.7%	32.0%	35.3%	20.5%
Flu like symptoms	15.4%	26.1%	32.0%	29.4%	25.6%
Breathing tightness	7.7%	34.8%	12.0%	29.4%	20.5%
Chest tightness	0.0%	8.7%	20.0%	17.6%	12.8%
Skin itching	15.4%	30.4%	20.0%	29.4%	24.4%
Ear rings	23.1%	30.4%	8.0%	11.8%	17.9%
Nausea	23.1%	17.4%	0%	5.9%	10.3%
Dizziness	15.4%	30.4%	24.0%	23.5%	24.4%
Muscle pain	0%	13.0%	8.0%	17.6%	10.3%

Among the occupants under a higher level of stress at work, a higher level of CO_2 in the workplace results in a slightly higher prevalence for symptoms including dry eyes, dry/sore throat, headache, lethargy, running nose, flu-like symptoms, breathing tightness, chest tightness, skin itching and muscle pain. Among these 10 symptoms, the SPP for dry eyes, dry/sore throat and dizziness, the decrease of CO_2 level only results in a SPP similar to the average, and for the other 7 symptoms the SPP drops significantly lower than average for a level of CO_2 lower than 800 ppm. For the symptom dizziness, the symptom prevalence is lower for a level of CO_2 below 800 ppm. The symptom prevalence rise to the average level when the CO_2 at the workplace is above 800 ppm. On the contrary, for symptoms stuffy/blocked nose, watering eyes, ear ring and nausea, the symptom prevalence is higher at a CO_2 level below 800ppm, while the prevalence decreases with an increased CO_2 level above 925 ppm. On the whole, for lower respiratory system symptoms and central nervous system symptoms, the prevalence is lower with a lower CO_2 level. For mucous membrane symptoms runny nose and dry/sore throat, a higher prevalence is observed when CO_2 level increases to a level of 1100 ppm or higher. Table 3.19 and 3.20 shows the sick-symptom scores (number of symptoms per person) for various workstations grouped according to the CO_2 level, which also shows that higher CO_2 level may be considered as an “antagonist” resulting in more sick symptoms.

Table 3.19 Sick-symptom score for various CO_2 level (all symptoms)

CO_2 level	Sick-symptom score (all stress level considered)	Sick-symptom score (Only include samples with level 4 or 5 stress at work)
< 800 ppm	1.77	2.69
800 ppm - 925 ppm	2.52	3.52
925 ppm - 1100 ppm	2.5	2.6
> 1100 ppm	2.63	3.71
All data average	2.36	3.05

Table 3.20 Sick-symptom score for various CO_2 level (basic 5 symptoms only)

CO_2 level	Sick-symptom score (all stress level considered)	Sick-symptom score (Only include samples with level 4 or 5 stress at work)
< 800 ppm	0.82	1.23
800 ppm - 925 ppm	1.0	1.3
925 ppm - 1100 ppm	1.04	0.92
> 1100 ppm	1.26	1.65
All data average	1.03	1.24

3.7.5 Thermal Comfort and Sick Building Syndrome

Fanger [1984] defines thermal comfort as the condition of mind which expresses satisfaction with the thermal environment. If dissatisfaction due to bodily discomfort to warm or cool conditions occurs, this may induce stress on the human body and as

a result sick symptoms may appear. In the Danish Town Hall study, a significant initial association between temperature and the prevalence of general and mucous membrane symptoms [Skov and Valbjorn 1987]. In a follow-up study of a portion of buildings in the Danish Town Hall study, Skov et al. [1990] observed a strong relation between office temperatures and prevalence of general symptoms, suggesting that the relative risk of general symptoms increased by a factor of three for every 3°C rise in temperature. In an epidemiological study of office building in Helsinki, Finland, Jaakola et al. [1989] observed a linear relationship between Sick Building Syndrome prevalence and temperatures above 22°C. Positive associations were observed between temperature and the sensation of dryness and warmth [Reinikainen and Jaakola 1993]. These findings are based on studies conducted in Scandinavian Europe, at which the climatic condition is different from the warm and humid subtropical climate like Hong Kong. The following sections attempt to evaluate if any potential associations exist between workplace thermal comfort conditions and sick symptom prevalence rate in offices in summer months in Hong Kong.

3.7.5.1 Air Temperature and Symptom Prevalence Percentage

Tables 3.21 and 3.22 shows the sick-symptom scores (number of symptoms per person) for various workstations grouped according to air temperature.

Table 3.21 Sick-symptom score for various air temperatures (all symptoms)

Air temperature	Sick-symptom score (all stress level considered)	Sick-symptom score (Only include samples with level 4 or 5 stress at work)
19.9˚C - 23.5˚C	2.34	3.12
23.5˚C - 24.5˚C	1.87	2.04
24.5˚C - 25.5˚C	2.18	3
25.5˚C - 27.6˚C	3.47	4.29
All data average	2.36	3.05

Table 3.22 Sick-symptom score for various air temperatures (basic 5 symptoms)

Air temperature	Sick-symptom score (all stress level considered)	Sick-symptom score (Only include samples with level 4 or 5 stress at work)
19.9˚C - 23.5˚C	1.22	1.59
23.5˚C - 24.5˚C	0.72	0.74
24.5˚C - 25.5˚C	0.86	1.0
25.5˚C - 27.6˚C	1.5	1.76
All data average	1.03	1.24

Fewer symptoms were reported from workstations with temperature between 23.5˚C to 24.5˚C. Within this temperature range the sick-symptom score is lower than the average, which may “alleviate” symptom manifestation, even under a higher level of stress at work. While the Hong Kong Government promotes an indoor air temperature of 25.5˚C, this study shows that for workstations with a higher temperature above 25.5˚C, more sick symptoms were reported. The number of sick symptoms may decrease when the indoor air temperature is maintained within a range of 2˚C below the government’s recommended level. Further decrease of air temperature below 23.5˚C would result in reporting more symptoms. To investigate the effect of indoor air temperature on the prevalence of individual symptom, table 3.23 (include all data) and table 3.24 (only considers the samples reporting similar, higher level {level 4 or 5} of stress at work) shows the sick symptom prevalence percentage of individual symptom, grouped according to the indoor air temperature of the workstation.

Table 3.23 Sick symptom prevalence percentage (SPP) for different temperature

Symptom	SPP (%) for workstations with air temperature between…				SPP (%)
	19.5 to 23.5	23.5 to 24.5	24.5 to 25.5	25.5 to 27.6	All data
Dry eyes	24.4%	14.9%	17.6%	34.4%	22.4%
Stuffy / blocked nose	22.0%	10.6%	17.6%	28.1%	19.4%
Dry, sore throat	26.8%	16.8%	13.7%	25.0%	19.4%
Headache	22.0%	19.1%	21.6%	43.8%	25.3%
Lethargy	26.8%	14.9%	15.7%	18.8%	18.8%
Watering eyes	7.3%	6.4%	7.8%	9.4%	7.6%
Running nose	9.8%	14.9%	15.7%	31.3%	17.1%
Flu like symptoms	19.5%	19.1%	19.6%	18.8%	19.4%
Breathing tightness	7.3%	10.6%	13.7%	31.3%	14.7%
Chest tightness	2.4%	10.6%	5.9%	12.5%	7.6%
Skin itching	24.4%	12.8%	9.8%	18.8%	16.5%
Rash	4.9%	0%	0%	6.3%	2.4%
Ear rings	12.2%	10.6%	13.7%	9.4%	11.8%
Nausea	7.3%	2.1%	9.8%	9.4%	7.1%
Dizziness	9.8%	17.0%	17.6%	28.1%	17.4%
Muscle pain	4.9%	10.6%	13.7%	15.6%	11.8%

Table 3.24 SPP at different air temperature for level 4 or 5 stress at work

Symptom	SPP (%) for workstations with air temperature between…				SPP (%)
	19.5 to 23.5	23.5 to 24.5	24.5 to 25.5	25.5 to 27.6	All data
Dry eyes	23.5%	13.0%	19.0%	41.2%	23.1%
Stuffy / blocked nose	29.4%	13.0%	19.0%	29.4%	21.8%
Dry, sore throat	41.2%	8.7%	19.0%	35.3%	24.4%
Headache	29.4%	21.7%	28.6%	52.9%	32.1%
Lethargy	35.3%	17.4%	14.3%	17.6%	20.5%
Watering eyes	17.6%	4.3%	14.3%	17.6%	12.8%
Running nose	11.8%	17.4%	19.0%	35.3%	20.5%
Flu like symptoms	17.6%	26.1%	23.8%	29.4%	25.6%
Breathing tightness	11.8%	8.7%	23.8%	41.2%	20.5%
Chest tightness	5.9%	8.7%	14.3%	23.5%	12.8%
Skin itching	35.3%	21.7%	14.3%	29.4%	24.4%
Rash	5.9%	0%	0%	5.9%	2.6%
Ear rings	11.8%	13.0%	28.6%	11.8%	17.9%
Nausea	17.6%	4.3%	14.3%	5.9%	10.3%
Dizziness	11.8%	17.4%	28.6%	35.3%	24.4%
Muscle pain	0%	8.7%	14.3%	17.6%	10.3%

An increase of indoor air temperature to a level of 25.5˚C or above results in a higher prevalence of all mucous membrane symptoms (dry eyes, watering eyes, stuffy/blocked nose, running nose and dry, sore throat), all lower respiratory system symptoms (flu-like symptoms {for stress at work level 4 or 5}, breathing tightness and chest tightness), and some central nervous system symptoms (including

headache and dizziness). This finding agrees with the observation from the study by Skov and Valbjorn [1987]. For symptom ‘lethargy’ the prevalence percentage is the highest when the temperature is 23.5°C or below. For skin symptoms the prevalence rate is the lowest when the air temperature is maintained between 24.5°C to 25.5°C.

3.7.5.2 Predicted Mean Vote (PMV) and Symptom Prevalence Percentage

Further to the air temperature, this section use the predicted mean vote index (PMV, from Fanger’s [1972] model) to represent the expected thermal sensation among the occupants in the workplace environment and compare with the sick symptoms score and the prevalence percentage of individual symptoms. The PMV index is calculated based on the measurement data from the Environmental Health and Comfort Analyzer as described in section 3.6 in this thesis. While the workstations surveyed has a temperature within a range of 19.5°C to 27.6°C, the range of PMV among the workstation is ranged from -2.5 (cool) to +1.14 (slightly warm). Tables 3.25 and 3.26 shows the sick-symptom scores (number of symptoms per person) for various workstations grouped according to the Predicted Mean Vote value.

Table 3.25 Sick-symptom score for various PMV (all symptoms)

Predicted Mean Vote	Sick-symptom score (all stress level considered)	Sick-symptom score (Only include samples with level 4 or 5 stress at work)
-2.5 to -1.1	2.57	3.86
-1.1 to -0.5	2.15	2.86
-0.5 to 0	2.14	2.28
0 to 1.14	2.67	3.18
All data average	2.36	3.05

Table 3.26 Sick-symptom score for various PMV (basic 5 symptoms)

Predicted Mean Vote	Sick-symptom score (all stress level considered)	Sick-symptom score (Only include samples with level 4 or 5 stress at work)
-2.5 to -1.1	1	1.29
-1.1 to -0.5	1.04	1.27
-0.5 to 0	0.97	1
0 to 1.14	1.21	1.29
All data average	1.03	1.24

The sick symptom score for the indoor environment with PMV between -0.5 to 0 (slightly cool to neutral) is the lowest, while the highest sick symptom score is observed from the group with PMV between 0 to 1.14 (slightly warm), except that for the group with higher level of stress at work, the sick-symptom score from workstation with PMV between -1.1 to -2.5 (cool) is the highest when considering

the full set of symptoms. To investigate the change on the prevalence of individual symptom at various PMV, table 3.27 (include all data) and table 3.28 (only considers the samples reporting similar, higher level {level 4 or 5} of stress at work) shows the sick symptom prevalence percentage of individual symptom, grouped according to the predicted thermal sensation (in terms of PMV) of the workstation.

Table 3.27 Sick symptom prevalence percentage (SPP) at various PMV

Symptom	SPP (%) for workstations with PMV between…				SPP (%)
	-2.5 to -1.1	-1.1 to -0.5	-0.5 to 0	0 to 1.14	All data
Dry eyes	11.8%	27.1%	27.6%	26.5%	22.4%
Stuffy / blocked nose	21.6%	16.7%	17.2%	20.5%	19.4%
Dry, sore throat	21.6%	22.9%	10.3%	17.9%	19.4%
Headache	27.5%	25.0%	17.2%	30.8%	25.3%
Lethargy	17.6%	16.5%	24.1%	25.6%	18.8%
Watering eyes	13.7%	6.3%	3.4%	5.1%	7.6%
Running nose	13.7%	16.7%	10.3%	28.2%	17.1%
Flu like symptoms	11.8%	14.6%	31.0%	28.2%	19.4%
Breathing tightness	13.7%	16.7%	6.9%	20.5%	14.7%
Chest tightness	5.9%	6.3%	13.8%	7.7%	7.6%
Skin itching	19.6%	18.8%	17.2%	10.3%	16.5%
Ear rings	17.6%	8.3%	6.9%	10.3%	11.8%
Nausea	15.7%	2.1%	3.4%	2.6%	7.1%
Dizziness	25.5%	15.5%	13.8%	15.4%	17.4%
Muscle pain	13.7%	4.2%	10.3%	15.4%	11.8%

Table 3.28 SPP at different PMV for level 4 or 5 stress at work

Symptom	SPP (%) for workstations with PMV between…				SPP (%)
	-2.5 to -1.1	-1.1 to -0.5	-0.5 to 0	0 to 1.14	All data
Dry eyes	23.8%	31.8%	22.2%	11.8%	23.1%
Stuffy / blocked nose	33.3%	13.6%	22.2%	17.6%	21.8%
Dry, sore throat	28.6%	22.7%	11.1%	35.3%	24.4%
Headache	33.3%	40.9%	16.7%	35.3%	32.1%
Lethargy	9.5%	18.2%	27.8%	29.4%	20.5%
Watering eyes	19.0%	13.6%	5.6%	11.8%	12.8%
Running nose	9.5%	22.7%	11.1%	41.2%	20.5%
Flu like symptoms	14.3%	18.2%	38.9%	35.3%	25.6%
Breathing tightness	23.8%	22.7%	5.6%	29.4%	20.5%
Chest tightness	13.6%	14.3%	5.6%	17.6%	12.8%
Skin itching	42.9%	18.2%	22.2%	11.8%	24.4%
Ear rings	38.1%	9.1%	11.1%	11.8%	17.9%
Nausea	23.8%	4.5%	5.6%	5.9%	10.3%
Dizziness	38.1%	22.7%	11.1%	23.5%	24.4%
Muscle pain	19.0%	9.1%	11.1%	0%	10.3%

The prevalence of lower respiratory symptoms (flu-like symptom, breathing tightness and chest tightness) is higher when the PMV is at a level of 0 to 1.14 (slightly warm), similar to the observation from the air temperature in section 3.7.5.1. For mucous membrane symptoms and central nervous system symptoms, the situation is not the same as observed from air temperature. The prevalence percentage is higher at the cooler side for symptoms like ‘dry eyes’, ‘stuffy/blocked

nose' and 'watering eyes'; for the symptom 'dry/sore throat', 'headache' and 'dizziness' the symptom prevalence is the lowest for a PMV between 0 to -0.5 (neutral to slightly cool); and for 'running nose' and 'lethargy', the cooler environment may alleviate the symptom manifestation, while a much higher prevalence at the slightly warm side is observed. On the whole, in this study, workstations with neutral to slightly cool thermal environment (PMV between 0 to -0.5) shall minimize the manifestation of sick symptoms.

3.7.5.3 Relative Humidity and Symptom Prevalence Percentage

Tables 3.29 and 3.30 shows the sick-symptom scores (number of symptoms per shows the sick-symptom scores (number of symptoms per person) for various workstations grouped according to the relative humidity.

Table 3.29 Sick-symptom score for different relative humidity (all symptoms)

Relative humidity	Sick-symptom score (all stress level considered)	Sick-symptom score (Only include samples with level 4 or 5 stress at work)
49% to 53%	2.7	3.35
53% to 57%	2.7	3.77
57% to 61%	2.16	2.5
61% to 68%	2.02	2.47
All data average	2.36	3.05

Table 3.30 Sick-symptom score for different relative humidity (basic 5)

Relative humidity	Sick-symptom score (all stress level considered)	Sick-symptom score (Only include samples with level 4 or 5 stress at work)
49% to 53%	1.15	1.41
53% to 57%	1.15	1.55
57% to 61%	1.04	1.05
61% to 68%	0.81	0.82
All data average	1.03	1.24

A much higher sick symptom score is observed from the workstation with relative humidity between 49% to 57%. To investigate the change on the prevalence of individual symptom at different relative humidity, table 3.31 (include all data) and table 3.32 (only considers the samples reporting similar, higher level {level 4 or 5} of stress at work) shows the sick symptom prevalence percentage of individual symptom, grouped according to the relative humidity of the workstation.

Table 3.31 Sick symptom prevalence percentage (SPP) at various relative humidity

Symptom	SPP (%) for workstations with relative humidity between…				SPP (%)
	49% to 53%	53% to 57%	57% to 61%	61% to 68%	All data
Dry eyes	22.2%	27.7%	20.0%	16.7%	22.4%
Stuffy / blocked nose	18.5%	14.9%	25.5%	14.3%	19.4%
Dry, sore throat	22.2%	14.9%	23.6%	14.3%	19.4%
Headache	33.3%	34.0%	23.6%	11.9%	25.3%
Lethargy	18.5%	23.4%	10.9%	23.8%	18.8%
Watering eyes	7.4%	12.8%	5.5%	2.4%	7.6%
Running nose	25.9%	19.1%	16.4%	21.4%	17.1%
Flu like symptoms	18.5%	21.3%	16.4%	21.4%	19.4%
Breathing tightness	18.5%	21.3%	7.3%	14.4%	14.7%
Chest tightness	7.4%	10.6%	3.6%	9.5%	7.6%
Skin itching	22.2%	10.6%	12.7%	23.8%	16.5%
Ear rings	3.7%	10.6%	12.7%	16.7%	11.8%
Nausea	7.4%	10.6%	12.7%	16.7%	7.1%
Dizziness	22.2%	23.4%	14.5%	11.9%	17.4%
Muscle pain	11.1%	12.8%	12.7%	7.1%	11.8%

Table 3.32 SPP at different relative humidity for level 4 or 5 stress at work

Symptom	SPP (%) for workstations with relative humidity between…				SPP (%)
	49% to 53%	53% to 57%	57% to 61%	61% to 68%	All data
Dry eyes	29.4%	36.4%	13.6%	9.1%	23.1%
Stuffy / blocked nose	17.6%	18.2%	31.8%	13.6%	21.8%
Dry, sore throat	29.4%	27.3%	27.3%	9.1%	24.4%
Headache	47.1%	45.5%	22.7%	9.1%	32.1%
Lethargy	17.6%	27.3%	9.1%	22.7%	20.5%
Watering eyes	11.8%	22.7%	4.5%	4.5%	12.8%
Running nose	35.3%	22.7%	18.2%	4.5%	20.5%
Flu like symptoms	17.6%	36.4%	22.7%	18.2%	25.6%
Breathing tightness	23.5%	31.8%	9.1%	13.6%	20.5%
Chest tightness	11.8%	13.6%	4.5%	18.2%	12.8%
Skin itching	23.5%	22.7%	13.6%	27.3%	24.4%
Ear rings	5.9%	13.6%	22.7%	22.7%	17.9%
Nausea	11.8%	9.1%	13.6%	4.5%	10.3%
Dizziness	29.4%	36.4%	18.2%	9.1%	24.4%
Muscle pain	11.8%	13.6%	9.1%	4.5%	10.3%

For some of the mucous membrane symptoms, i.e. ‘dry eyes’, ‘watering eye’ and ‘running nose’ the prevalence percentage is higher for a lower relative humidity

(49% to 57%); and for ‘dry, sore throat’ and ‘stuffy/blocked nose’, the symptom prevalence percentage is lower for a relative humidity between 61% to 68%. It may be hypothesized the presence of an optimal quantity of moisture may alleviate the mucous membrane symptoms. For symptoms ‘headache’ and ‘breathing tightness’, the symptom prevalence percentage is also lower for a relative humidity between 61% to 68%; however, for symptom ‘chest tightness’, a higher relative humidity of 61% to 68% results in a higher symptom prevalence percentage, and for this symptom the lowest prevalence is observed when the relative humidity is between 57% to 61%.

3.7.6 Indoor Environmental Quality Satisfaction

3.7.6.1 Percentage of IEQ dissatisfaction vs. building sick-symptom score

Figures 3.9 to 3.12 show the building sick-symptom score in office plotted against the four basic indoor environmental quality components: thermal comfort, indoor air quality, visual comfort and aural comfort. Observed from the figures, the correlation is not strong while for Indoor Air Quality the correlation is relatively high. All intercepts are relatively high, indicating that there is an “initial” building sick-symptom score even if no occupant feels dissatisfied with any indoor environmental quality components. There could be other factors causing the “initial”

building sick-symptom score, which may include personal factors or sick symptom triggered by airborne infection.

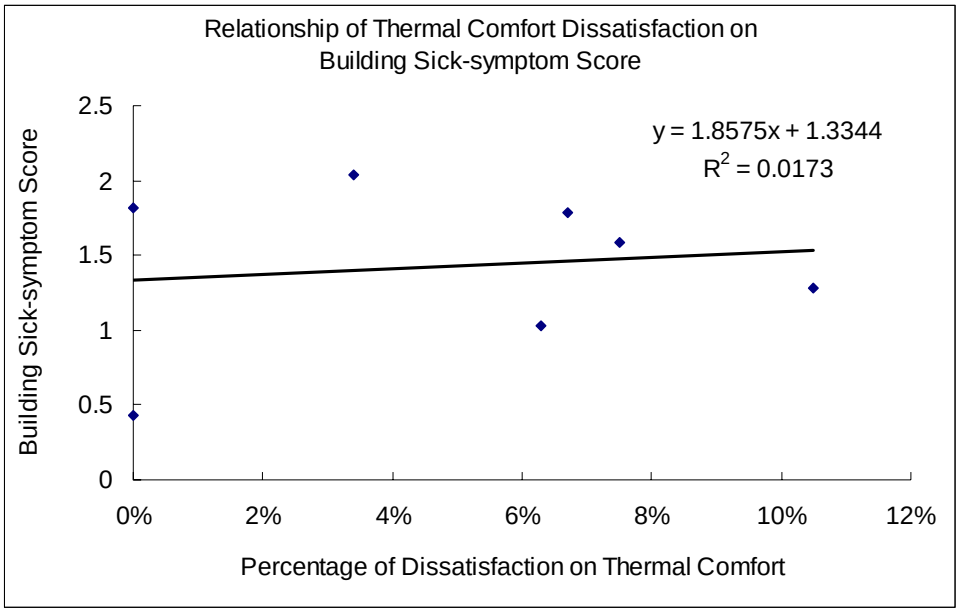

Figure 3.9 Thermal comfort dissatisfaction vs. building sick-symptom score

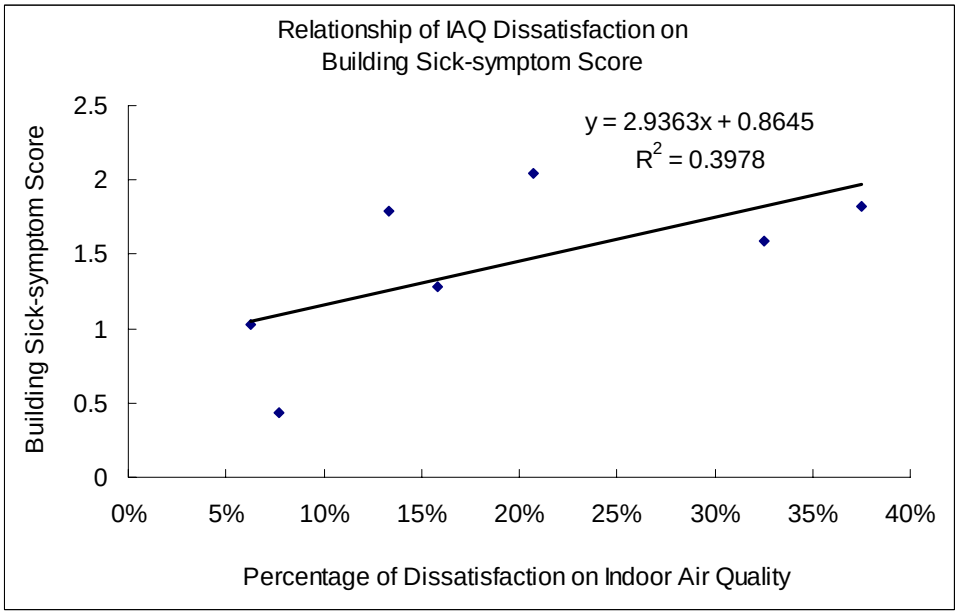

Figure 3.10 IAQ dissatisfaction vs. building sick-symptom score

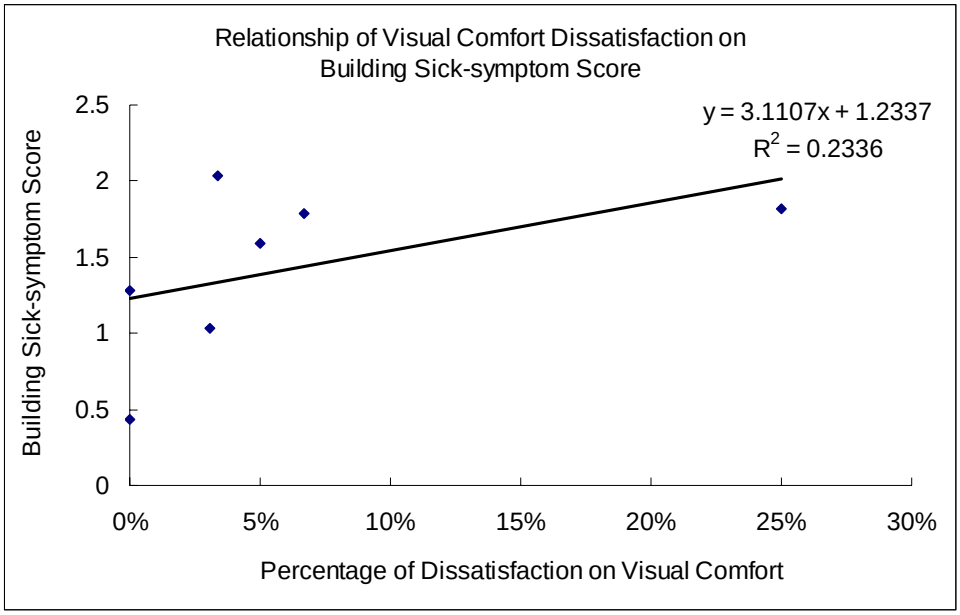

Figure 3.11 Visual comfort dissatisfaction vs. building sick-symptom score

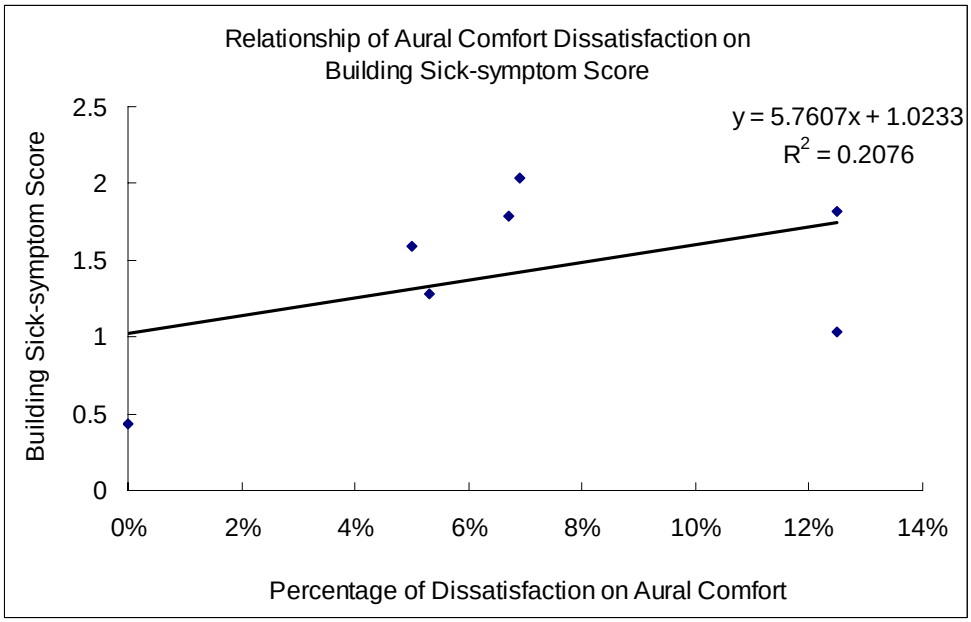

Figure 3.12 Aural comfort dissatisfaction vs. building sick-symptom score

3.7.6.2 Percentage of overall IEQ dissatisfaction vs. each IEQ component

By considering a linear regression model, the Indoor Environmental Quality equation is formed such that the percentage of dissatisfaction (PD) on overall IEQ is related with respect to each of the indoor environmental qualifiers {equation 3.1}.

$$\text{PDIEQ} = a_1 \times \text{PDTC} + a_2 \times \text{PDIAQ} + a_3 \times \text{PDVC} + a_4 \times \text{PDAC} \quad \{\text{equation 3.1}\}$$

Where:

PDIEQ = percentage of dissatisfaction on overall indoor environmental quality

PDTC = percentage of dissatisfaction on thermal comfort

PDIAQ = percentage of dissatisfaction on indoor air quality

PDVC = percentage of dissatisfaction on visual comfort

PDAC = percentage of dissatisfaction on aural comfort

a_1, a_2, a_3, a_4 are the coefficients for each of the comfort indices.

The multiple regressed IEQ equation is generated {equation 3.2}, as given in table 3.33.

$$\text{PDIEQ} = -0.43 \times \text{PDTC} + 0.08 \times \text{PDIAQ} + 0.59 \times \text{PDVC} + 0.48 \times \text{PDAC}$$

{equation 3.2}

Table 3.33 First regression analysis for IEQ prediction

	Coefficients	Standard error	t statistic	P value	Lower 95%	Upper 95%
PDTC	-0.43	0.44	-0.96	0.41	-1.83	0.98
PDIAQ	0.08	0.15	0.52	0.64	-0.41	0.57
PDVC	0.59	0.40	1.48	0.24	-0.68	1.87
PDAC	0.48	0.50	0.96	0.41	-1.11	2.08

From the IEQ equation as shown in equation 3.2, the coefficient for thermal comfort percentage dissatisfaction is negative, which is illogical. One possible explanation is that the overall IEQ percentages of dissatisfaction in 3 offices in the analysis are 0%, while the thermal comfort percentages of dissatisfaction among these offices are relatively higher compared with the others. In addition, in one office with 25% dissatisfaction on overall IEQ, the thermal comfort dissatisfaction in that office is 0%, such that in the offices investigated in this study, the thermal comfort dissatisfaction makes no significant contribution to the dissatisfaction on overall IEQ. When PDTC is taken out of the regression analysis, the PDIEQ is regressed with the other three PDs, and the result is shown in equation 3.3 and table 3.34.

$$\mathrm{PDIEQ} = 0.06 \times \mathrm{PDIAQ} + 0.86 \times \mathrm{PDVC} + 0.01 \times \mathrm{PDAC} \qquad \{\text{equation 3.3}\}$$

Table 3.34 Second regression analysis for IEQ prediction

	Coefficients	Standard error	t statistic	P value	Lower 95%	Upper 95%
PDIAQ	0.06	0.15	0.38	0.72	-0.36	0.48
PDVC	0.85	0.29	2.98	0.04	0.06	1.66
PDAC	0.01	0.11	0.11	0.92	-0.28	0.31

For the offices investigated in this study, the coefficient for visual comfort is the highest. One possible explanation is that visual comfort is more readily discernable, while it is less readily discernable for indoor air quality. For aural comfort, the background noise level in the office fluctuates with the activity level inside an office and it is less controllable.

3.7.6.3 Percentage of IEQ dissatisfaction vs. physical parameters

For the physical measurements conducted inside the offices, calculation has been performed to obtain various comfort indices for each of the indoor environmental qualifiers, and for the comparison with the percentage of dissatisfaction. For thermal comfort the operative temperature is calculated and plotted with the percentage of dissatisfaction (figure 3.12). For indoor air quality, visual comfort and aural comfort, the corresponding physical parameters, namely carbon dioxide concentration, horizontal illuminance and L_{eq} in dBA, respectively, are plotted against the

percentage of dissatisfaction for the corresponding indoor environmental qualifier (figure 3.13 to 3.15)

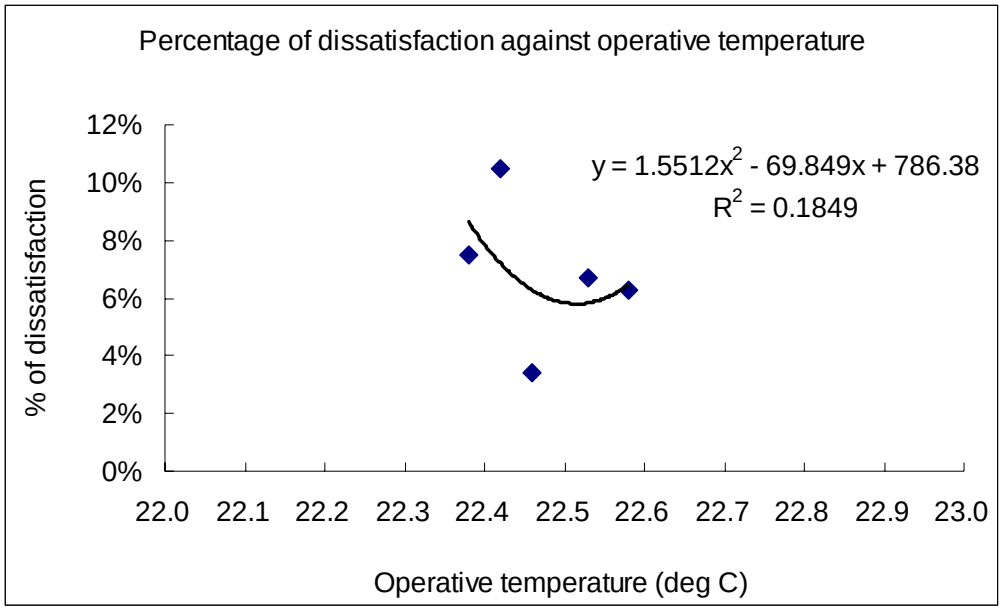

Figure 3.13 Percentage of dissatisfaction against operative temperature

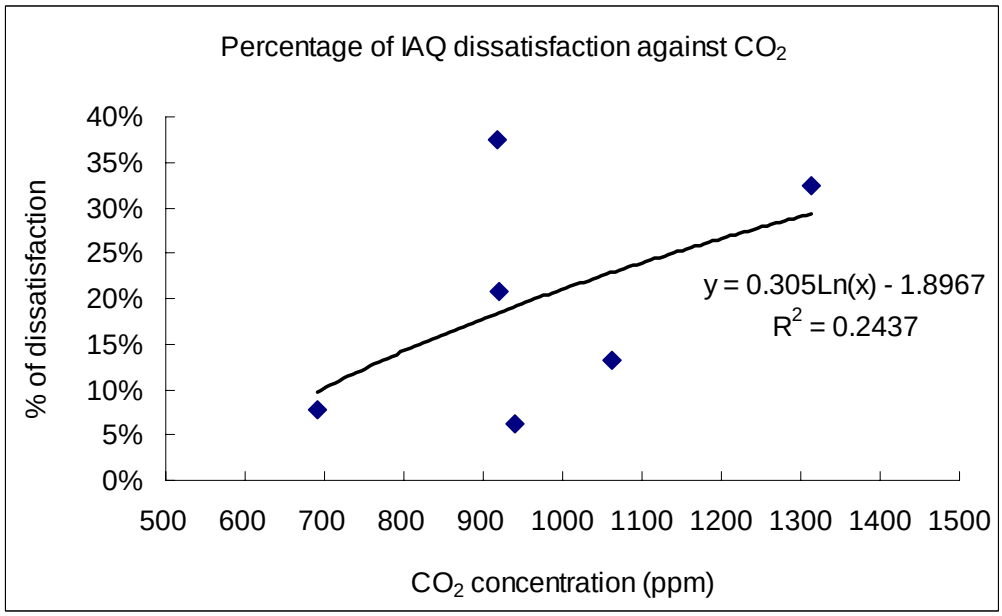

Figure 3.14 Percentage of dissatisfaction against carbon dioxide concentration

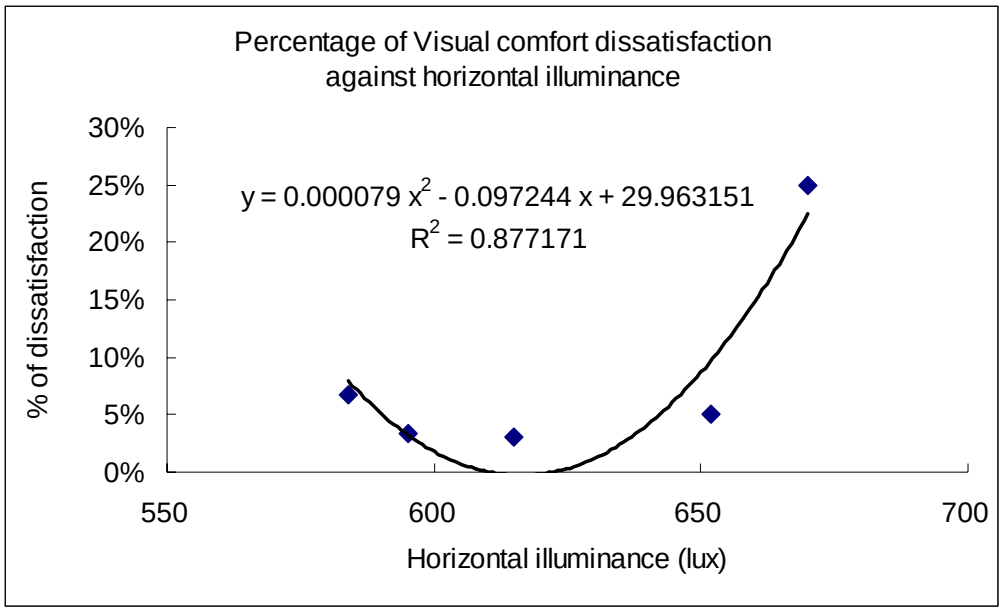

Figure 3.15 Percentage of dissatisfaction against horizontal illuminance

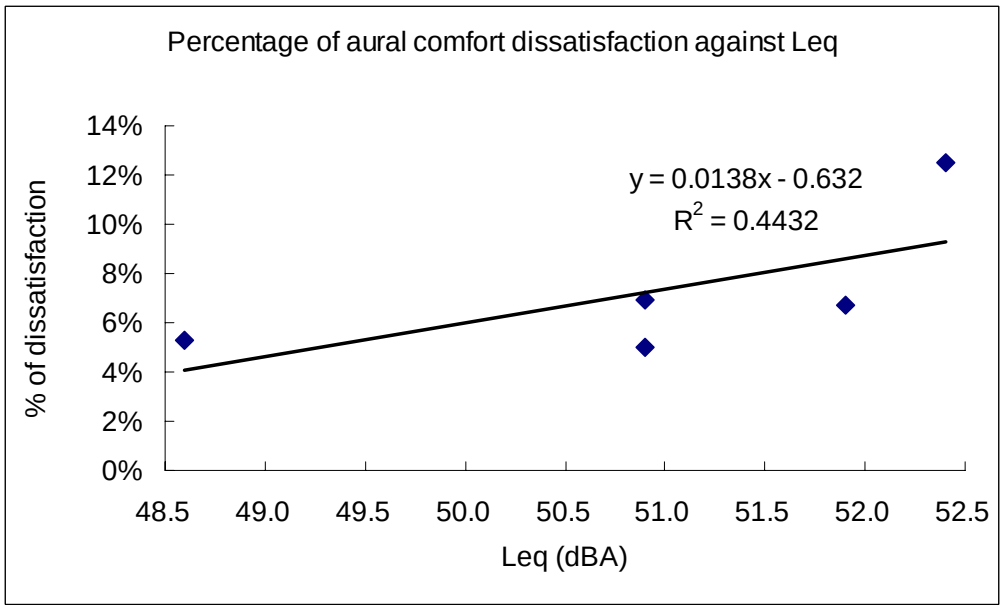

Figure 3.16 Percentage of dissatisfaction against L_{eq}.

3.7.6.4 The Indoor Environmental Quality Equation

The IEQ equation for the prediction of percentage of dissatisfaction on overall IEQ based on physical parameters is formed as equation 3.7, by substitution of equation 3.4 to 3.6 into equation 3.3.

$$PDIAQ = [0.305 \times \ln(CO_2 \text{ in ppm}) - 1.8967] \times 100\% \quad \{\text{equation 3.4}\}$$

$$PDVC = [0.000079 \times (\text{lux})^2 - 0.0972 \times (\text{lux}) + 29.9632] \times 100\% \quad \{\text{equation 3.5}\}$$

$$PDAC = [0.0138 \times (L_{eq} \text{ in dBA}) - 0.632] \times 100\% \quad \{\text{equation 3.6}\}$$

$$\begin{aligned} PDIEQ = \{&0.06 \times [0.305 \times \ln(CO_2 \text{ in ppm}) - 1.8967] + \\ &0.86 \times [0.000079 \times (\text{lux})^2 - 0.0972 \times (\text{lux}) + 29.9632] + \\ &0.01 \times [0.0138 \times (L_{eq} \text{ in dBA}) - 0.632]\} \times 100\% \end{aligned} \quad \{\text{equation 3.7}\}$$

The indoor environmental quality equation enables the prediction of percentage of dissatisfaction on the indoor environment, when the physical parameters are measured. The physical parameters, namely carbon dioxide concentration, horizontal illuminance, and L_{eq} in dBA are used as surrogate indicators.

3.7.7 Number of sick days vs. building sick-symptom score

Figure 3.16 shows the normalized building sick-symptom score ($ABSS_{N10}$) plotted against the average number of sick days in a year per person. Figure 3.17 shows the normalized building sick-symptom score ($ABSS_{N10}$) plotted against the average number of sick days due to adverse effect of workplace environmental quality within a year per person.

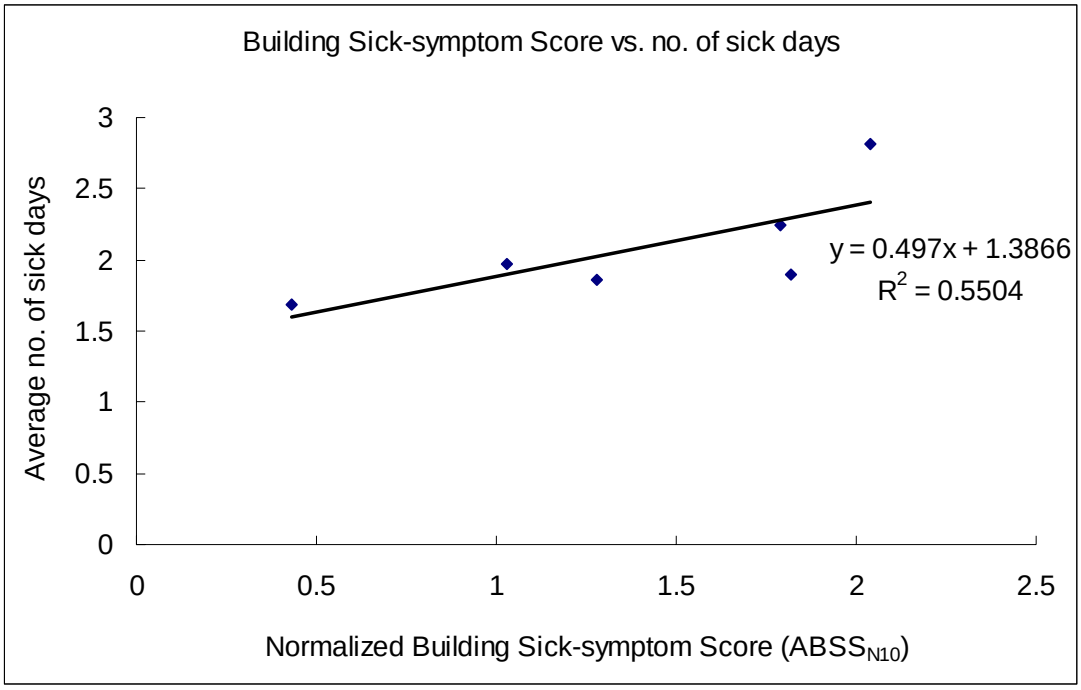

Figure 3.17 Building Sick-symptom Score ($ABSS_{N10}$) vs. no. of sick days

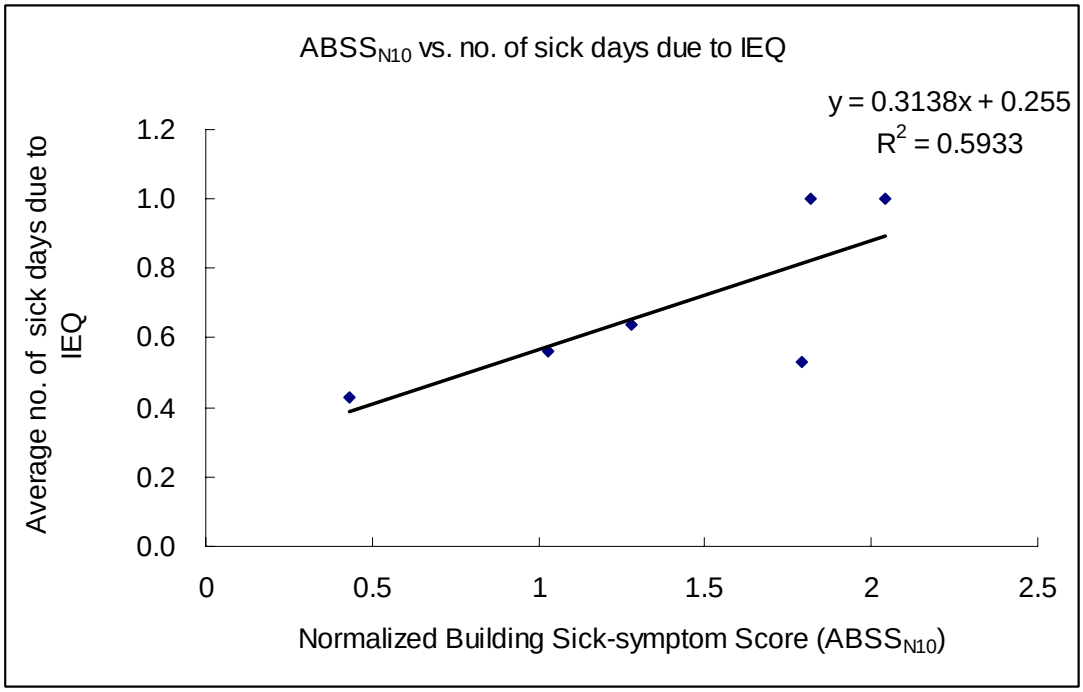

Figure 3.18 Building Sick-symptom Score ($ABSS_{N10}$) vs. no. of sick days due to adverse effect of IEQ

From figure 3.16 it can be observed that the normalized building symptom score ($ABSS_{N10}$) is below 2 for all the offices. The result obtained from study from Chan [1999] (as shown in figure 3.18) is compared. By combining the results from the two studies, figure 3.19 is plotted. It can be observed that a higher sick-symptom score in an office would result in a higher number of sick leave days.

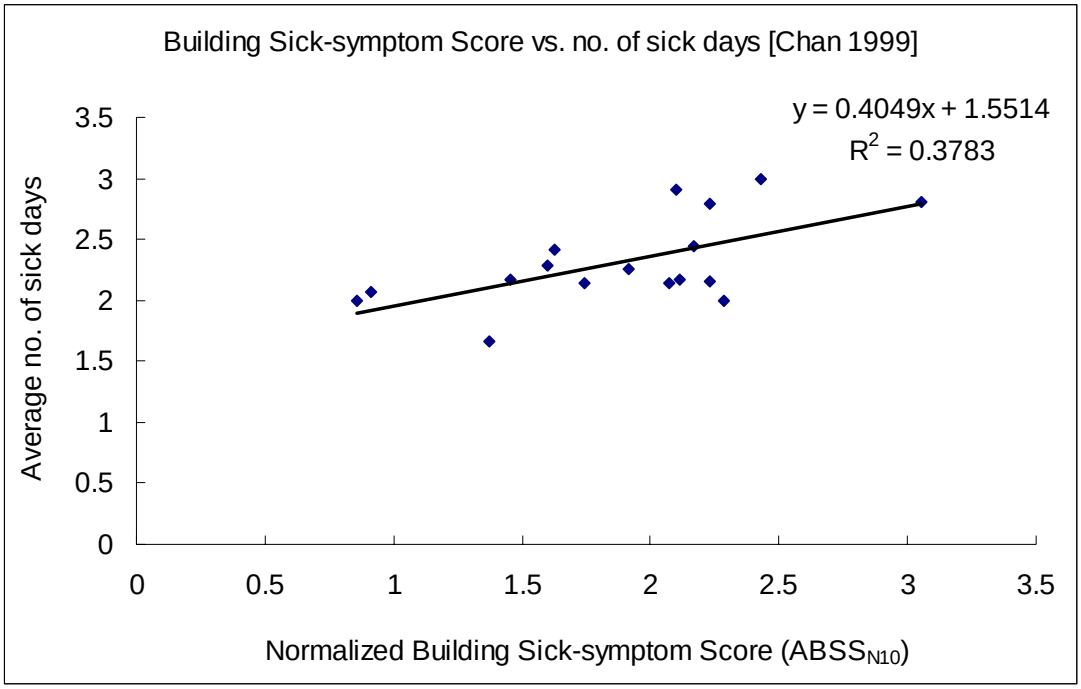

Figure 3.19 $ABSS_{N10}$ vs. no. of sick days [Chan 1999]

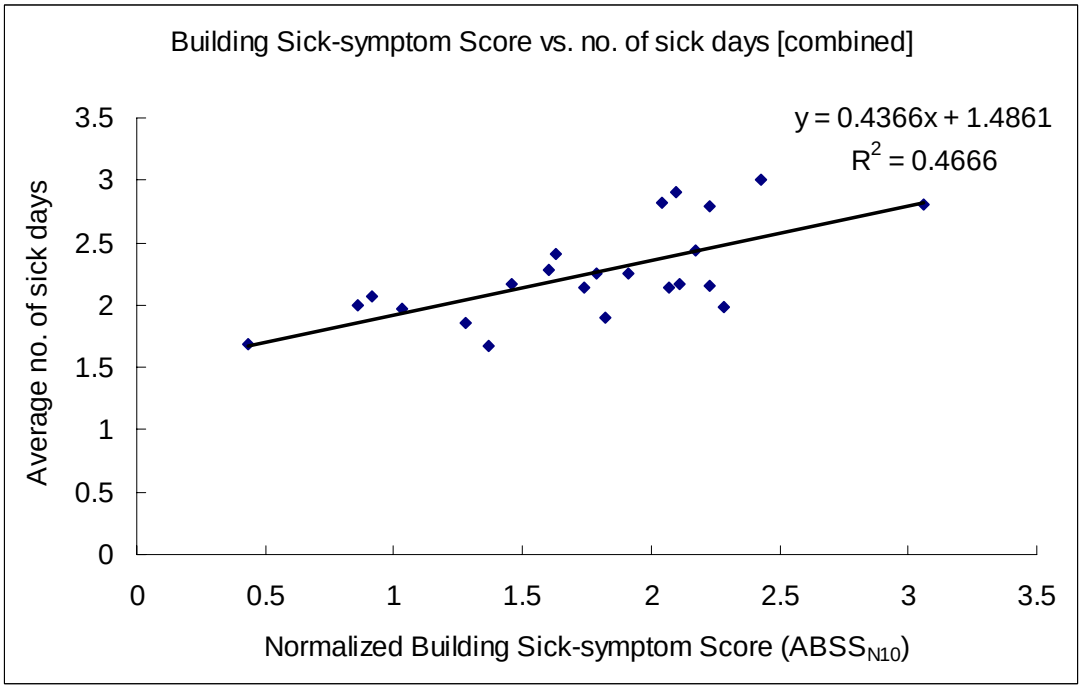

Figure 3.20 $ABSS_{N10}$ vs. no. of sick days [This study combined with Chan 1999]

For an increment of building sick-symptom score by 1 symptom per person, it would be expected that half sick leave day occur. The positive intercept of 1.4 sick leave days is also observed from the graphs, even if there is no symptom (as listed in the questionnaire) exists. One possible explanation is that other types of illness or infection can occur without manifestation of symptoms that are listed in the questionnaire. Such an illness or infection can also induce sick leaves.

On the other hand, the symptoms of respiratory illness or infection, such as influenza, are tiredness, sore throat, runny or stuffy nose and body ache [Centers for Disease Control and Prevention 2007]. All these symptoms are included in the sick building syndrome survey questionnaire. Thus an increase in building sick-symptom score can also be a result of high prevalence of respiratory infection among office workers, in addition to the possible causes including increased stress level, degraded indoor environmental quality, or a low ventilation rate as mentioned in the previous sections. The average number of times getting flu or cold per person among the occupants increase slightly with an increased building sick-symptom score to a level of $ABSS_{N10}$ more than 2.0 (figure 3.20), while the effect of outdoor air ventilation rate per person on the number of times getting flu or cold is less significant (figure 3.21).

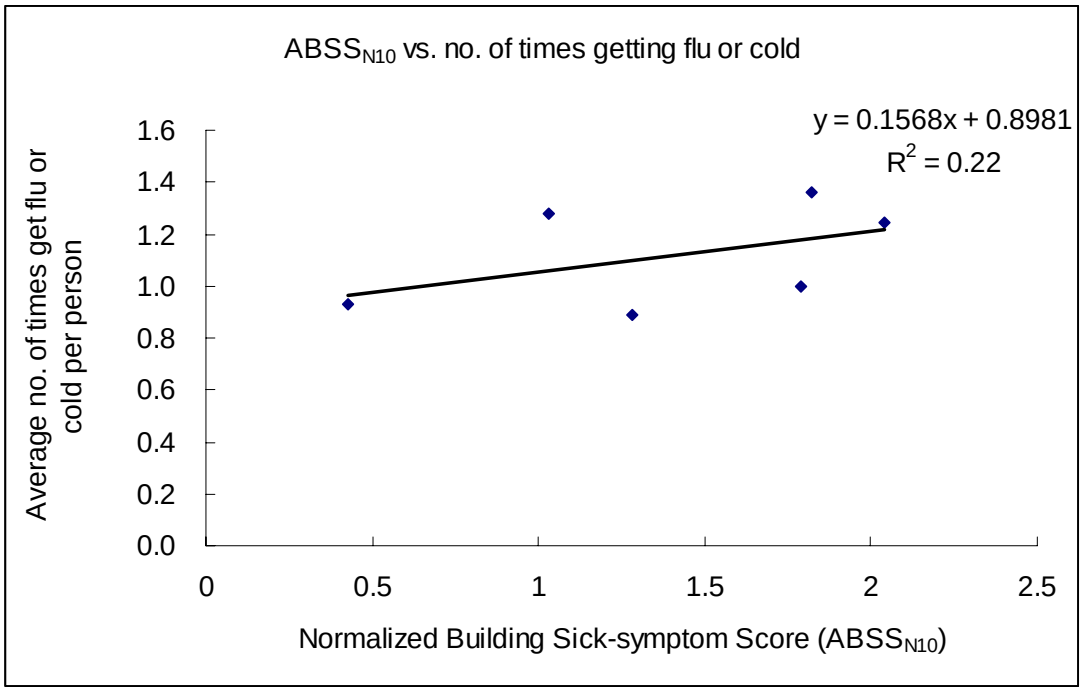

Figure 3.21 Building Sick-symptom Score (ABSS$_{N10}$) vs. average no. of times getting flu or cold per person

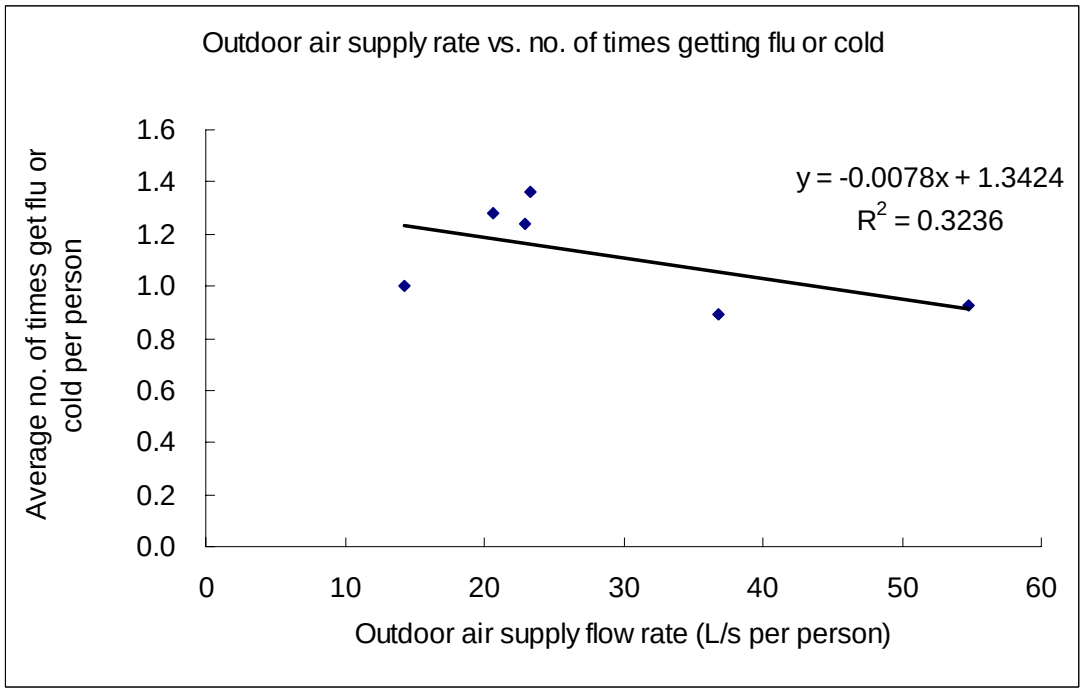

Figure 3.22 Outdoor air flow rate vs. average no. of times getting flu or cold per person

As the symptoms of respiratory infections like influenza or common cold are also the symptoms of sick building syndrome, the monitoring of the prevalence of respiratory symptoms through the questionnaire provides an indirect clue on the risk of respiratory illness among the occupants inside the built environment.

3.8 Chapter Summary

In this chapter the investigation of sick building syndrome prevalence and the indoor environmental quality on office buildings in an education institution is discussed. An Environmental Health and Comfort Analyzer is developed for the monitoring of indoor environmental quality and the calculation of thermal comfort indices base on measured data.

To provide a common platform for the comparison of sick building syndrome indices between this study and those reported in the literature, a normalized 5-symptoms building sickness score is used. The average $ABSS_{N5}$ for the investigated offices is within the range of 0.21 to 1.18, which is lower than the threshold value of 1.76 reported from sick buildings investigated in the literature.

Based on the sick building syndrome model suggested by Jones et al. [1995], sick

building syndrome can be described as the state of the mind caused by one's responses from his immunity system as a result of exposure to the physical environment of surrounding (at home, in office or in between) and one's interaction with the social environment, triggered by the physical environment and psychological pressure at work for then the immune system may be seriously lowered. The combat of occurrence of SBS will then be to eliminate or alleviate the 'antagonists' and to enhance the 'alleviators'.

This chapter attempts to identify the 'antagonists' and 'alleviators'. 'Stress at work' is a possible antagonist; the reduction of work stress and a surplus supply of outdoor air (to a high level of 54.8 L/s per person) alleviates sick symptoms, as observed from the significantly lower building sickness score in such environment. A lower sick symptom prevalence is reported from workstations with indoor air temperature of 23.5°C to 24.5°C, while increased symptom prevalence is observed from workstations with air temperature above 25.5°C. Maintaining a neutral or slightly cool indoor thermal environment (with Fanger's Predicted Mean Vote value between -0.5 to 0), and maintaining a relative humidity between 57% to 68% alleviates sick symptoms among the investigated offices. These findings offer a possible way of indoor environmental quality maintenance such that the building can be immune

from sick building syndrome.

The high prevalence of respiratory symptoms can be a result of high prevalence of respiratory infection, thus the monitoring the sick-symptoms prevalence through the use of the Indoor Environmental Health and Comfort Analyzer developed in this chapter provides an indirect way to monitor the risk of respiratory illness or infection among the occupants in the indoor environment, as the symptom list inside the Indoor Environmental Health and Comfort analyzer included those symptoms of airborne infection. If the IEQ problem and the “stress at work” problem are solved while the building sickness score is still high, then it is more likely that those symptoms could be triggered by airborne pathogens, which cannot be sampled by building facility managers in an economical way at the present stage of technology, thus the risk of real “presence of pathogens” but not be able to confirm by present technology would be higher, and the phenomenon may be interpreted as “sick building syndrome” instead.

The Indoor Environmental Health and Comfort analyzer can also help building facility managers to monitor the IEQ level in terms of percentage of satisfaction. The IEQ equation is useful to help managers to improve the specific IEQ qualifiers and

create a better indoor environment for occupants. Based on the hypothesis proposed by Jones [1996], improving IEQ can sustain a normal immunity of human body, which may help to block the propagation of cross-infection.

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CHAPTER 4: AIR CLEANER PERFORMANCE EVALUATION

On the control of communicable disease transmission through airborne contagion, dilution ventilation serves as a common strategy to reduce the concentration of infectious droplet nuclei within an enclosed indoor atmosphere; however, ventilation system, although intended to create a safe and comfortable environment, may also contribute to spread of diseases by disseminating pathogens and allergens. Furthermore, the recommended ventilation rate for infection control is much higher than the quantity for managing healthy and comfortable indoor air quality. For instance, to avoid cross infection of tuberculosis among patient, a physician in the United State recommended a ventilation rate of 28 Litre per second per person in 1893 [BSOMES 2003]. The Centers for Disease Control and Prevention in the United States recommends a ventilation rate of 12 air changes per hour (ACH) for health-care facilities constructed in 2001 onward, while for facilities built before 2001, a ventilation rate of 6 ACH is recommended [CDC 2003]. The ventilation requirement may exceed the capacity of the mechanic ventilation systems in existing facilities, and may impose cost impact in terms of energy utilization. Use of air cleaners have been suggested as alternative way to achieve the equivalent air

changes for the purpose of reducing airborne infectious particles. This chapter presents the study on the performance evaluation of air cleaners.

4.1 Review on Air Cleaner Testing Standard and Guideline

The Association of Home Appliances Manufacturers (AHAM) in the United States suggests a method to quantify the performance of air cleaners for particulates removal inside test chambers, in terms of Clean Air Delivery Rate. The AHAM testing method determines the CADR for three different particulate matter challenges, including smoke, dust, and pollen. The Electrical and Mechanical Services Department (EMSD) in Hong Kong drafted a guideline for testing the performance of potable air cleaners in 2003, adopting a similar approach to the AHAM method. The guideline defines an Air Cleaning Rate to represent the performances on respirable suspended particulates (RSP) and total volatile organic compounds (TVOC) removal. The Air Cleaning Rate can be calculated on the same equation for CADR calculation as shown in equation 1. The Air Cleaning Rate is defined based on a mass balance analysis of air contaminants inside test chamber. The Air Cleaning Rate combines the air flow rate and the removal efficiency of the air cleaning element to become a single parameter that represents the performance of an air

cleaner as a whole system. While models and testing method for air cleaning performance in terms of particulates and VOC removal are well-established, bacteria removal performance is less reported. In this study, the performance of air cleaners on bacteria removal in field application is the main focus, which is evaluated base on the percentage of reduction on bacteria count with the use of air cleaner inside a room. Section 4.2 first reviews the air cleaning technologies available for the reduction of bacteria count in air, and section 4.3 reports a statistical method to evaluate the performance of air cleaners.

4.2 Review on Technologies Used in Typical Air Cleaners

Typical technologies adopted in air cleaners include ultraviolet germicidal irradiation (UVGI), ozone generation, high-efficiency particulate air (HEPA) filter, ionizers and photo-catalytic oxidation (PCO). Some air cleaners may adopt only one of the above-mentioned technologies, while some may employ a combination of two or more technologies. The following sections briefly account each of the technologies.

4.2.1 Ultraviolet Germicidal Irradiation

The use of UVGI for air disinfection has been studied from 1930s. Microbes are vulnerable to the effect of night near 2537 Angstroms (or 254nm, i.e. UV-C segment)

due to the resonance of this wavelength with the molecular structure of microbe [Kowalski 1997]. The ultraviolet light penetrates the organism's nucleus, disrupting the molecular bonds of its DNA and damaging the DNA of the micro-organism. Under such irradiation, the microbe loss its reproduction ability, and dies without leaving any new offspring [Russell 2003]. Experiment performed by Beggs et al. found that 97.19% of Staphylecoccus aureus were killed by UV device in the ward space when two 552W UV lamps were in operation [Beggs and Sleigh 2002]. A higher UV irradiance results in greater reduction in bacteria concentration. The effectiveness of UVGI in indoor environment and in HVAC system is well researched early since a hundred years by Niels Finsen, who use UV against tuberculosis, and become the winner of Nobel Prize for Medicine in 1903 [The Nobel Foundation, information retrieved in 2006], and new research articles appear continuously now [Kowalski et al. 2000, Noakes et al. 2004, Schafer et al. 2008], it is appropriate to use UVGI, a principal disinfection method, in practical use when there is no eye contact between the installation and building occupants.

4.2.2 Photo-Catalytic Oxidation (PCO)

Photo-catalytic oxidation use titanium Dioxide (TiO_2), a typical semiconductor catalyst, to generate hydroxyl radicals (OH•), which has high oxidation power for

oxidation process. For pure titanium dioxide catalyst, the presence of UV energy is required to generate hydroxyl radicals. The initial oxidative damage takes place in the cell wall of bacteria when it contacts with TiO_2 material. A series of oxidization will damage the inner cells of the microbe. Mineralization of bacteria can be observed in the experiments performed by Jacoby et al. [1998]. Besides micro-organisms, hydroxyl radicals can also oxidize volatile organic compounds (VOCs) and organic odorous substances adsorbed on the catalytic surfaces [Jacoby et al. 1996].

4.2.3 High Efficiency Particulate Air (HEPA) filters

High efficiency particulate air (HEPA) filters are made of fibrous media that captures microscopic particles from air passing through the filter. Typical HEPA filters can remove 99.97% of particles with 0.3 microns (which falls within the most penetrating particle size region) that pass through the filter. The particles with either larger or smaller size than 0.1 to 0.3 μm are less penetrating [Etkin 1995]. The "particle" size of typical pathogens is within 0.08 to 2 μm and theoretically HEPA is effective to bacteria and fairly effective on virus [Kowalski 1997]. However, quantitative data on real-world efficiencies on pathogens removal is limited [Harstad and Filler 1969, Thorne Burrows 1960, Gougeon et al. 1993]. Pathogens may not

behave as dry particulate, and may have a low affinity for attachment to glass fibre [Kowalski 1997]. In addition, HEPA filters only capture particles on the filtration media, the actual “removal” of bacteria and possibly virus on HEPA filters is not completed unless the filter is disposed. Frequent replacement of HEPA filters is required in environment with large dust loading and microbial loading, which add to the operating cost of the HEPA filtration system. In addition, the fan system in the air distribution system should be capable for the high pressure drop of HEPA filters.

4.2.4 Negative Ionization

Air contains electrically charged air ions produced in nature usually by radiation, for example radioactivity or cosmic radiation. Many types of equipment can produce ionization, including electrostatic precipitators, UV lamps, and ozone generators, but ionization may not be the intent of these systems. Air ions can also be generated with electric corona discharge, which uses a high voltage applied to sharp emitter points or grids to induce a strong electric field. Gas molecules enter the field will be ionized and acquire a charge of the same polarity of the electric field. Ionizers may be pulsed direct current, steady-state direct current or alternating current. Direct current devices produce positive or negative ionization depending on their charge. Alternating current devices produce bipolar ionization, which generates alternate

clouds of positive and negative ions within each cycle. Negative ionization is more common as a means of cleaning air [Kowalski 2006]. For the ionization of airborne microbes, it has been suggested that the growth of colonies of some micro-organisms is altered and the decay of aerosol is faster [Krueger and Reed 1976, Makela et al. 1979], the effect appears to result from the ionization of bioaerosols and micro-organisms carrying dust particles to settle more rapidly through enhancing agglomeration, creating larger particles out of small particles, thereby increasing settling rate. Ionization may also cause attraction between ionized particles and grounded surface. Negative air ionization has an effect on reducing the incidence of respiratory infection transmission, while it is species-dependent and can be affected by relative humidity [Estola et al. 1979, Happ et al. 1966]. Philips et al. [1964] found that a high concentration of air ions increases the exponential decay rates of aerosols of Serratia marcescens. Some success on the reduction of infections through negative ionization was reported in hospital wards [Chard 2005, McDowell 2003], in burn wards, classrooms and dental offices [Gabbay 1990, Makela et al. 1979]. Negative air ionization may also enhance the effectiveness of ozone at inhibiting microbial growth [Tanimura et al. 1997]

4.2.5 Chemical Disinfectants

4.2.5.1 Hypochlorite solution

Early in 1928 the use of bactericidal mist to control airborne respiratory infection was reported in the literature [Robertson et al. 1942]. Douglas et al. [1928] reported the use of electrolyzed sea water containing NaOCl with about 1% available chlorine, which provides a marked or complete killing of Bacillus coli dispersed in the air, in a concentration of 1 gram of chemical solution in two million cc. of air. Trillat [1938] tested a number of common bactericidal compounds at that period and found that certain germicidal agents are capable to causing death of airborne bacteria. Resorcinol and sodium hypochlorite were found to be satisfactory, while the use of hypochlorite produces odour, leaving resorcinol as the agent of choice. Despite this, Middleton and Gilliland [1941] reported the use of hypochlorite solution to control an epidemic of respiratory infections in army huts. In 1940 Andrewes et al. reported that a few viruses, including the influenza, are susceptible to the mist action from the use of bactericidal mists for air sterilization, as observed by the reduced infectivity of the pathogen among mice.

4.2.5.2 Glycol vapor

The use of other chemical agent, such as propylene and triethylene glycols for killing airborne bacteria and virus, was also reported in 1940s. Puck [1947] tested the mechanism of aerial disinfection by these glycols and suggested that the condensation of molecules of glycol vapor on to the bacterial particles leads to an accumulation of a lethal concentration of the bactericidal agent on the micro-organism. A low vapor pressure, high hygroscopicity, and toxicity for bacterial metabolism were the properties cited by Puck [1947] as being required of a compound if it were to be an efficient aerial disinfectant [Lester W et al. 1950]. A wide variety of micro-organisms, dispersed into the air from broth cultures, was found to be susceptible to the germicidal activity of the glycol vapors, including the *Staphylococcus albus* and *aureus*; *streptococcus hemolyticus*, group A and C; *Bacillus subtilis*; *Hemophilus influenzae* and *pertussis*; Friedlander's bacillus; and *Escherichia coli* [Bourdillon RB et al. 1948; Lester et al. 1952]. In addition, it was found that *Serratia marcescens* and *Salmonella pullorum* [de Ome 1944]; *Penicillium notatum* [Bigg and Mellody 1946]; and tubercle bacilli [Potter 1944] were killed when the glycol was atomized into atmosphere. Vaporized triethylene glycol is found to provide germicidal effect, which is effective against a considerable part of airborne microflora, including influenza virus. It is a non-irritant and nontoxic

substance that can be used in building environment [Jokl 1989].

On the effectiveness of reduction in bacteria, or incidents of infection in indoor environment with the use of glycol vapor, Hamburger et al. [1945] reported a 60% reduction when triethylene glycol vapor was used in hospital wards in Army Camp. Loosli et al. [1947] reported a similar reduction on bacteria count when using triethylene glycol vapor in infants' ward in a hospital, while the decrease of incidence of infections was not significant between the experiment ward and control ward. Bigg et al. [1944, 1945] applied the glycol vapors for chemical disinfection of air, attempting to control the respiratory diseases among military personnel, at which a reduction of 64% fewer infections were reported among the glycol-treated quarters. Harris and Stokes [1942, 1943, 1945] observed the effect of propylene, and later, triethylene vapor on the incidence of respiratory infection in a children's convalescent home. It was reported that only 13 infections was observed in the period using the glycol, while 132 infection was observed during the control period. These studies show that using chemical disinfectant can be a possible mean of minimizing the incidence of airborne infection.

One concern on the use of chemical disinfectant is that the agent should have no harmful effect on human being. While some biocidal chemicals are likely to be hazardous to human as well [Popendorf and Selim 1995], triethylene glycol was found to be non-toxic, non-irritating, odorless, tasteless and invisible [Robertson 1947], such that it can be used for air disinfection purpose in occupied space. Robertson et al. [1947] conducted tests for chronic toxicity of propylene glycol and triethylene glycol on monkeys and rats that no deleterious effects, either functional or organic, could be found among monkeys and rats that were exposed with propylene glycol vapor for periods of 12 to 18 months through vapor inhalation. For triethylene glycol, the monkeys and rats did not show pathological changes among the monkeys and rats exposed with triethylene glycol vapor for a period of 8 to 13 months of continuous exposure in an environment fogged with triethylene vapor. The clinical tests of effectiveness of triethylene glycol vapor for aerial disinfection can also provide evidence of the safeness of the disinfectant. In the studies by Harris and Stokes [1945], Hamburger et al. [1945] and Bigg et al. [1945], no untoward effects of the glycol were observed among the people exposed with triethylene vapor for periods ranging from several weeks to over a month. In the study by Loosli et al. [1947] no disturbance of skins or other organs were found among very young infants kept continuously for 5 to 6 months in an atmosphere containing bactericidal

concentration of glycol. It was considered relatively safe for the use of triethylene glycol vapor for air disinfection.

4.2.5.3 Traditional herb

Apart from the glycol vapor, the use of liquefied traditional Chinese herbs for air disinfection is also reported in the literature. Zhang and Yan [1992] reported the test by spraying solution of traditional Chinese herb in patient wards, at a concentration of 0.5 ml/m^3 to 1.5 ml/m^3. A reduction of 60% of bacteria count in air was reported. Antimicrobial properties of plant extracts and natural products have been intensively investigated in the literature [Grayer and Harborne 1994; Sohn et al. 2004]. In this study, a disinfectant with matrine ("Kushen", a component of the traditional Chinese medical herb Sophora flavescens) and spearmint (Mentha spicata) as active ingredients was tested for its performance of air disinfection, and the antimicrobial properties of these two herbs were reviewed as below. Extracts of the root of Sophora flavescens has been used as traditional medicine for microbial infection [Yagi et al. 1989; Yamaki et al. 1990]. Dried root of Sophora flavescens was found to have potent antibacterial activity against Gram-positive bacteria [Kuroyanagi et al. 1999], and antiviral effect against coxsackievirus B3 [Zhang et al. 2006]. For Mentha spicata (spearmint), Gangwar and Kumar [2006] tested the antibacterial

efficacy of the essential oil from leaves of Mentha spicata, and found that the essential oil reveals antibacterial effect on bacteria including Escherichia coli, Salmonella typhi, Proteus vulgaris, Staphylo-coccus aureus and Pseudomonas aeruginosa [Gangwar and Kumar 2006]. Similar observations were found in studies conducted by Sivropoulou et al. [1995] and Ela et al. [1996]. Rastogi and Mehrotra [1998] also suggested that spearmint has antifungal, antiviral, antimicrobial activity. Rasooli et al. [2008] conducted a test for antimicrobial activity of essential oils of Mentha spicata by disc diffusion method and confirmed antimicrobial effect on bacteria including Bacillus cereus, Escherichia coli and Staphylo-coccus aureus. These studies show the potential antibacterial effect for the disinfectant with essential oil extract from Sophora flavescens and spearmint.

4.2.6 Other Technologies

4.2.6.1 Botanical Air Purifier

The use of botanical extracts for air purification becomes more popular. In addition to the traditional herb extracts (as discussed in section 4.2.5.3), evaporation of botanical extracts solution to reduce environmental fungal load [Dennis 2003], or for the reduction of formaldehyde [Godish and Guindon 1989] has been reported in the literature.

4.2.6.2 Ozonation

Ozone systems that produce low levels of ozone in indoor air for air quality control are marketed in commercial application [Kowalski 2006]. Early since the study conducted by Elford and van den Eude [1942], ozone has been investigated as an aerial disinfectant while in the studies conducted in the twentieth century, for example the one conducted by Rodberg et al. [1991] and the 1942 study, the results are inconclusive. Ishizaki et al. [1986] suggested that relative humidity in the indoor air plays a major role on the biocidal effect of ozone. For studies conducted in the twenty-first century, Currier et al. [2001] used humidified air with 9000 ppm of ozone to decontaminate biological pathogen spores of *Bacillus subtilis* var. *niger*, and found that with 70% relative humidity, over seven logs of reduction can be achieved within 60 minutes. In another study, Khurana [2003] reported that frequent treatment with ozone at 9 ppm in air conditioning systems was sufficient to prevent microbial growth.

4.2.6.3 Activated carbon adsorption

Activated carbon adsorption is used mainly for the removal of gases and vapors. Carbon adsorption has some reported ability to remove botulinum toxin [Gomez et al.

1995]. The typical size of activated carbon pore size is typically 0.001 micron, which is too small to accommodate the smallest virus which is at least 0.01 micron in diameter. If the pore size were on the order of 0.05 microns, it is anticipated that activated carbon adsorption may have some effect in the removal of airborne viruses [Kowalski 2003], but the possibility is to be studied in future research.

4.2.6.4 Electrostatic precipitator with ionization

Electrostatic precipitators are commonly used to remove particles from airstreams at large steady flow rates, commonly found in industrial sector. For residential or other non-industrial applications, there are “electronic air cleaners” employing a small electrostatic precipitators and ionization function. Offerman et al. [1992] commented that these electronic air cleaner would have some value for the means of simply improving air quality and decreasing levels of dust, smoke and airborne microbes.

4.3 Air Cleaner Performance Test on Bacteria Removal

4.3.1 Description of Air Cleaners

The objective of this study is to quantify the effectiveness, in terms of the fractional reduction of bacteria count, resulting from the operation of air cleaners in residential settings. Three air cleaners were tested in this study. Table 4.1 describes the air

cleaning mechanisms and the recommended coverage area of these cleaners.

Table 4.1 Information on the air cleaners under investigation

Air cleaner	Mechanisms adopted	Coverage area
A	(1) Air ionization, (2) Composite filter containing (i) layer coated with Catechin and enzyme for inactivation of allergen, viruses and bacteria and (ii) Intense field dielectric plasma.	38 m^2
B	(1) HEPA filter (2) Activated carbon filter (3) Photo-Catalytic Oxidation (4) UVGI (5) Negative air ionization	21.3 m^2
C	Vaporized disinfectants (extracts from traditional herbs including matrine and spearmint)	Information not available

4.3.2 Site description and testing procedures

The tests were conducted in a flat inside a mechanically ventilated residential service apartment building with central air-conditioning system. The room has a floor area of 16.7 m^2 and a height of 2.7 m, such that the total volume is 45.3 m^3. During each test, there were three persons presence in the room, and all the windows were kept closed. The air temperature and relative humidity inside the test room were measured by TSI QTrak and the air change rate was measured by the concentration decay of the tracer gas. Sulphur hexafluoride (SF_6) was injected to the room, and the concentration of SF_6 was monitored continually by a photoacoustic gas analyzer Bruel and Kjaer model 1302. The air change rate of the room during the test is shown in table 4.2. The air-conditioning system was in operation and the window of the room was closed during all the test trials.

Table 4.2 Air change rate in the room during air cleaner test

Air cleaner test	Air change rate ($hour^{-1}$)		
	Minimum	Maximum	Average
A	0.60	0.68	0.64
B	0.67	0.76	0.72
C	1.21	1.30	1.26

Airborne bacteria samples were collected by Burkard Air Sampler at a constant flow rate of 20.0 litre per minute for 5 minutes and are allowed to grow on a suitable agar inside an incubator at a constant temperature of 30°C for 48 hours. After that the number of colonies formed on the surface of agar will be counted. the predominant bacterial genera were identified. One bacterial colony of each predominant genus was selected from the agar plate and subjected to a panel of biochemical tests including Gram's stain, catalase, and oxidase. These tests allow tentative classification of the bacterial species into genus level. This was followed by further identification using the relevant identification kit: RapID^{TM} NH System was used to identify Gram-negative cocci, RapID^{TM} ONE System was used to identify Gram-negative bacilli and oxidase-negative species, Rapid^{TM} NF Plus System was used to identify Gram-negative and oxidase positive species and Staphaurex (Remel, USA) was used to identify Staphylococcus aureus.

Bacteria sampling was conducted at two locations as indicated in figure 4.1. At stage 1 the background bacteria level was measured, and bacteria sampling was conducted at an interval of 1 hour for 8 hours. The air cleaner was switched OFF during this period. At stage 2, the air cleaner was switched ON, and the bacteria sampling was conducted to observe if a reduction on bacteria count occurred.

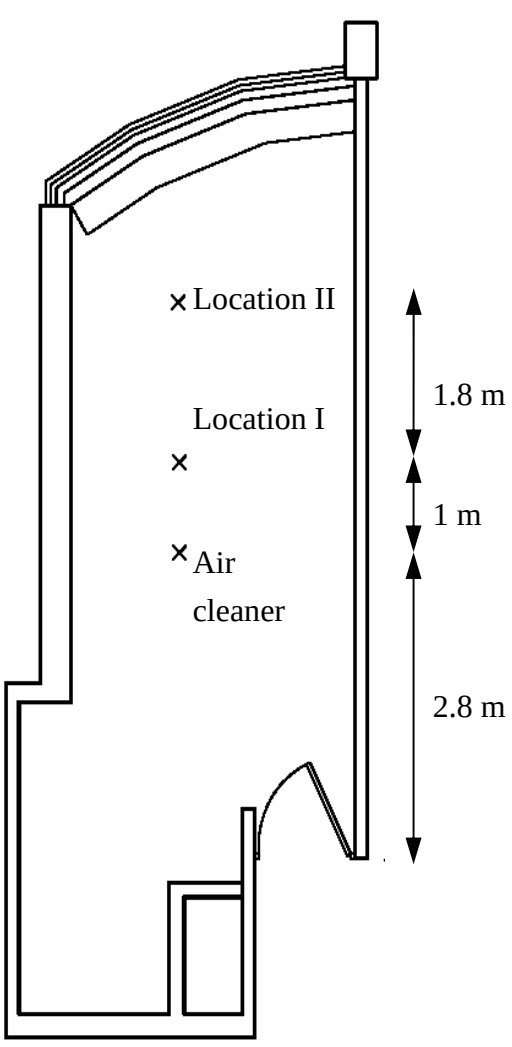

Figure 4.1 Layout of the test room

4.3.3 Results and Analysis

The bacteria count removal efficiency is defined as the ratio of reduction in bacteria count with the use of air cleaner, to the bacteria count without (or before) the use of cleaner (equation 4.1).

$$\text{Bacteria count removal efficiency} = \frac{\text{cfu}_1 - \text{cfu}_2}{\text{cfu}_1} \qquad \{\text{equation 4.1}\}$$

where cfu_1 is the indoor bacteria count, in terms of colony of forming unit, without the use of air cleaner, and cfu_2 is the colony of forming unit with the use of air cleaner.

The denominator of equation 4.1, $\text{cfu}_1 - \text{cfu}_2$, is determined by a statistical analysis on the measure data during the test. The mean values of bacteria count measured during the period with and without the use of air cleaner ($\overline{\text{cfu}_1}$ and $\overline{\text{cfu}_2}$) are determined respectively, and a one-tailed test of hypothesis about ($\mu_1 - \mu_2$) is conducted. The null hypothesis is H_0: ($\mu_1 - \mu_2$) = D and the alternative hypothesis is H_a: ($\mu_1 - \mu_2$) > D where D is the difference between the two population mean (one of the population is the bacteria counts obtained when the air cleaner was switched OFF, and the other population is the bacteria counts obtained during the operation of air cleaner). The test statistic is determined by equation 4.2, and the rejection region is $t > t_{0.05}$ for a 95% significance level.

$$\text{Test statistics}: \quad t = \frac{(\overline{cfu_1} - \overline{cfu_2}) - D}{\sqrt{s_p{}^2 (\frac{1}{n_1} + \frac{1}{n_2})}} \qquad \{\text{equation 4.2}\}$$

and $s_p^{\,2} = \dfrac{(n_1 - 1)\, s_1^{\,2} + (n_2 - 1)\, s_2^{\,2}}{n_1 + n_2 - 2}$ {equation 4.3}

where n is the sample population, s is the standard deviation of the sample, and s_p is the weighted average of the two sample variances, $s_1^{\,2}$ and $s_2^{\,2}$. Table 4.3 to table 4.5 show the result and the calculated percentage of reduction of total bacteria count for the three air cleaners.

Table 4.3 Bacteria removal percentage for air cleaner A

	Test period	Location I	Location II
No of samples collected when air cleaner is OFF, n_1	1	**8**	**8**
Minimum bacteria count	1	31	34
Maximum bacteria count	1	129	124
Mean bacteria count, $\overline{cfu_1}$	1	**78**	**78**
Standard deviation, s_1	1	**41**	**32**
No of samples collected when air cleaner is ON, n_2	2	**20**	**15**
Minimum bacteria count	2	7	9
Maximum bacteria count	2	60	60
Mean bacteria count, $\overline{cfu_2}$	2	**23**	**24**
Standard deviation, s_2	2	**14**	**15**
Degree of freedom, $n_1 + n_2 - 2$		26	21
Significance level		95%	95%
t - value		1.706	1.721
Difference between two samples, D		**37**	**38**
Test statistics		1.684	1.649
Air cleaner bacteria removal percentage		**47.7%**	**48.7%**

Table 4.4 Bacteria removal percentage for air cleaner B

	Test period	Location I	Location II
No of samples collected when air cleaner is OFF, n_1	1	**15**	**15**
Minimum bacteria count	1	42	36
Maximum bacteria count	1	136	120
Mean bacteria count, $\overline{cfu_1}$	1	**85**	**79**
Standard deviation, s_1	1	**25**	**30**
No of samples collected when air cleaner is ON, n_2	2	**24**	**24**
Minimum bacteria count	2	15	19
Maximum bacteria count	2	85	80
Mean bacteria count, $\overline{cfu_2}$	2	**46**	**46**
Standard deviation, s_2	2	**19**	**17**
Degree of freedom, $n_1 + n_2 - 2$		37	37
Significance level		95%	95%
t - value		1.688	1.688
Difference between two samples, D		**28**	**20**
Test statistics		1.573	1.660
Air cleaner bacteria removal percentage		**32.9%**	**25.4%**

Table 4.5 Bacteria removal percentage for air cleaner C

	Test period	Location I	Location II
No of samples collected when air cleaner is OFF, n_1	1	**13**	**13**
Minimum bacteria count	1	52	44
Maximum bacteria count	1	216	260
Mean bacteria count, $\overline{cfu_1}$	1	**129**	**135**
Standard deviation, s_1	1	**63**	**71**
No of samples collected when air cleaner is ON, n_2	2	**24**	**22**
Minimum bacteria count	2	13	24
Maximum bacteria count	2	219	141
Mean bacteria count, $\overline{cfu_2}$	2	**82**	**75**
Standard deviation, s_2	2	**40**	**29**
Degree of freedom, $n_1 + n_2 - 2$		35	33
Significance level		95%	95%
t - value		1.691	1.693
Difference between two samples, D		**19**	**32**
Test statistics		1.688	1.668
Air cleaner bacteria removal percentage		**14.7%**	**23.7%**

Among the three air cleaners under investigation, air cleaner A achieves the highest percentage of reduction on bacteria count, more than 45% for both the centre point in the room (location I, near the air cleaner) and location II (2.8m away of the air

cleaner). The claimed coverage area of 38m^2 is much larger than the area of room (16m^2) in this test means that air cleaner A should be capable to achieve air cleaning for both the centre location and the further location in our test room. Air cleaner B achieves a 32.9% reduction on bacteria count at the centre point (location I) while the reduction percentage drops to 25.4% at location II, when the bacteria samples were collected at the location further away from the cleaner. One possible explanation is the smaller claimed coverage area of 21 m^2 reported from air cleaner B, which results in marginal performance at a location further away from the cleaner. Air cleaner C employs vaporized Chinese herb extracts as disinfectant, and according to our result the bacterial removal percentage is relatively lower than the others employing air ionization and filtration as means of bacteria removal.

4.4 Air Cleaning Rate Estimation

In section 4.3 the effectiveness of air cleaners, defined by Nazaroff (2000) as the difference in indoor concentration due to air cleaning compared with the "no cleaning" case [Shaughnessy and Sextro 2006], is stated in equation 4.1 and calculated in section 4.3.3. Assuming that the indoor bacteria concentration is well-mixed and evenly distribution, and under a same generation rate of bacteria (both in indoor and outdoor), and a fairly constant outdoor air supply flow rate

during the entire testing period (before and during switching ON the air cleaner), the indoor bacteria concentration inside the room can also be estimated by applying a mass balance, and expressed by equations 4.4 and 4.5.

$$C_{noAC} = \frac{S + V \times \lambda_V \times p \times C_{outdoor}}{V \times (\lambda_V + \lambda_D)} \qquad \{\text{equation 4.4}\}$$

$$C_{AC} = \frac{S + V \times \lambda_V \times p \times C_{outdoor}}{V \times (\lambda_V + \lambda_D) + ACR} \qquad \{\text{equation 4.5}\}$$

Where C_{noAC} is the concentration when air cleaner is not in use, C_{AC} is the concentration when air clean is in use, S is the source generation rate, V is the volume of the room (m^3), λ_V is the outdoor air change rate ($hour^{-1}$), p is the penetration factor, $C_{outdoor}$ is the outdoor concentration, λ_D is the deposition loss rate ($hour^{-1}$), and ACR is the air cleaning rate achieved by the air cleaner (m^3/hour).

Substitute equations 4.4 and 4.5 into the effectiveness equation (4.6), the ACR can be estimated by equation 4.7, assuming all the parameters (except ACR) are not changed throughout the test.

$$\text{Effectiveness E} = \frac{C_{noAC} - C_{AC}}{C_{noAC}} \qquad \text{\{equation 4.6\}}$$

$$\text{Effectiveness E} = \frac{ACR}{V \times (\lambda_V + \lambda_D) + ACR} \qquad \text{\{equation 4.7\}, or}$$

$$ACR = \frac{E \times V \times (\lambda_V + \lambda_D)}{1 - E} \qquad \text{\{equation 4.8\}}$$

For the estimation of ACR for each air cleaner, the effectiveness (i.e. the bacteria removal percentage) of air cleaner is shown in table 4.3 to 4.5. The outdoor air change rate is shown in table 4.2. The deposition loss rate is to be estimated in section 4.4.1 below.

4.4.1 Deposition rate of bacteria

The deposition rate of bacteria mainly depends on the diameter. By identification of the predominant bacterial genera, a representative terminal velocity of the bacteria can be estimated. For each airborne bacteria sample collected during the air cleaner test, one bacterial colony of each predominant genus was selected from the agar plate

and subjected to a panel of biochemical tests including Gram's stain, catalase, and oxidase. These tests allow tentative classification of the bacterial species into genus level. This was followed by further identification using the relevant identification kit: RapID$_{TM}$ NH System was used to identify Gram-negative cocci, RapID$_{TM}$ ONE System was used to identify Gram-negative bacilli and oxidase-negative species, RapID$_{TM}$ NF Plus System was used to identify Gram-negative and oxidase positive species and Staphaurex (Remel, USA) was used to identify Staphylococcus aureus. For all of the agar plates collected during the air cleaner test, two species were found to be predominant; the first is *micrococcus* and the second is coagulate-negative *staphylococcus*. For micrococcus the typical size range is between 0.5 to 3 μm and for a typical coagulate-negative *staphylococcus,* the size range is between 0.4 to 1.5 μm [Kowalski 2006]. In this study, the diameter of 1.5 μm is selected for the estimation of terminal velocity and the deposition loss rate. Density of bacteria is estimated to be 1.1 times the water density, as suggested by Porter [1946]. The settling velocity can be calculated by equation 4.9.

$$V_{TS} = \frac{\rho_p d_p^{\,2} g C_c}{18\eta} \qquad \{\text{equation 4.9}\}$$

Where V_{TS} is the settling velocity, ρ_p is the density of infectious particle (1100

kg/m^3 [Porter 1946]), d_p is the diameter of droplet nuclei, g is the gravity (9.81 Nm^{-2}), C_c is the slip factor (equation 1.6), and η is the viscosity of air (1.81×10^{-5} Pa・s)

$$C_c = 1 + 0.8715 \times \frac{\lambda_o}{d_p} \times \frac{T}{P} \qquad \{\text{equation 4.10}\}$$

Where λ_o is 0.066 μm for air, T is air temperature (293 K) and P is atmospheric pressure (101.325 kPa). For a bacteria with diameter of 1.5 μm, the slip factor C_c is 1.111, and the settling velocity is estimated to be 0.3 m/hour. For a room height of 2.7 m, the deposition loss rate is 0.111 hour $^{-1}$.

4.4.2 Air cleaning rate on bacteria removal

The air cleaning rates for the air cleaners under test are presented in table 4.6. The effectiveness is the average value of location I and location II as shown in figure 4.1. On the species identification, Staphylococci is selected as an indicator for air cleaner performance testing, since it is responsible for community-acquired pneumonia (lung inflammation) among immuno-compromised persons. The testing result is useful, at least for these needed persons, if the engineer needs to create an immune indoor environment for them.

Table 4.6 Air Cleaning Rate of the three air cleaners (Total bacteria)

	Air cleaner		
	A	B	C
Average Effectiveness, *E*	0.482	0.292	0.192
Room volume, *V*	45.3 m^3		
Outdoor air change rate, λ_V	0.63 $hour^{-1}$	0.72 $hour^{-1}$	1.26 $hour^{-1}$
Deposition loss rate, λ_D	0.11 $hour^{-1}$		
Air cleaning rate on indoor total bacteria, *ACR*	31.23 m^3/hr	15.49 m^3/hr	14.76 m^3/hr
Equivalent air change rate contributed by air cleaner	0.69 $hour^{-1}$	0.34 $hour^{-1}$	0.33 $hour^{-1}$

Table 4.7 Air Cleaning Rate of the three air cleaners (Staphylococci)

	Air cleaner		
	A	B	C
Room volume, *V*	45.3 m^3		
Outdoor air change rate, λ_V	0.63 $hour^{-1}$	0.72 $hour^{-1}$	1.26 $hour^{-1}$
Deposition loss rate, λ_D	0.11 $hour^{-1}$		
Air cleaning rate on Staphylococci	30.4 m^3/hr	13.2 m^3/hr	12.9 m^3/hr

4.5 Chapter Summary

This chapter reviews the currently available standards for testing performance of air cleaners, and the technologies for bacteria removal adopted by commercially available air cleaners. In view of a lack of information on bacteria removal performance from the manufacturers of air cleaner, this chapter adopts field performance evaluation approach, and proposes a statistical method to test the bacteria count removal performance when the air cleaner is applied in a typical air-conditioned room. This offers a common platform for the test of air cleaning 'black boxes' employing a combination of various air cleaning technologies. The effectiveness and the air cleaning rate of the air cleaner is tested using bacteria species that are typically found in indoor environment, and in this test *Micrococcus* and coagulate-negative *staphylococcus* are predominant. To investigate the role of air cleaners on reducing the risk of airborne infection like measles, tuberculosis or influenza accurately it requires an air cleaning rate estimated by using the real pathogen during the air cleaning test. While in this study the available resource cannot support a performance test using the specific pathogen, the use of indoor bacteria in this study can provide an initial estimation of equivalent air change rate produced by the air cleaner against indoor microbes, such that the contribution by the air cleaner can be compared with outdoor air ventilation, deposition loss or air

filtration. In our test an equivalent air change rate of 0.3 to 0.7 ACH is estimated for the air cleaners under the test. For air cleaner B and C the equivalent air change achieved is less significant compared with the air change rate achieved by outdoor air ventilation (as investigated in chapter 7). On the whole, this chapter provides a method to test the degree of contribution on reducing the bacteria count in the indoor environment through the measurement of equivalent air change rate. While the test result only provides performance information for a specific room, for real engineering application the field performance data at the site (which need air purification) is far more important than a generalized manufacturers' performance data. This study also proposes the bacteria count of Staphylococci as air cleaner performance testing criteria, the species that is the most dominant for community-acquired pneumonia infection among immuno-compromised persons.

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CHAPTER 5: TESTING OF FILTRATION PERFORMANCE OF AIR FILTERS

On the management of safe indoor air quality, air filtration through the use of high efficiency filters can protect against airborne pathogens in indoor environment. For non-pathogenic particulates, epidemiological researches have shown that presence of suspended particulates in air can also increase the rates of hospital admission, morbidity, and mortality [Dockery and Pope 1994, Seaton el al. 1995, Ministry of Environment B.C. 1997]. The World Health Organization [WHO 1997] based on her study of exposure to indoor air pollutants has reported that no definite threshold concentration can be indicated below which the effects do not occur. Ambient dust often follows air stream into buildings, however the amount of outdoor dust transmitted indoor depends on air change rate [Tung et al. 1999, Chao and Tung 2001], geometry of building gaps, and size spectrum of particles [Liu and Nazaroff 2001, Chao et al, 2003]. In term of mass concentration, fine dust ($PM_{2.5}$) is dominated in indoors because larger size particles are removed by the processes of interception and impaction during airflow across building gaps. Nevertheless, the mechanism of diffusion also plays a main role in removing ultra fine dust.

Hong Kong is a highly populated city and is located in a subtropical area. The population of the city is close to 8,000,000. In hot summer, ambient temperature and humidity are high enough exceeding the comfort zone. To achieve thermal comfort, giant HVAC systems are used in commercial buildings but mini air conditioners are applied in residential apartments. There are two types of air conditioners available on the market. One is a window type air conditioner with air-flap to control venting of air as shown in Figure 5.1. The other is commonly called a “split unit”, of which the air-flap design is disabled to limit outdoor fresh air drifting in. The air change rate provided by the split unit is smaller than that of air conditioner. Unless otherwise indicated, “air conditioner” refers to the window type air conditioner.

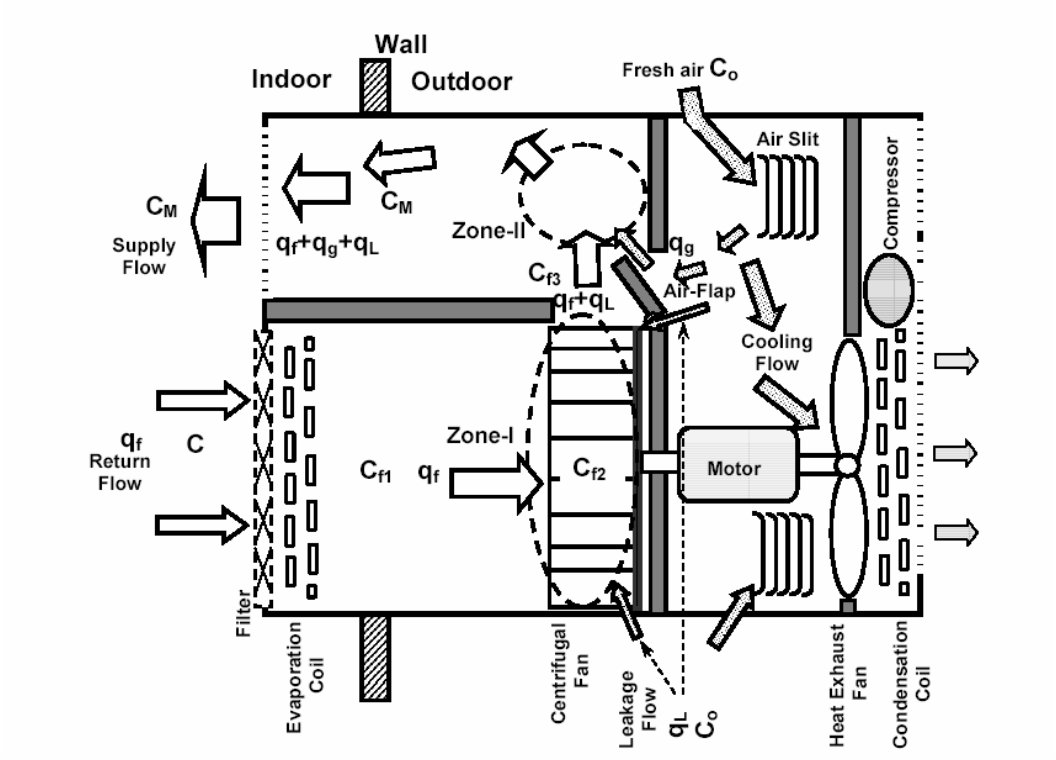

Figure 5.1 Schematic diagram of a typical household the air-conditioner unit

If we assume that a typical family in Hong Kong with 4 members sharing one air conditioner per apartment, the total number of air conditioners and split units is estimated to be more than 2,000,000. According to walkthrough inspections at 100 high-rise residential buildings, there are 90% of apartments equipped with air conditioners, 9% with split units, as well as 1% without any installation. Air conditioners have the ability to filter air of a function that was originally designed to protect the unit from soiling. Recently, some of residents prefer using an air conditioner instead of air cleaner to remove suspended particulates for convenience and to minimize space utilization. The American Society of Heating,

Refrigerating and Air-Conditioning Engineers (ASHARE) has provided a sophistic procedures in rig test to examine the performance of cleaning devices to (1) measure the ability of air cleaning device in reducing the staining potential of atmospheric dust from test air named ASHRAE dust-spot efficiency; and to (2) measure the ability of cleaning device in removing synthetic dust from test air so called as ASHRAE weight arrestance [ASHRAE 52.1-1992]. Since filter efficiency is particle size-dependent, ASHARE has further provided a set of practical standard procedures to evaluate the performance of a cleaning device on different particle sizes [ASHRAE 52.2-1999]. Three different size ranges of 0.3-1, 1-3, and 3-10μm were used in evaluation. From the experimental particle size-efficiency curves, a term of Minimum Efficiency Reporting Value (MERV) was defined to award the tested filter. Other than ASHRAE, the Association of Home Appliance Manufacturers [AHAM, AC-1-2002] presents a systematic method to examine the performance of air cleaner. A specified chamber was designed to examine the air cleaner on target particulate including generated dust, tobacco smoke, and pollen grain. An exponential index, Clean Air Delivery Rate (CADR), obtained from the decay profile of suspended dust was used to justify the performance of the cleaning device. While the standard procedures and methods provided by ASHARE and AHAM are excellent, the procedures and

methods can merely be carried out in laboratories equipped with specified facilities. Furthermore, the influence of ventilation rate on indoor dust due to building gaps, open air-flap, and leakage of centrifugal fan must be considered. Here we take the approaches of ASHRAE and AHAM and modify them in the study.

5.1 Test of fine dust removal efficiency of a/c unit air filters

5.1.1 Methodology

Indoor fine dust concentrations were measured by an aerosol monitor (TSI DustTrak, Model 8520). To discriminate particulate size, a $PM_{2.5}$ impactor was attached behind the sampling inlet of the monitor. Since the monitor used was factory calibrated based on light scattering of Arizona Test Dust, the test dust may not have similar characteristics to the particulates of residential buildings in Hong Kong. Therefore, the monitor was re-calibrated against by non-viable multi-stage Anderson Cascade Sampler (manufactured by Graseby Anderson, USA) through a series of experiments on twelve residential premises before the measurement. The calibrated reading was equal to DustTrak reading divided by 1.94, while the coefficient of determination R^2 was 0.9047 [Tung 2001].

The size spectrum of indoor particles falls within a wide range. It is mainly classified into three different size modes, namely ultra-fine (≤0.1μm), accumulation (0.1-2μm), and coarse (>2μm), in which characteristics vary from mode to mode [Nazaroff 2004]. For example, gravitational force is dominated in coarse mode particles but Brownian diffusion is recognized as a significant factor in deposition for those particles in accumulation and ultra-fine modes. Nazaroff [2004] stated that there is no simple equation to govern the characteristics of particles lying in three modes. Modeling the characteristics of particles should be according to the specific mode. The path of air flow between the sampled room and the air conditioner is shown in Figure 5.2. In the absence of the vigor activities like cooking, incense burning, smoking, and housekeeping, rate of change of fine dust in an air conditioned room can be represented by Equation 5.1.

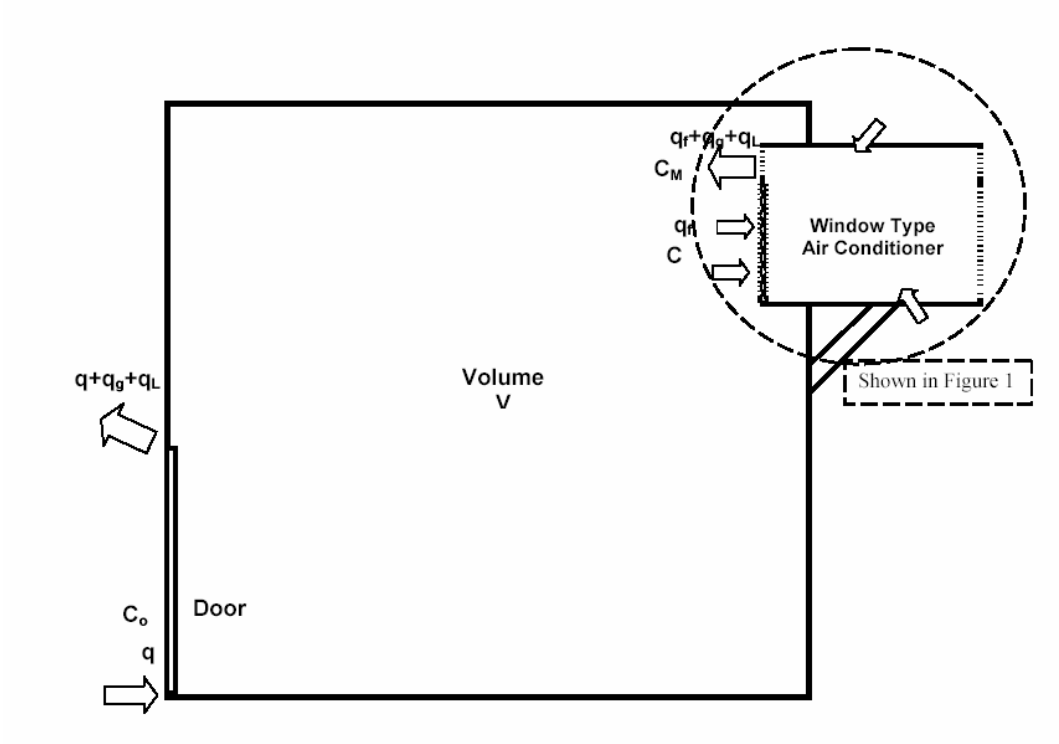

Figure 5.2 Schematic diagram of the test room with window-type air-conditioner

$$\frac{dC}{dt}=\left[\frac{pq+(1-\eta_C)p_L q_L+p_g q_g}{V}\right]C_o-\left(\frac{q+q_L+q_g}{V}\right)C-\left(\frac{\eta_F+\eta_C-\eta_F\eta_C}{V}\right)q_f C-\left(\frac{\sum\sigma_j U_j}{V}\right)C$$

{equation 5.1}

In Equation 5.1, the re-suspension of fine dust is negligible when compared with coarse particles [Thatcher and Layton 1995]. Besides, the influence of the re-suspension of fine dust is much less than the loss rate contributed by a running air conditioner. The first term on the right hand side of Equation 5.1 represents the entrance of outdoor fine dust from building gaps, centrifugal fan house gaps,

and the air-flap; the second term describes the escape rate of indoor fine dust; the third indicates the loss of fine dust caused by the filter mat and fan house, and the last term shows the lump sum of indoor fine dust deposited on to the internal surfaces per unit time, including the floor, walls, ceiling, and furniture. Here, C is the indoor fine dust concentration and outdoor is denoted by C_o ($\mu g.m^{-3}$); t is the elapsed time (hour); p, p_L, and p_g, are the penetration coefficients of fine dust respect to building gaps, house of centrifugal fan gaps, and air-flap opening (dimensionless); η_F is the filter efficiency of the air conditioner (dimensionless); η_C is the dust collection efficiency caused by centrifugal fan and its house (dimensionless); V is the effective volume of the sampled room (m^3); σ_j is the exposed area of indoor material-*j* (m^2); U_j is the deposition velocity of fine dust on to material-*j* ($m.h^{-1}$); q is the fresh air flow across the building gaps ($m^3.h^{-1}$); q_L is the fan house leakage flow ($m^3.h^{-1}$); q_g is the air flow through the open air-flap induced by running centrifugal fan ($m^3.h^{-1}$); and q_f is the return flow created by the centrifugal fan ($m^3.h^{-1}$). The velocities of air flow at the faces of supply and return are respectively measured in the pattern of 4-point and 9-point matrix by an anemometer (THERMO-ANEMOMETER DATALOGGER, Model DTA4000). If the initial concentration of fine dust C_i is given, the solution of Equation 5.1 is presented by Equation 5.2.

$$C = (C_i - C_\infty)e^{-(EI)t} + C_\infty \qquad \{\text{equation 5.2}\}$$

where

$$C_\infty = \left[\frac{pq + (1-\eta_C)p_L q_L + p_g q_g}{(q + q_L + q_g) + (\eta_F + \eta_C - \eta_F\eta_C)q_f + (\sum \sigma_j U_j)}\right] C_o \qquad \{\text{equation 5.3}\}$$

$$EI = \left(\frac{q + q_L + q_g}{V}\right) + \left(\frac{\eta_F + \eta_C - \eta_F\eta_C}{V}\right) q_f + \left(\frac{\sum \sigma_j U_j}{V}\right) = (Ach)_{Room} + \Phi_F + D_{Loss}$$

$$\{\text{equation 5.4}\}$$

where

$$(Ach)_{Room} = \frac{q + q_L + q_g}{V} \qquad \{\text{equation 5.5}\}$$

$$\Phi_F = \frac{Q_{Eff}}{V} \qquad \{\text{equation 5.6}\}$$

$$D_{Loss} = \frac{\sum \sigma_j U_j}{V} \qquad \{\text{equation 5.7}\}$$

$$Q_{Eff} = (\eta_F + \eta_C - \eta_F\eta_C)q_f \qquad \{\text{equation 5.8}\}$$

$$\eta_p = (\eta_F + \eta_C - \eta_F\eta_C) \qquad \{\text{equation 5.9}\}$$

Q_{Eff} is the effective air flow rate of the air conditioner, which is less than or

equal to q_f. η_p is the effective fine removal efficiency of the air conditioner including η_F and η_C. The exponential factor of Equation 5.2, EI, is denoted as fine dust exponential decay index and is important to the decay of fine dust. EI, shown in Equation 5.4, is the value representing the performance of the air conditioner Φ_F in removing fine dust, air change rate $(\mathrm{Ach})_{\mathrm{Room}}$, and indoor fine dust deposition rate D_{Loss}.

The parameters of Φ_F, $(\mathrm{Ach})_{\mathrm{Room}}$, and D_{Loss} can be obtained from site measurements following the protocols of that the indoor real-time concentrations of fine-dust are monitored on Day-I (target on D_{Loss}), Day-II (for Φ_F, without additional filter), and Day-III (for Φ_F, with additional filter). On Day-I, the window and door of sampled room were fully opened for at least one hour before sampling in order to balance the indoor/outdoor dust levels. Then, maintaining the air conditioner at off-mode, switched the air-flap to the vent-off position, closed the window/door, dosed tracer gas smoothly, and sealed the gaps of window and door tightly. On Day-II, the window and door were re-opened again, the air-flap was switched to the vent-on position to simulate the practice of a room user, the air conditioner was turned on with the fan speed set to high, the window and door were closed once more, dosed tracer gas and then sealed the

room gaps. Day-III was designed to examine the effects of an additional filter on dust removal. On Day-III, the original filter was retained within the air conditioner filter carriage. The sampling procedures remained the same as Day-II, except with the use of an additional filter to cover the return of the air conditioner completely. In the determination of air change rate $(\mathrm{Ach})_{\mathrm{Room}}$, the tracer gas decay method was employed [Thatcher and Layton 1995, Chao and Tung 2001]. The tracer gas is a non toxic carbon dioxide gas which was dosed up to 2000–2500ppm in each scenario. The gas was measured by TSI Q-Trak (Model 8551). The logging intervals of fine dust and tracer gas were set as one data per minute. The detail background information of five sites is summarized in Table 5.1.

Table 5.1 Information of sites

Site code	Location	Terrain
A	Sha Tin	Near a small road
D	Kwun Tong	Next to a hillside
F	Tseng Kwan O	Near a hillside
G	Hung Hom	Surrounded by residential buildings
K	Tsz Wan Shan	Surrounded by residential buildings

During analysis, the least squares fitting technique was used to obtain the corresponding exponential values from the decay profiles of dust and tracer gas via Equation 5.2, since the initial and steady state concentrations of fine dust/tracer gas are inspected from the decay curves. The least squares fitting analysis is a common objective method to determine the optimized curve from measured data [Tung et al. 2006]. With the help of Equation 5.4 to 5.9, the performance and the effective fine dust removal efficiency of air conditioner can be determined. Based on same approach on fine dust, the values of air change of the room can be quantified via Equation 5.2 but with C_i replaced by initial concentration of CO_2 and C_∞ by the outdoor concentration of the gas.

5.1.2 Results

5.1.2.1 Air change rate in the test room

The summary of measurements on air change rates is presented in table 5.2 to table 5.4. It was found that the values of air change rates measured at sealed modes were the smallest. The largest value of ventilation rate occurred in the presence of additional filtration and the smallest was found in sealed mode, while the normal filtration results fell in between the others. Indeed, the air-flap was designed to increase the ventilation rate of in the room while the air conditioner

is running.

Table 5.2 Site measurement result for day 1, window and door sealed

Site code	Room area (m^2)	Height (m)	ACH ($hour^{-1}$)	DI ($hour^{-1}$)	D_{Loss} ($hour^{-1}$)
A	4.8	2.5	0.52	0.90	0.38
D	5.66	2.44	0.15	0.60	0.45
F	3.96	2.5	0.45	0.80	0.35
G	6.16	2.5	0.21	0.78	0.57
K	10.11	2.5	0.27	0.45	0.18

Table 5.3 Site measurement result for day 2, air-conditioner switched ON

Site code	Room area (m^2)	Height (m)	ACH ($hour^{-1}$)	DI ($hour^{-1}$)	η_{p1}
A	4.8	2.5	0.95	2.22	2.91%
D	5.66	2.44	0.64	1.55	2.39%
F	3.96	2.5	1.70	3.35	3.27%
G	6.16	2.5	0.52	1.85	3.18%
K	10.11	2.5	0.57	1.30	2.21%

Table 5.4 Site measurement result for day 3, a/c switched ON with extra filter

Site code	Room area (m^2)	Height (m)	ACH ($hour^{-1}$)	DI ($hour^{-1}$)	η_{p2}
A	4.8	2.5	1.70	6.60	18.51%
D	5.66	2.44	2.32	3.95	13.48%
F	3.96	2.5	2.80	6.30	24.15%
G	6.16	2.5	1.74	6.29	21.85%
K	10.11	2.5	1.22	4.20	14.78%

At normal filtration, the increased air change rate is composed of induced air flow and a small amount of leakage flow. The induced air flow drifts from the air-flap (see figure 5.1) and a small amount of the leakage flow comes from the gaps of the fan house. Figure 5.2 is a schematic diagram to indicate the path of air flow between the sampled room and air conditioner. A driving force of the induced flow can be described by Bernoulli's Equation. Without considering the pressure drop across the centrifugal fan, the total pressure of the main return flow should be considered a constant along the flow. It is approximately equal to the sum of dynamic and static pressures of the flow itself, when the pressure difference ($\rho_a g \Delta h$) caused by the height difference is neglected. The density of

air flow and the height difference between return and supply are represented by ρ_a and Δh, respectively. At the outlet of the centrifugal fan, the main flow is accelerated and departed from Zone-II, indicated in Figure 5.1. Based on Bernoulli Equation, the flow accelerated at the outlet of fan is equivalent to reduce the static pressure at Zone-II. Air pressure at the right hand side of air-flap becomes higher than Zone-II allowing the static pressure at Zone-II to become low enough to suck outdoor fresh air from the air-flap. The flow created by this mechanism is as the so-called induced flow.

With the additional filter, the scenario is drastically different from that of induced flow. The application of an additional filter resulted in a larger ventilation rate as compared to normal filtration, while the speed of return flow was notably reduced by the additional filter. Unexpectedly, with the exception of Site-F, the air change rates increased by a magnitude of 2 to 4 times than normal filtration (see Table 5.2). The increase of air change rate with additional filtration is believed to be due to the contribution of the increase of leakage flow from the fan house, while the additional filter caused the flow drop at return. The drop makes running fan in flow starvation that creates a great negative pressure at Zone-I. In order to minimize the negative pressure at Zone-I, more fresh leakage

air flow was required from the gaps of the fan house. Comparatively, the negative pressure created at Zone-I was larger than the suction pressure generated at Zone-II. If the gaps of fan house were wide enough, the leakage flow may contribute a larger portion of fresh air than induced flow. As a result, the air change rate measured with the additional filter is larger than that of normal filtration. This phenomenon may not occur in an ideal situation, if the fan house is without gaps or holes.

5.1.2.2 Deposition rate

Deposition velocities of particles indoors depend on the sizes of the particles, gravitational attraction, surface interactions, diffusion effects, and air movement. Polymeric or plastic materials rubbed by dry clothes can easily generate electrostatic charges which will induce attraction to the boundary particles. It is favor to deposition of fine dust indoors. The effect is particularly dominated at low humidity environments. Particles with higher density and large diameters can settle faster than fine size aerosols due to gravitation attraction, but diffusion is often considered one of mechanisms in removing fine particles [Hinds 1999, Chao et al. 2003]. Surface interactions can affect particle loss. Cold objects often allow particles to deposit on their surface, unlike warm surfaces. This

phenomenon is called the thermophoresis effect, which states that the movement of gas molecules and tiny particles drift along temperature gradients, from hot to cold region. Nazaroff and Cass [1987] studied the phenomenon of dust deposition on a vertical isothermal flat plate and they reported that fine particles easily deposit on cold surface rather than warm one because of the thermophoresis effect. Furthermore, the deposition rate of particles is influenced by room air movement. It has been investigated by Thatcher et al. [2002] who studied the relationships of the deposition rate between various particle sizes and air movements at different future settings. They found that deposition rate seems to be proportional to air movement and particle size. The mechanisms of deposition are very complex and a detailed investigation on the mechanisms of deposition velocities against dust spectrum is beyond the scope of our study. In our study, the deposition rates of fine dust were estimated using the mean of transient decay profiles suggested by Nazaroff [2004]. From the decay profiles, the deposition rates can be simply calculated via Equation 5.2 and 5.4, made easier as the air change rate of the room $(\mathrm{Ach})_{\mathrm{Room}}$ was determined by tracer gas test and the removal rate of air conditioner Φ_{F} is zero at off mode. Indoor fine dust deposition rates (D_{Loss}) at five sites were measured in the range of 0.18 to 0.57 $hour^{-1}$, as shown in Table 5.2. From the table, Site-K had the smallest

deposition rate at 0.18 $hour^{-1}$ unlike Site-G, which had a rate of 0.57 $hour^{-1}$. The difference is probably due to the inherent characteristics of each site. From our site visits, it was observed that the volume of Site-K is larger than Site-G, and Site-G is more fully furnished than Site-K. The surface to volume ratio at Site-K was considered to be smallest among the sites. Hence, Site-G had the highest deposition rate and Site-K is the smallest. The other three sampled rooms had moderate deposition rates in comparison.

5.1.2.3 Fine dust exponential decay rate

In everyday life, a dust decay curve is not commonly observed in a natural vented building and fluctuates with outdoor concentrations. Air change rate is one of the parameters in the transmission of outdoor pollutants [Tung et al. 1999, Chao and Tung 2001]. These studies have illustrated that indoor and outdoor concentration ratio is a function of air change when contaminants cross a building's shell. In Hong Kong, the residential apartments are roughly categorized into three typical classes: luxury-, middle-, and low-rank buildings. Luxury- and middle-ranks have better air tightness performance than low-rank apartments. In our study, no luxury apartments were selected in the measurements. For the aim of obtaining a systematic decay profile, sealing

became a necessary procedure to avoid over-leakage. Gaps of windows and doors were sealed tightly. The results of the measurements are summarized in Table 5.2. Since the profiles of dust and tracer gas at each of the five sites have similar patterns, the results of measurements at Site-A were selected for demonstration. Figures 5.3 to 5.8 illustrate the decay curves recorded while the sites were sealed, at normal filtration, with the additional filter, and their corresponding tracer gas curves, respectively.

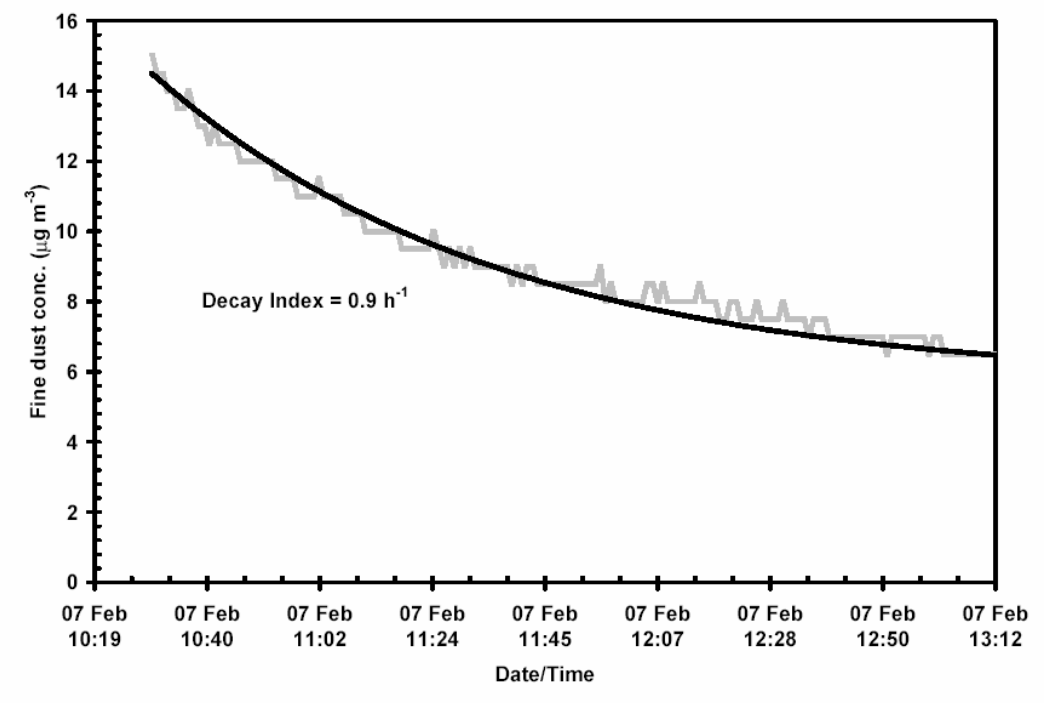

Figure 5.3 Fine dust decay profile for site A sealed mode

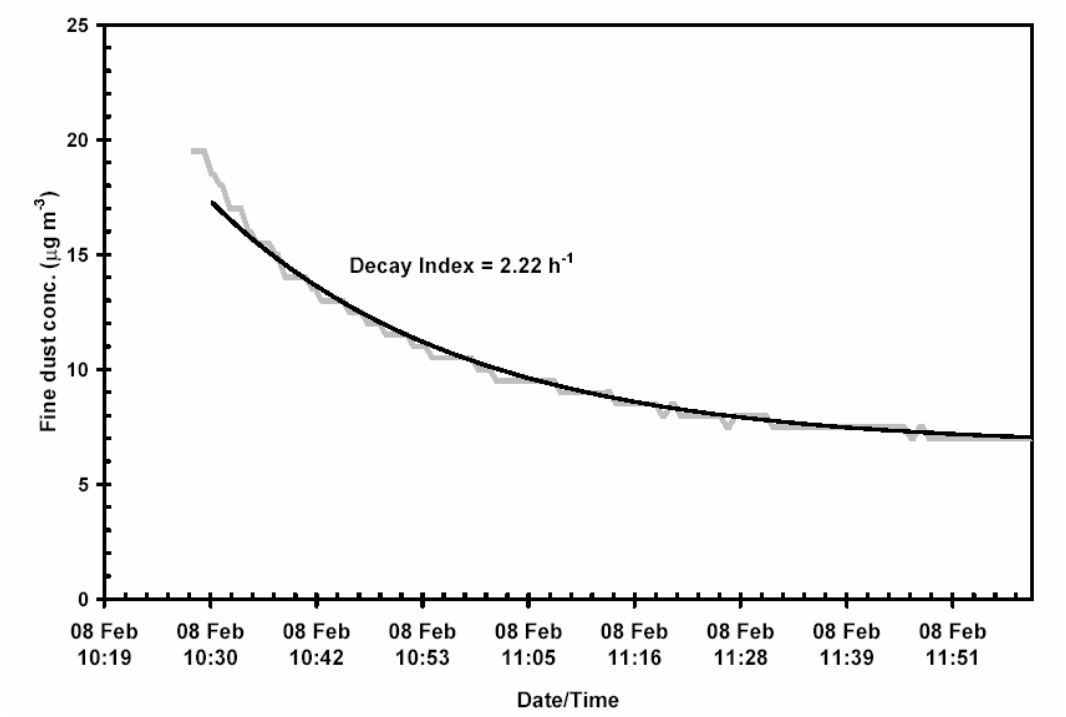

Figure 5.4 Fine dust decay profile for site A, air-conditioner switched ON using a/c unit filter

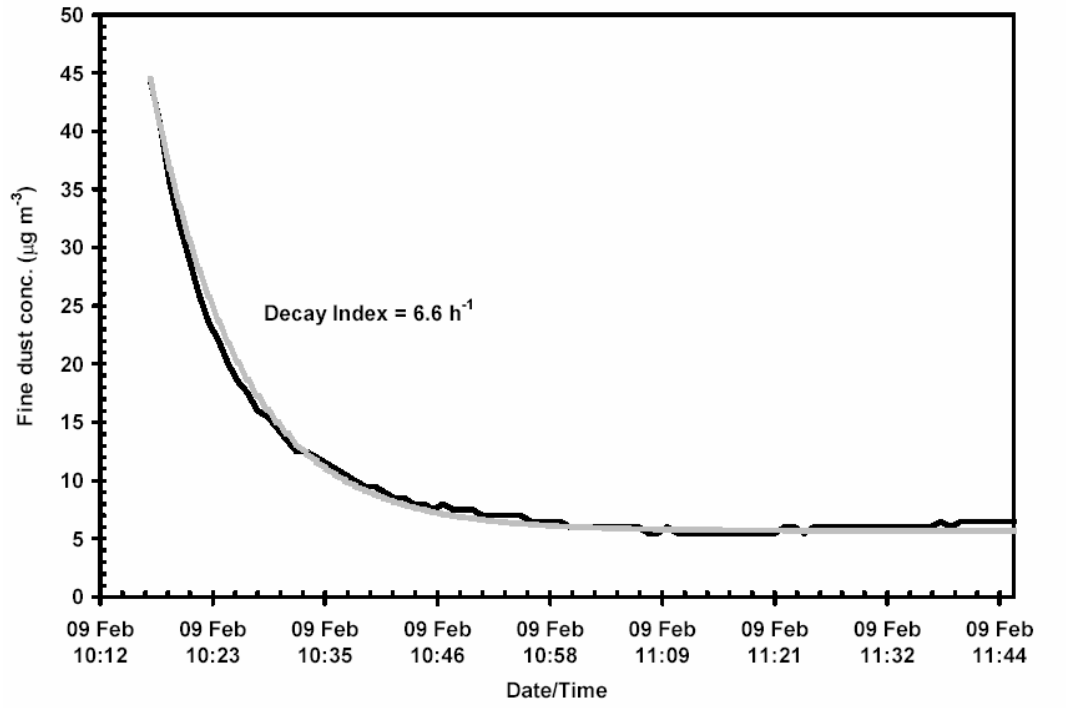

Figure 5.5 Fine dust decay profile for site A, air-conditioner switched ON, with extra filter

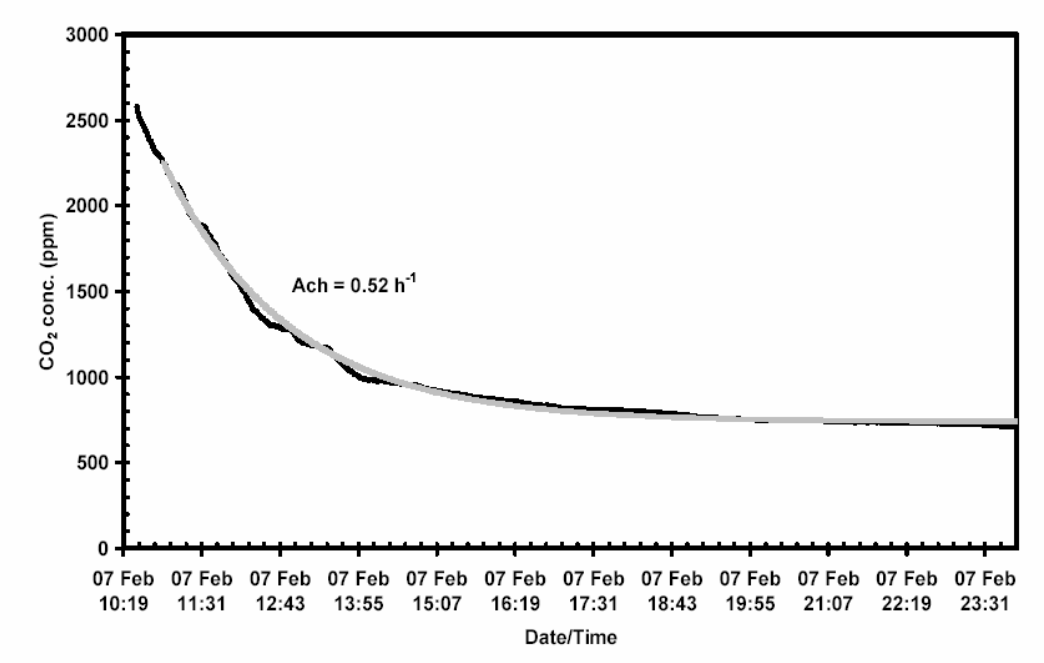

Figure 5.6 CO_2 tracer gas decay profile for Day-I, sealed mode

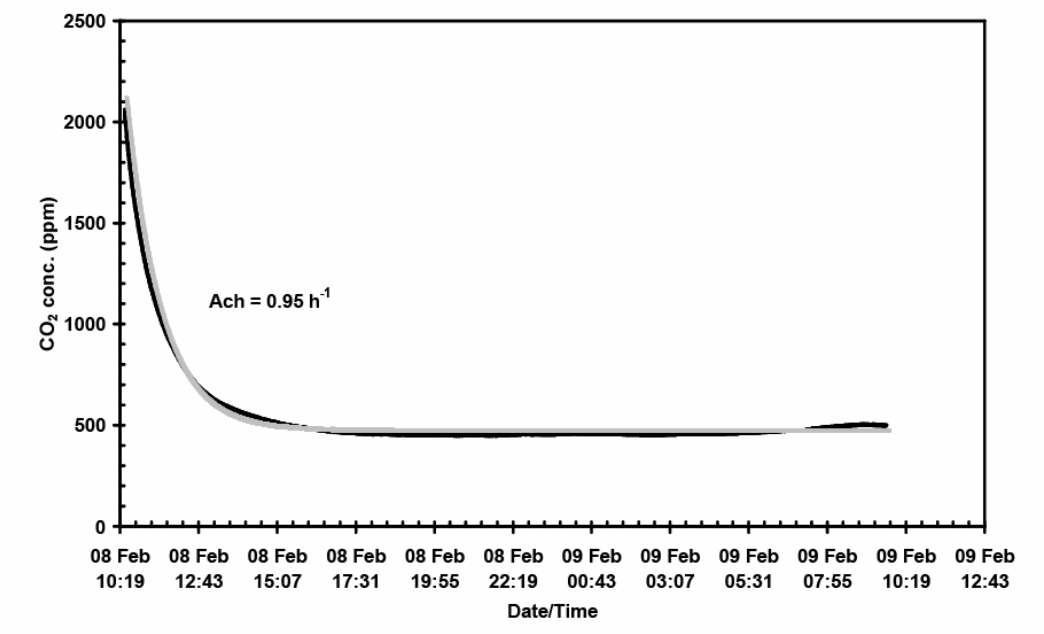

Figure 5.7 CO_2 tracer gas decay profile for Day-II, a/c ON using a/c unit filter

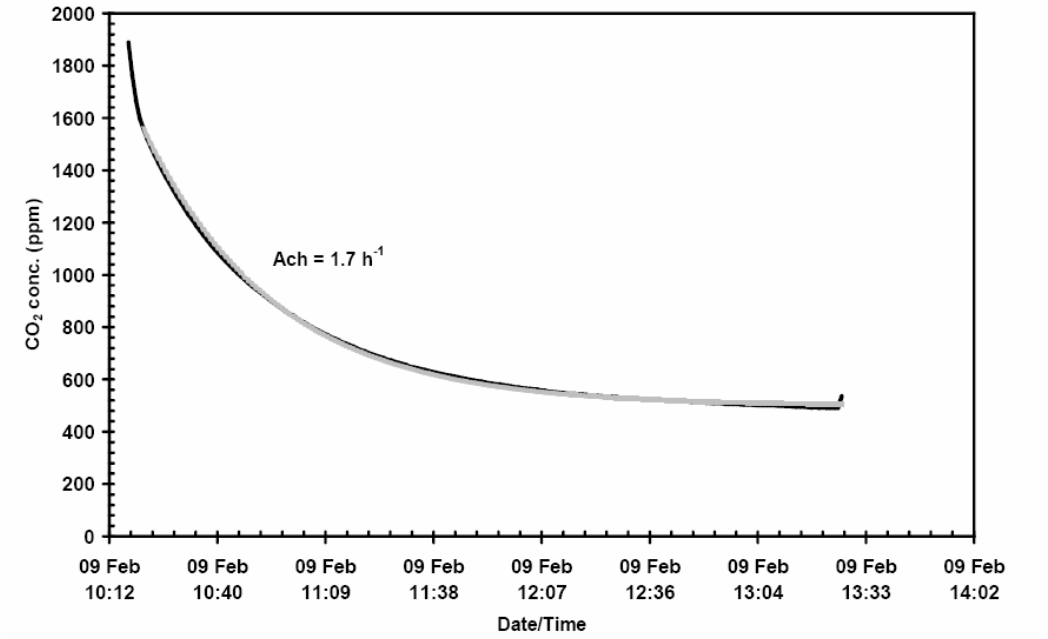

Figure 5.8 CO_2 tracer gas decay profile for Day-III, a/c ON using extra filter

The effect of sealing is accepted while the background ventilations of sampled rooms were reduced to below 0.5 hour^{-1}. The exponential decay indexes measured in when the rooms were sealed, at normal filtration, and with the application of an additional filter are 0.45 to 0.9, 1.3 to 3.5, and 3.95 to 6.6 hour^{-1} correspondingly (see Table 5.2 to 5.4). The decay indexes measured with the presence of additional filter scenario were relatively higher than other two modes. It is believed due to the characteristics of filter mats, deposition rates, and air change rates of the rooms. Detailed quantifying and analysis on filtrations are discussed in the following section.

5.1.2.4 Effect of additional filter on filtration performance

After applying an additional filter, the return air flow rate was reduced from 20.2 to 67.2% when compared to normal filtration (see Table 5.5).

Table 5.5 Airflow measurement at return and supply flow rate of a/c unit

Site code	A	D	F	G	K
Return airflow (m^3/hr) normal filtration	367	264	393	368	569
Supply air flow (m^3/hr) normal filtration	374	272	406	374	582
Fresh air flow increase (m^3/hr) normal filtration	7	8	13	6	13
Return airflow (m^3/hr) using extra filter	293	121	129	280	432
Supply air flow (m^3/hr) using extra filter	311	155	142	303	455
Fresh air flow increase (m^3/hr) using extra filter	18	34	13	23	23
Drop in return flow rate when extra filter is used	20.2%	54.2%	67.2%	23.9%	24.1%

One possible explanation on the reduction of return air flow rate is the characteristics of the filter mat and fan properties. The filter mats of the air conditioners at five sites were provided by different manufactures but have similar designs. The filter mat was made of plastic material which seems without strong electrostatic attraction as the additional filter. All the frames of the filter were rectangular. The mat of filter was cast into a net pattern with fine strings orthogonally weaved together. The thickness of the mat was around 0.5 to 1mm and the mesh size was $0.5mm^2$ on average. The performances of the air conditioners measured at normal filtration were in the range of 2.2 to 3.3%, much less than the performances of air conditioners equipped with an additional filter at 13.5 to 24.2% (normal filter was not removed from the carriage), shown in table 5.2 to 5.4. The performance differences between the units with normal and additional filters were because (1) the normal filter mat was a thin single layer formed by fine strings, but the additional filter mat was composed of tightly packed fiber material with thickness of 2 to 2.5mm; (2) normal filters had no protruding fibers but the additional filters had numerous protruding fiber to collect fine dust; (3) the normal filter had no electrostatic property, unlike the additional filters. Although the material of additional filter was not given by manufacturer, the raw material was believed composing a polymer polypropylene

or polyethylene. These materials can induce electrostatic charge during rushing and air blowing. A dry airflow passing the additional filter can generate static charge and induce electrostatic force to capture incoming dust. Lastly, fan properties at normal filtration may be altered by additional filter because manufactures have a specified fan curve for their air conditioner.

5.2 Test of particle size efficiency of a/c unit air filters

5.2.1 Testing Method

In this section the test of particle size filtration performance of air filters inserted in typical household window unit air conditioners was conducted. The bedroom of a residential flat, with openable windows and installed with a window unit air-conditioner, was selected. The dimension of the room is 1.97m×2.38m, and the room height is 2.56m. Three trials were conducted, the first trial with all windows and door closed and sealed, air-conditioner switched OFF and without installing the air filters. In the second trial a coarse air filter was installed, and in the third trial an electrostatic filter was installed. The air-conditioner was switched ON and the windows and door were closed and sealed. No occupants were allowed to stay in the room for all trials, such that there was no generation of particulates due to human activity. The deposition rate of particulates can be

determined from the first trial and the particulate removal rate achieved by the air filter can be determined in the second trial. Before each trial the windows of the room were opened for one hour, and the particulate from outdoor was extracted with the use a fan. After one hour the windows were sealed and the extraction fan was switched OFF and removed. The particle number concentration inside the room was measured by Grimm aerosol spectrometer (model 1.108) with a sampling rate of 1.2 litres per minute, displaying particle count per litre for 15 sizes ranging from 0.3 to 20 microns.

The deposition rate and the particulate filtration rate can be determined by conducting a mass balance analysis on the particle number concentration in the room, as shown in equation 5.10.

$$\frac{\mathrm{d}C_n}{\mathrm{d}t} = \frac{S}{V} + P\lambda_v C_o - (\lambda_v + \lambda_d + \lambda_f)C_n \qquad \{\text{equation 5.10}\}$$

where C_n is the particle number concentration inside the room, t is the time, S is the particle generation rate, V is the volume of the space, P is the penetration factor, Co is the outdoor particle number concentration, λ_V is the air leakage rate, c is the particle removal rate due to deposition and λ_f is the particle

removal rate achieved by the air filter. When conducting each trial no occupants were stayed inside such that no particle was generated due to human activity. The windows facing outdoor were closed and sealed, and with a larger particle number concentration inside the test room compared with the outdoor, the particle generation rate *S* become zero and the particle infiltration from outdoor can be neglected. As a result, equation 5.10 reduces to

$$\frac{\mathrm{d}C_n}{\mathrm{d}t} = -(\lambda_V + \lambda_d + \lambda_f)C_n \qquad \{\text{equation 5.11}\}$$

The solution to equation 5.11 is

$$C_n(t) = C_n(0)\, e^{-(\lambda_V + \lambda_d + \lambda_f)t} \qquad \{\text{equation 5.12}\}$$

And taking natural log of both sides gives,

$$\lambda_V + \lambda_d + \lambda_f = \frac{\ln C_n(0) - \ln C_n(t)}{t}$$

or, $$\ln C_n(t) = -(\lambda_V + \lambda_d + \lambda_f)\, t + \ln C_n(0) \qquad \{\text{equation 5.13}\}$$

The terms λ_d and λ_f can be determined by observing the natural decay constant from the plotting the natural log of particle number concentration

against time *t*.

The air leakage rate of the room λ_V was determined by carbon dioxide (CO_2) tracer gas decay measurement. Carbon dioxide gas was injected into the room just before each trial, and measured by the instrument TSI Q-Trak. The air leakage rate λ_V is calculated using the following equation:

$$C_{CO_2}(t) = C_{CO_2}(0)\, e^{-\lambda_V\, t} \qquad \text{\{equation 5.14\}}$$

where C_{CO_2} is the concentration of tracer gas at time t, λ_V is the air leakage rate and *t* is the time. Re-arranging the above equation yields the following equation:

$$\lambda_V = [\ln C_{CO_2}(0) - \ln C_{CO_2}(t)]/t \qquad \text{, or}$$

$$\ln C_{CO_2}(t) = -\lambda_V\, t + \ln C_{CO_2}(0) \qquad \text{\{equation 5.15\}}$$

5.2.2 Particle Deposition Rate

In trial 1 of the test the filter was not installed and the window-type air-conditioner was switched OFF. In this case equation 5.11 reduces to

$$\frac{dC_n}{dt} = -(\lambda_V + \lambda_d)C_n \qquad \{\text{equation 5.16}\}$$

and equation 5.13 reduces to

$$\ln C_n(t) = -(\lambda_V + \lambda_d)\, t + \ln C_n(0) \qquad \{\text{equation 5.17}\}$$

During this trial the decay of carbon dioxide tracer gas concentration is shown in figure 5.9 and figure 5.10. The air leakage rate is 0.0013 per minute (or 0.08 air change per hour).

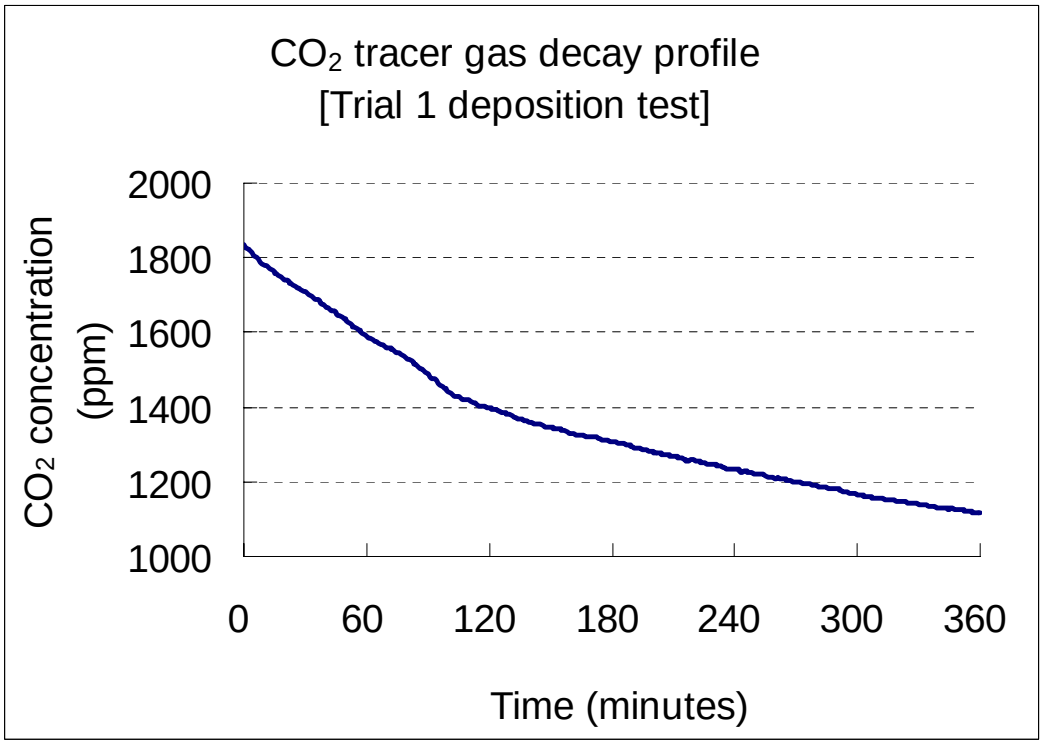

Figure 5.9 CO_2 tracer gas decay profile for trial 1

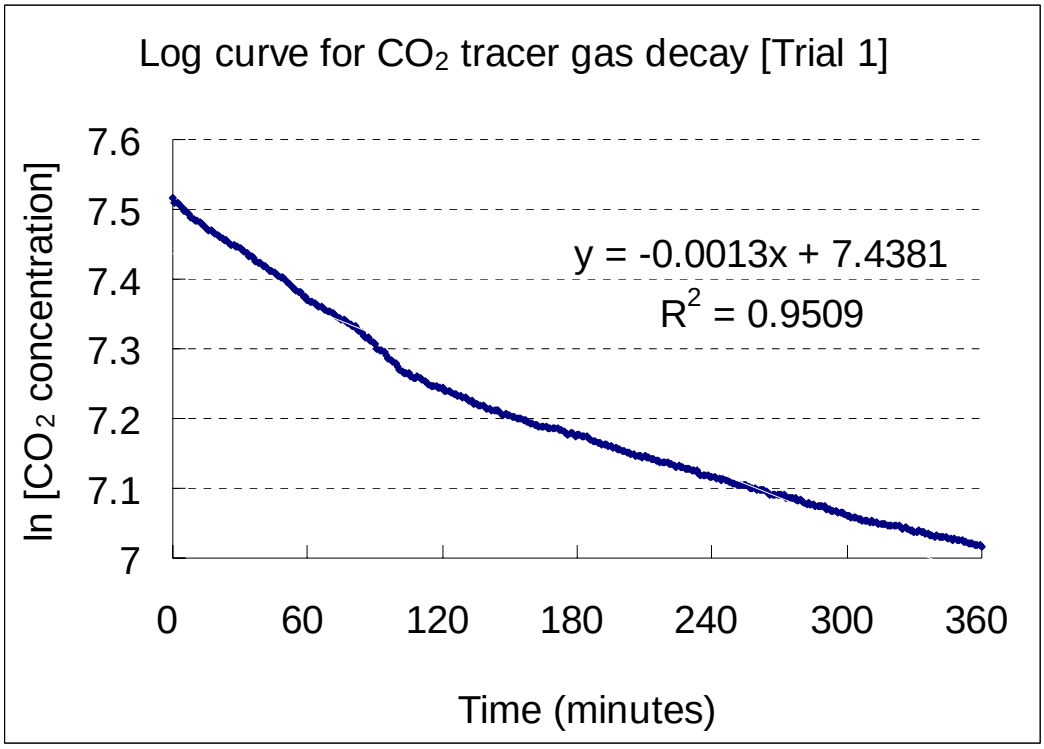

Figure 5.10 Log curve for CO_2 decay for trial 1

The particle decay curve and the log curve for particle size of 0.3 - 0.4 μm and 2.0 – 3.0 μm are shown in figure 5.11 to figure 5.14. For the entire size range between 0.3 μm to 15 μm the decay curves are shown in Appendix A2, section A2.1. The decay rate is obtained from the slope of the natural log curve.

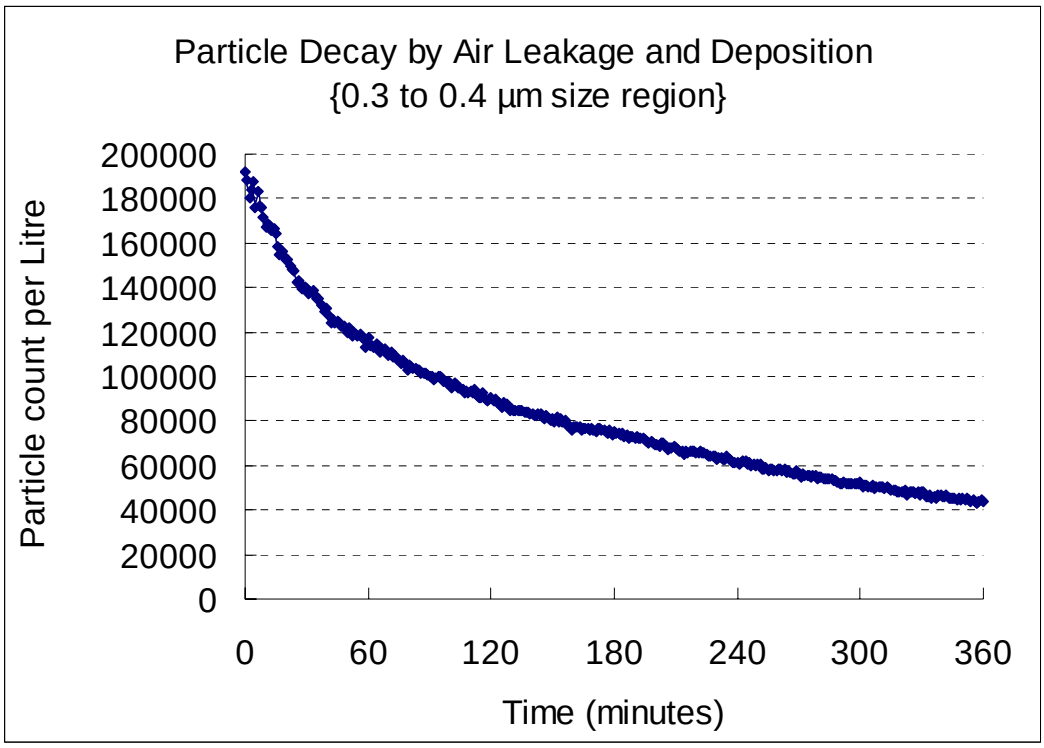

Figure 5.11 Particle decay profile in trial 1, 0.3 μ m to 0.4 μ m particle size range

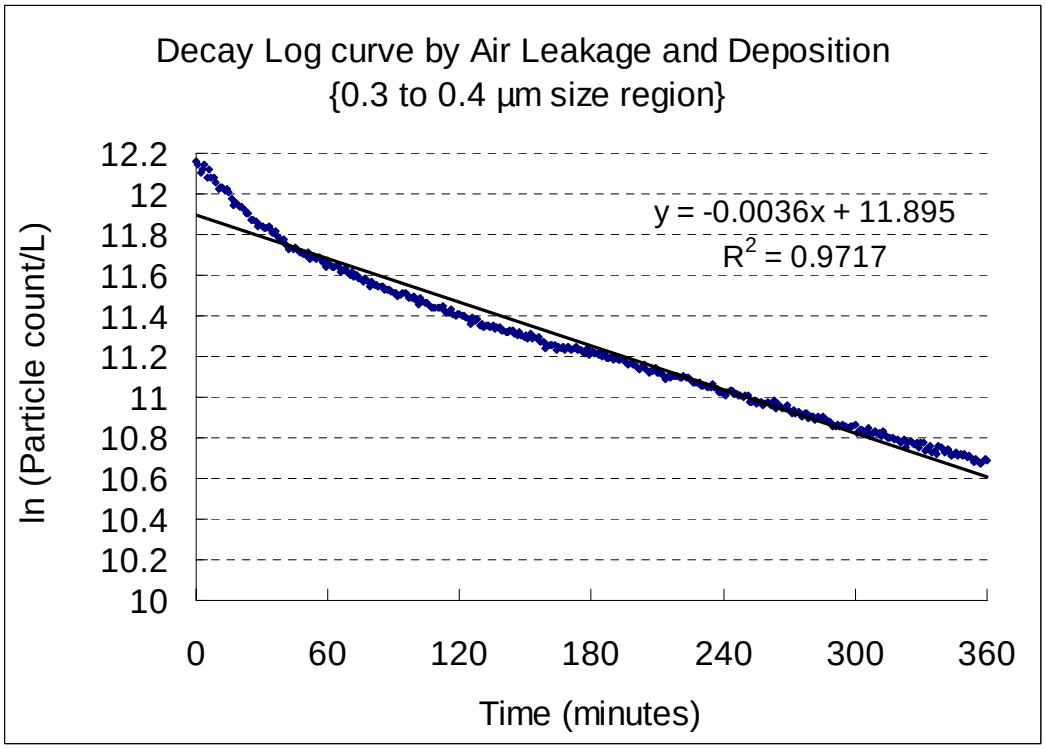

Figure 5.12 Natural log curve for trial 1, 0.3 μ m to 0.4 μ m particle size range

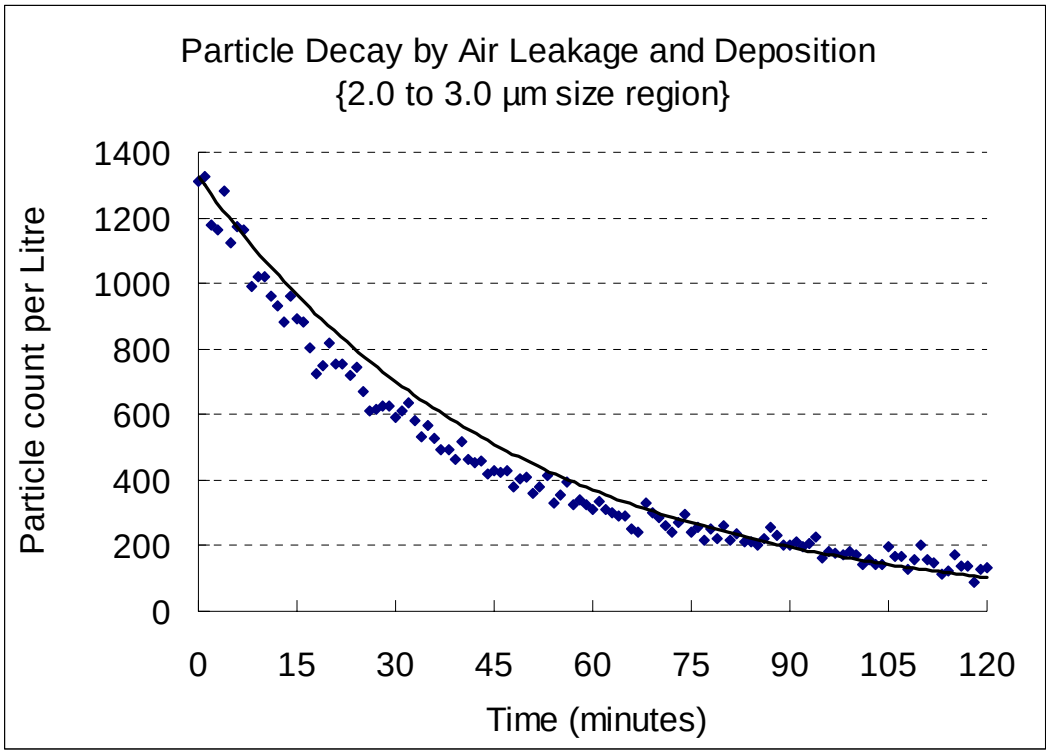

Figure 5.13 Particle decay profile in trial 1, 2.0 μ m to 3.0 μ m particle size range

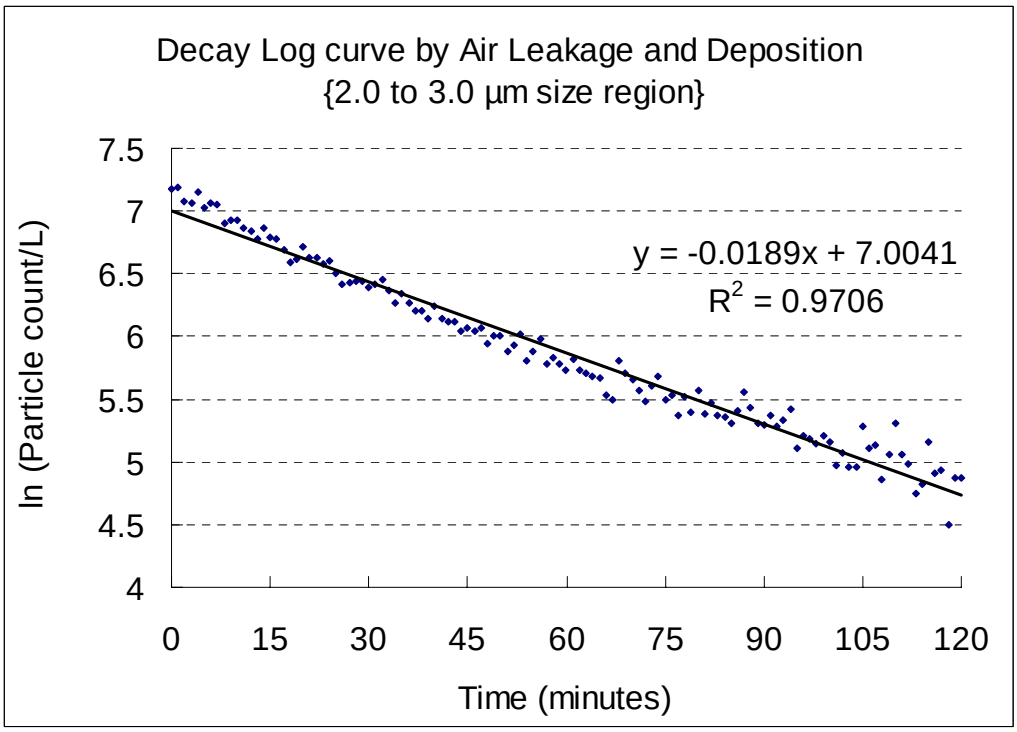

Figure 5.14 Natural log curve for trial 1, 2.0 μ m to 3.0 μ m particle size range

5.2.3 Particle filtration rate of coarse filter

In trial 2 a coarse filter was installed and the window-type air-conditioner was switched ON. The decay of carbon dioxide tracer gas concentration is shown in figure 5.15 and figure 5.16. The air leakage rate is 0.0090 per minute (or 0.54 air change per hour).

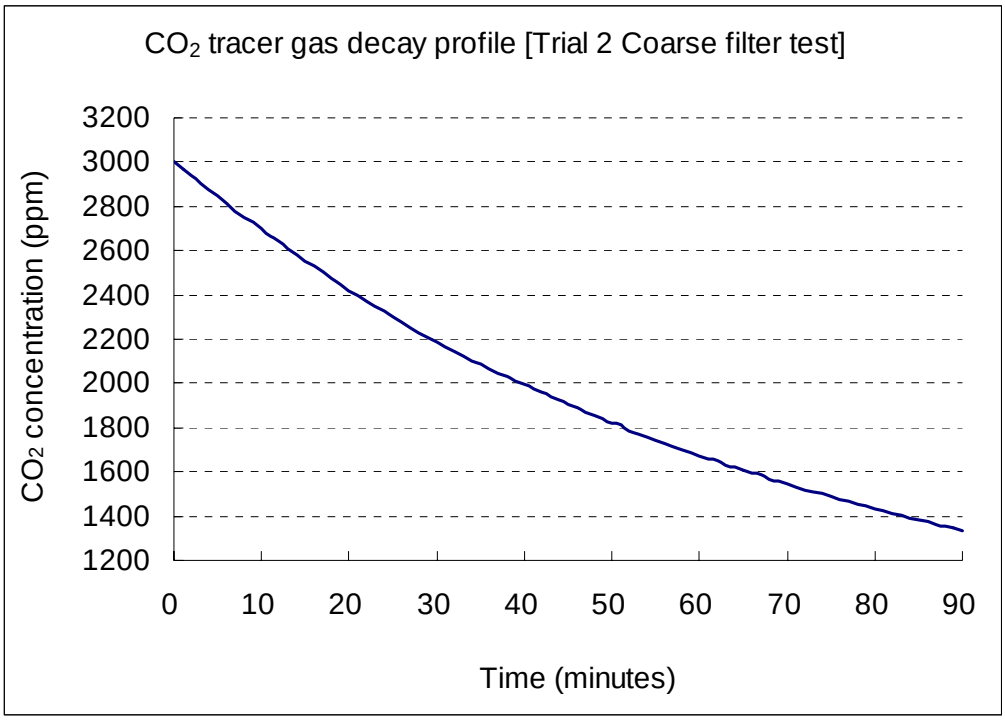

Figure 5.15 CO_2 tracer gas decay profile for trial 2

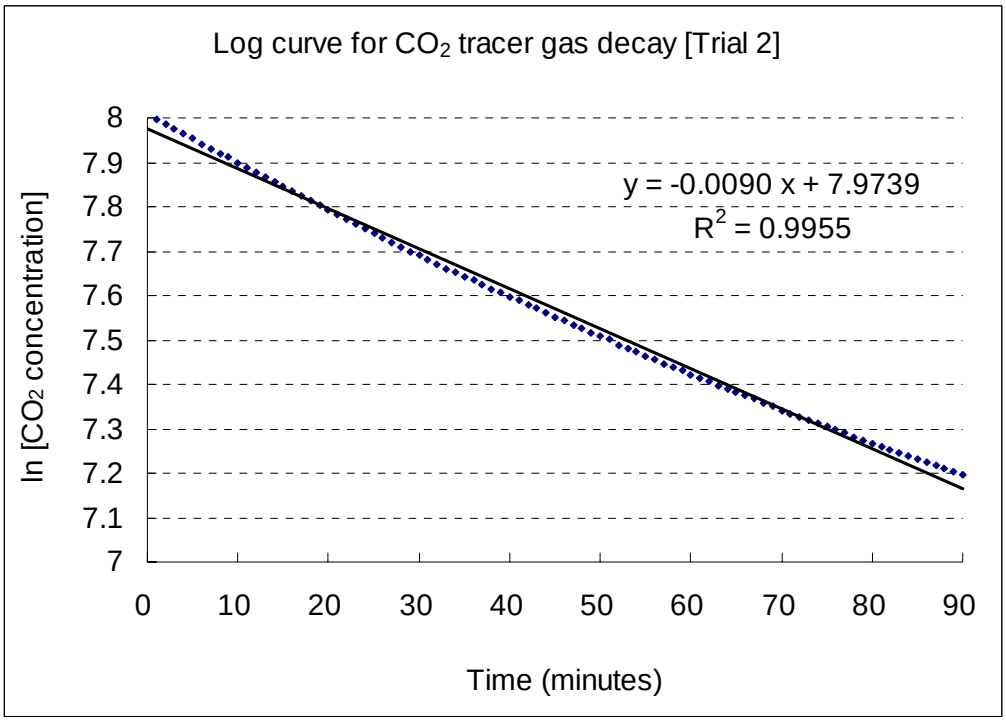

Figure 5.16 Log curve for CO_2 decay for trial 2

The particle decay curve and the log curve for particle size of 0.3 - 0.4 μm and 2.0 – 3.0 μm are shown in figure 5.17 to figure 5.20. For the entire size range between 0.3 μm to 15 μm the decay curves are shown in Appendix A2, section A2.2. The decay rate is obtained from the slope of the natural log curve.

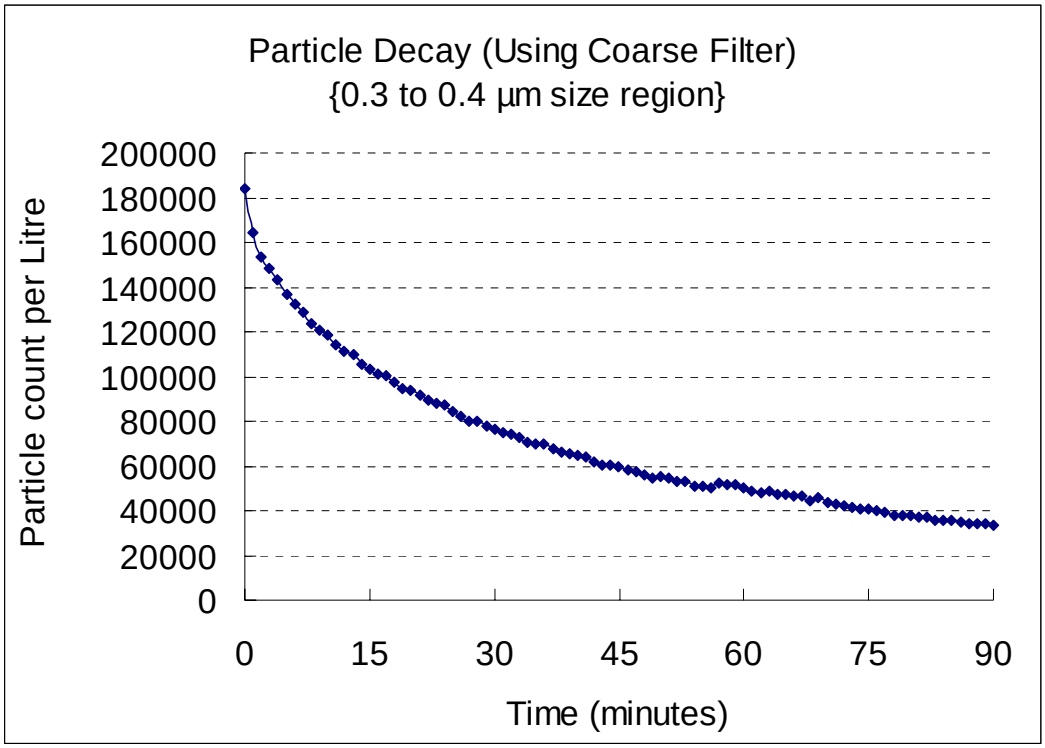

Figure 5.17 Particle decay profile in trial 2, 0.3 μ m to 0.4 μ m particle size range

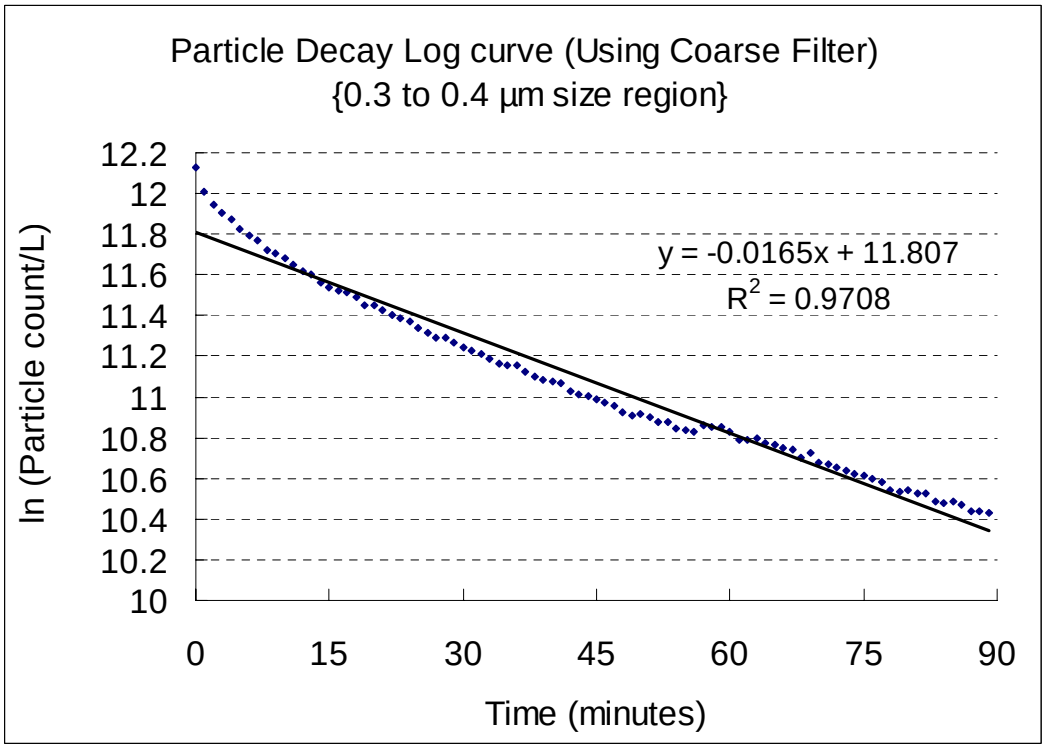

Figure 5.18 Natural log curve for trial 2, 0.3 μ m to 0.4 μ m particle size range

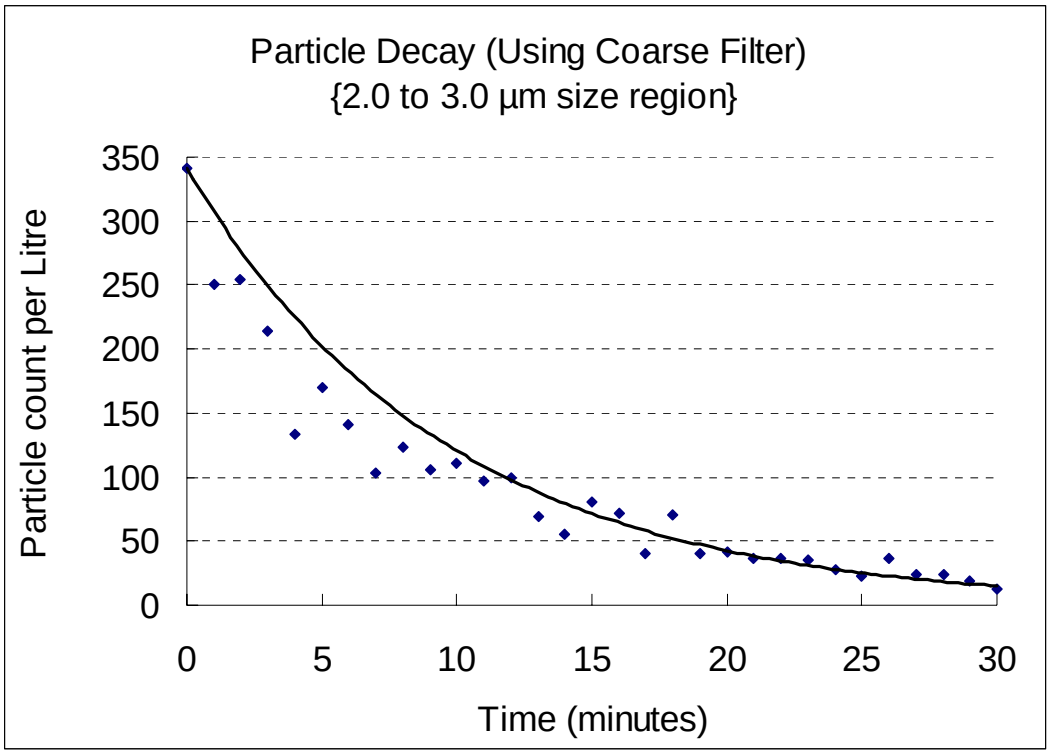

Figure 5.19 Particle decay profile in trial 2, 2.0 μ m to 3.0 μ m particle size range

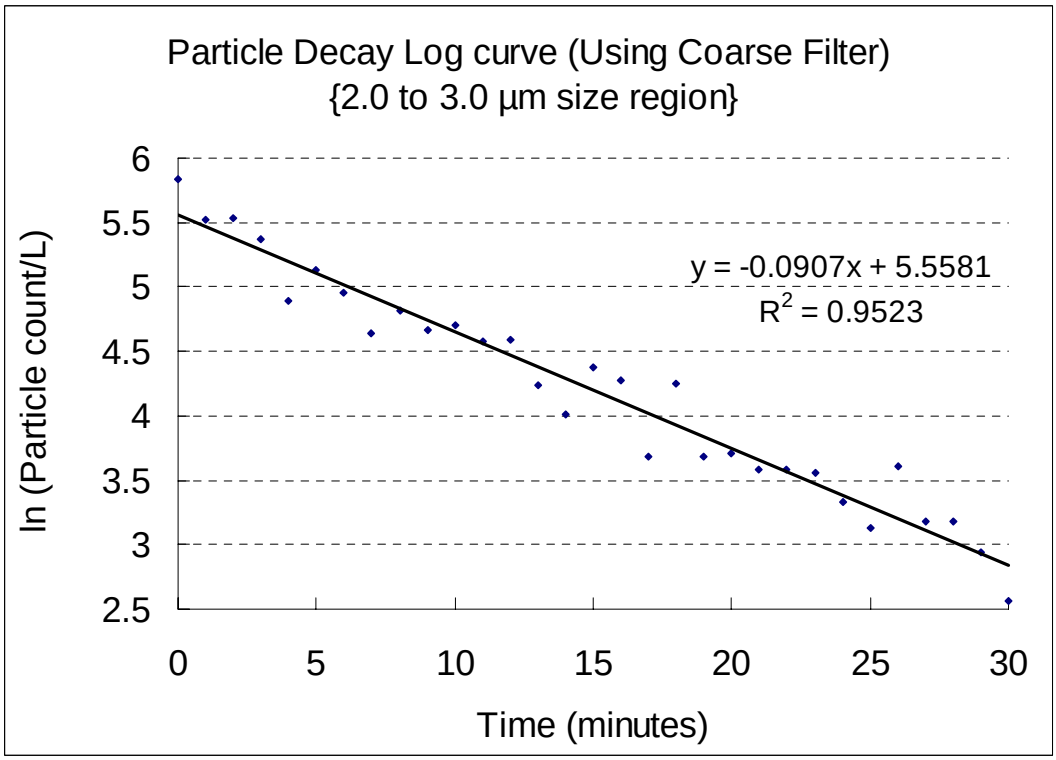

Figure 5.20 Natural log curve for trial 2, 2.0 μ m to 3.0 μ m particle size range

5.2.4 Particle filtration rate of electrostatic filter

In trial 3 an electrostatic filter was installed and the window-type air-conditioner was switched ON. The decay of carbon dioxide tracer gas concentration is shown in figure 5.21 and figure 5.22. The air leakage rate is 0.0133 per minute (or 0.8 air change per hour).

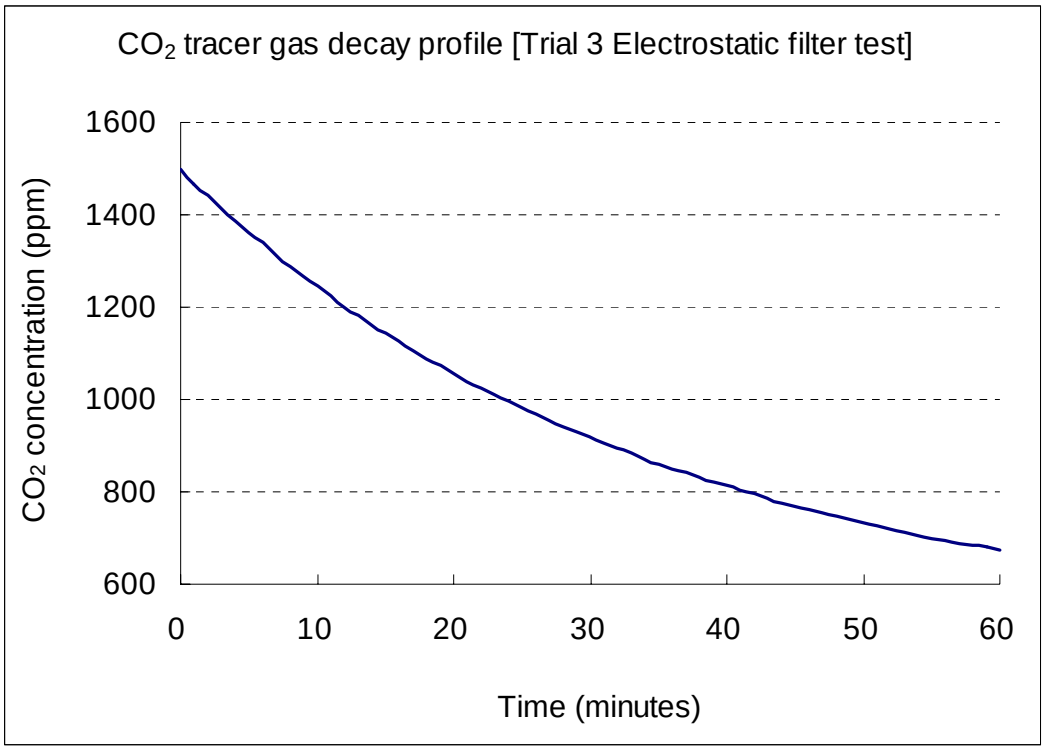

Figure 5.21 CO_2 tracer gas decay profile for trial 3

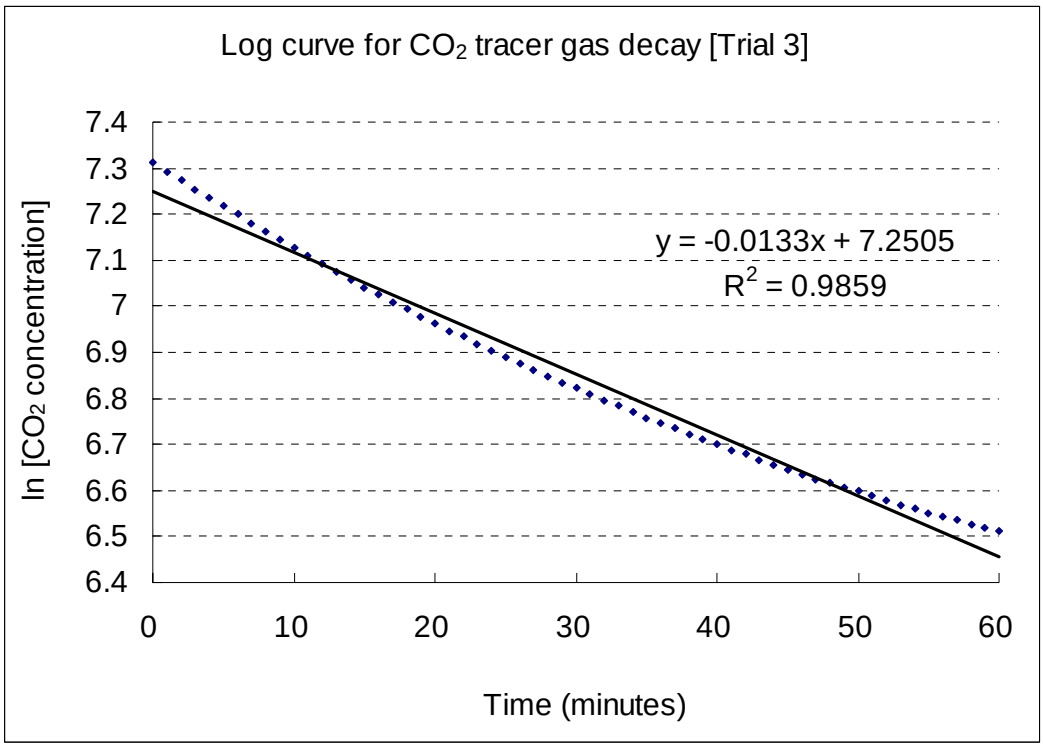

Figure 5.22 Log curve for CO_2 decay for trial 3

The particle decay curve and the log curve for particle size of 0.3 - 0.4 μm and 2.0 – 3.0 μm are shown in figure 5.23 to figure 5.26. For the entire size range between 0.3 μm to 15 μm the decay curves are shown in Appendix A2, section A2.3. The decay rate is obtained from the slope of the natural log curve.

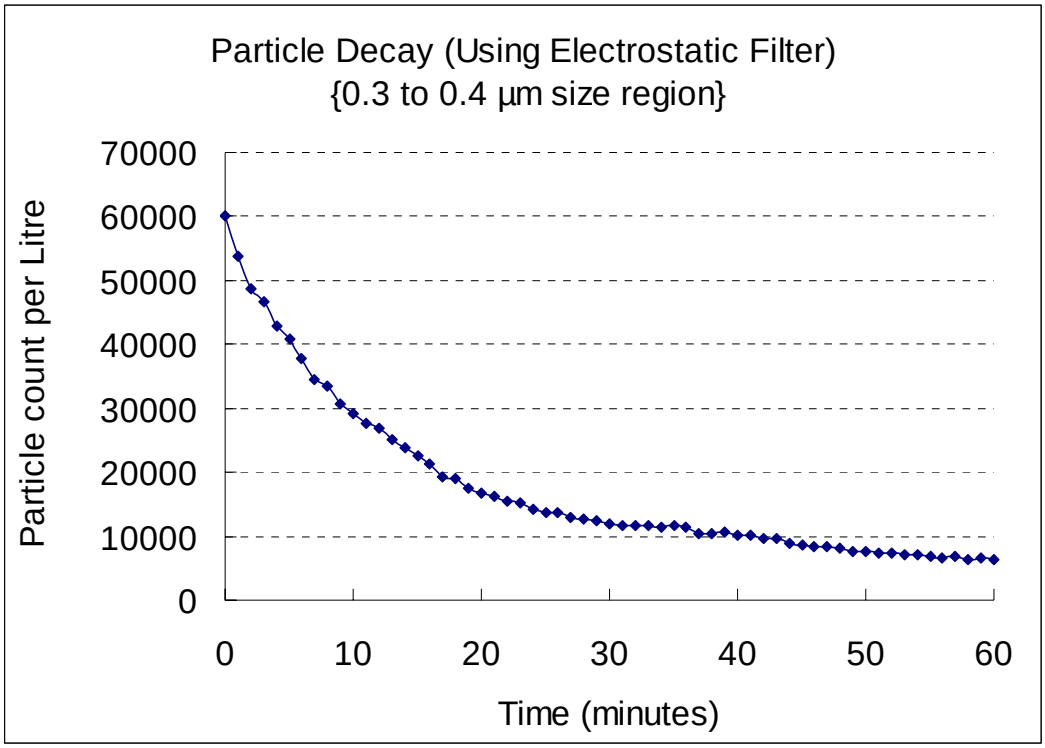

Figure 5.23 Particle decay profile in trial 3, 0.3 μ m to 0.4 μ m particle size range

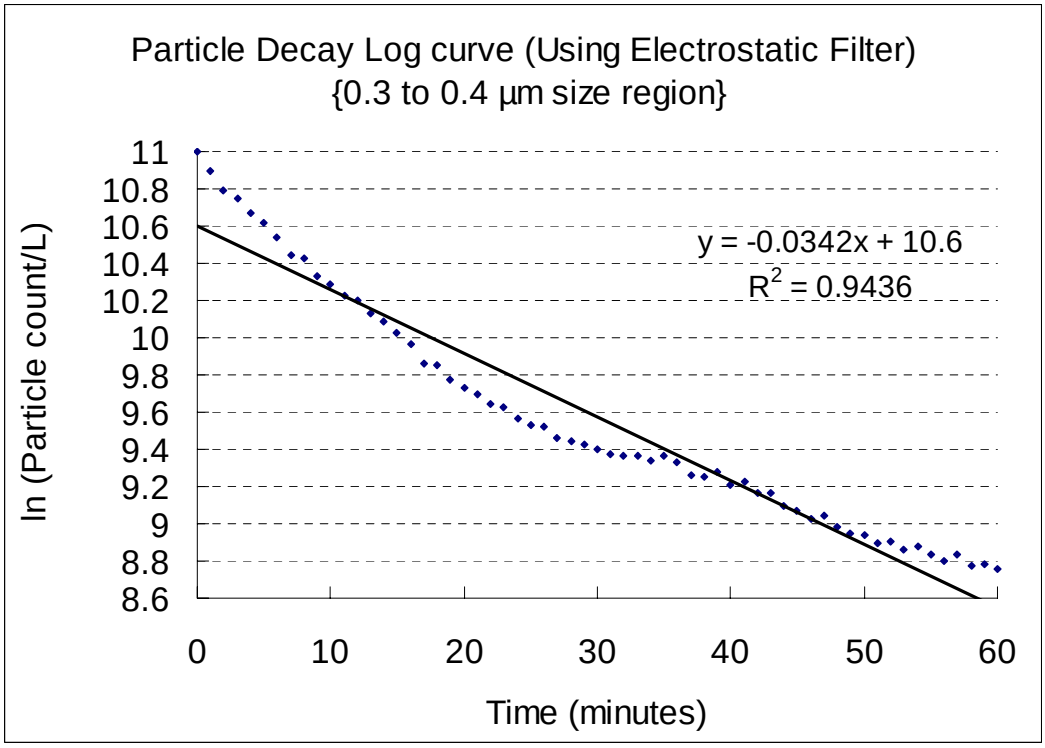

Figure 5.24 Natural log curve for trial 3, 0.3 μ m to 0.4 μ m particle size range

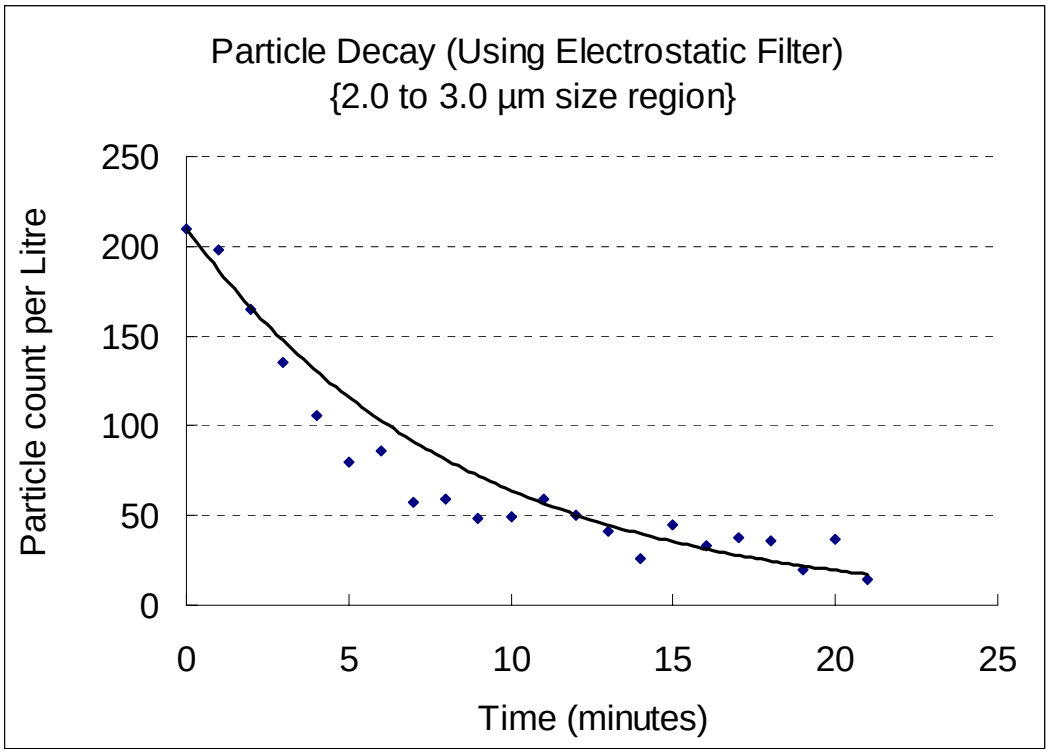

Figure 5.25 Particle decay profile in trial 3, 2.0 μ m to 3.0 μ m particle size range

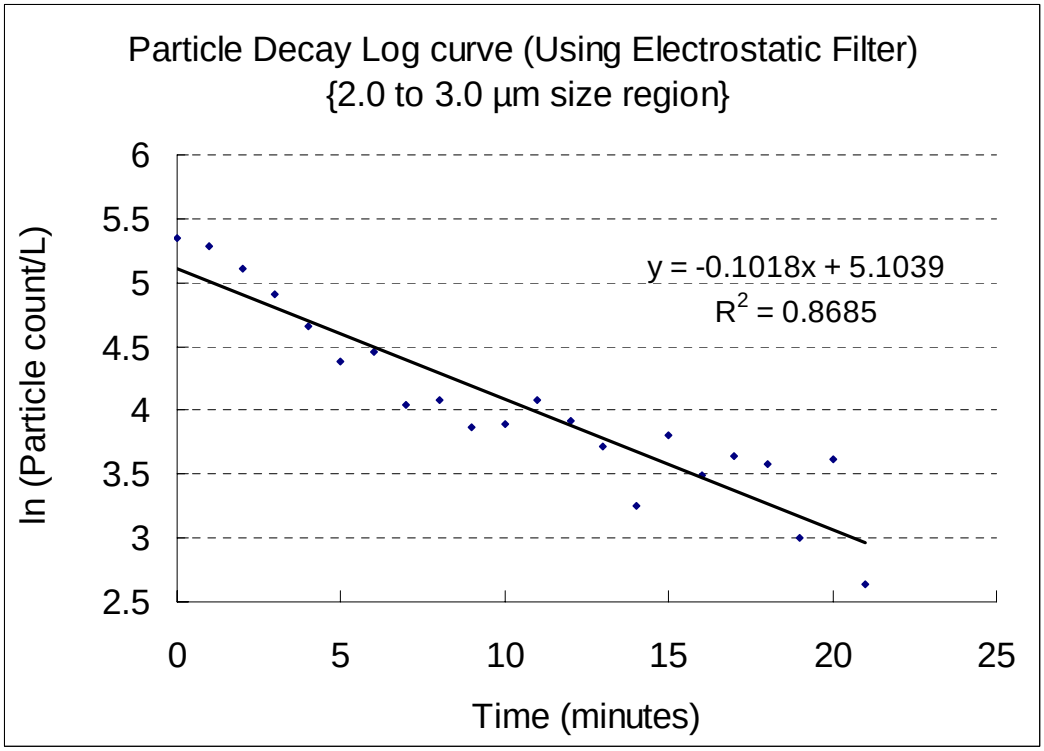

Figure 5.26 Natural log curve for trial 3, 2.0 μ m to 3.0 μ m particle size range

5.2.5 Summary of test results

Table 5.6 shows the deposition rate and the particle filtration rates of the coarse filter and electrostatic filter, calculated base on the slope of natural log curves as shown in section 5.2.2 to 5.2.4, for various particle size ranges.

Table 5.6 Particle deposition rate and filtration rate of tested filters

	Test 1	Test 2	Test 3
	Deposition	Coarse filter	Electrostatic filter
Air leakage rate during the test ($hour^{-1}$)	0.08	0.54	0.80
Particle size range	Deposition rate ($hour^{-1}$)	Particle filtration rate ($hour^{-1}$)	
0.3 μm to 0.4 μm	0.14	0.31	1.12
0.4 μm to 0.5 μm	0.23	0.34	1.34
0.5 μm to 0.65 μm	0.26	0.33	1.44
0.65 μm to 0.8 μm	0.29	0.58	1.43
0.8 μm to 1.0 μm	0.32	0.71	2.17
1.0 μm to 1.6 μm	0.49	0.82	3.52
1.6 μm to 2.0 μm	0.65	0.78	4.23
2.0 μm to 3.0 μm	1.05	3.85	4.25
3.0 μm to 4.0 μm	2.45	6.11	6.65
4.0 μm to 5.0 μm	4.10	10.50	11.30
5.0 μm to 7.5 μm	5.73	9.76	15.49
7.5 μm to 10 μm	6.69	12.71	24.35
10 μm to 15 μm	11.81	8.23	26.48

The Clean Air Delivery Rates (CADR) for the coarse filter and electrostatic filter, at various particle size ranges, are calculated using equation 5.18 (room volume of 12 m^3) and listed in table 5.7.

$$\text{CADR} = \text{Volume of space} \times k_f \qquad \{\text{Equation 5.18}\}$$

where k_f is the particle filtration rate.

Table 5.7 Clean Air Delivery Rate (CADR) of tested filters

Particle size range	CADR (m^3/hour)	
	Coarse filter	Electrostatic filter
0.3 μm to 0.4 μm	3.72	13.44
0.4 μm to 0.5 μm	4.08	16.08
0.5 μm to 0.65 μm	3.96	17.28
0.65 μm to 0.8 μm	6.96	17.16
0.8 μm to 1.0 μm	8.52	26.05
1.0 μm to 1.6 μm	9.84	42.25
1.6 μm to 2.0 μm	9.36	50.77
2.0 μm to 3.0 μm	46.21	51.01
3.0 μm to 4.0 μm	73.34	79.82
4.0 μm to 5.0 μm	126.03	135.63
5.0 μm to 7.5 μm	117.15	185.92
7.5 μm to 10 μm	152.56	292.27
10 μm to 15 μm	98.78	317.83

The filtration rates found in section 5.2.5 provides information for the prediction of removal rates on airborne microbes according to their diameter. According to the experimental study conducted by Yanagi and Ikeda [2005], the filtration efficiency over selected airborne microbes (*Staphylococcus aureus* and fungal spore) of low- and medium-efficiency filters installed in air-conditioning system was almost equal to the filtration efficiency over suspended particles. Kowalski [2006] also suggested that the filtration of micro-organisms nearly approximates the filtration of particles of identical size. Thus the particle filtration rate obtained from the performance test is adopted to predict the removal rates of airborne micro-organisms. The result in table 5.7 is used for the estimation of equivalent germ-free air delivery rate to the indoor air contributed by air filter, and hence facilitates the estimation of the impact on predicted infection risk by using different of air filters, as reported in chapter 7 in this thesis. Observing from table 5.7, the performance of coarse air filter on particles with size less than 2.0 μm is relatively lower, which belongs to the size range of virus or small size droplet nuclei. The electrostatic filter tested in this study performs better at this size range.

5.3 Chapter Summary

The performance of air filter installed in window type air conditioner with respect to normal and additional filtrations on particles has been studied. It was found that the performances can be estimated from transient decay curves through site measurements. The particle exponential decay index obtained from the curve is composed of parameters including air change rate, particle deposition rate, and the air filter performance. The return and supply flow rates measured with an additional filter are smaller than normal filtration, but the air change rates at this scenario are larger than normal filtration. The increase of air change rate is expected due to over-compensation of leakage flow. The application of an additional filter is noticeably more effective than a normal filter in particle removal. Using an additional filter is favorable for some susceptible groups such as those suffering from respiratory illness, children, and the elderly, to reduce substances that may trigger asthma. In addition, using air filter would reduce the concentration of infectious particles in the indoor environment when infected person is presence, subject to the efficiency of the air filter. By this way the risk of infection can be reduced as the air filter can delivers more germ-free air complement to the outdoor air ventilation. The test result in this chapter will be used in chapter 7 for the estimation of airborne infection risk in a residential

flat.

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CHAPTER 6: ROLE OF DRAINAGE SYSTEM ON AIRBORNE TRANSMISSION OF INFECTION IN RESIDENTIAL BUILDINGS

6.1 Introduction

At the beginning of the twenty-first century, several disease outbreaks appeared over the world, in particular the Severe Acute Respiratory Syndrome (SARS) outbreak in 2003 and the Avian Influenza outbreaks in the Asian region. The outbreak cases in hospitals and high-rise residential buildings attract an alarming attention among the medical and building engineering professions. Several research works on the SARS viral transmission in buildings are published afterwards, suggesting several possible viral transmission routes to explain how the epidemic spread inside a building. Chan [2003] proposed a hypothesis that the vertical stack of the drainage system takes a role as the viral transmission route, causing a viral attack to the occupants in several flats in flat 7 of the Block E, Amoy Gardens. A presentation was conducted by Chan [2003] to a delegate from the World Health Organization (WHO) on the 30th of April 2003, on the possibility of uprising of contaminated air in drainage system. The World Health Organization [2003a, 2003b] accepted that the vertical drainage stack in building is a possible route for the propagation of SARS virus. The objective of

this study is to further investigate of air-flow characteristic of drainage system verified by using tracer gas technique, and evaluate the risk of airborne infection in a flat, if the water trap in sanitary drainage system was dried up, how the operation of the air exhaust system in the room would affect the risk of infection inside when epidemic outbreak occurs in a building, like the case of Severe Acute Respiratory Syndrome occurred in Amoy Gardens in Hong Kong in year 2003.

The SARS outbreak in Amoy Gardens was one of the super-spreading event with more than 320 infected cases [Hong Kong Department of Health 2003] in Hong Kong that a strong putative environmental etiology, such as sewage pipes, building design, and poor environmental hygiene, could exist [Lai et al. 2004]. The case is a community transmission and the SARS coronavirus, the etiological agent, was suggested to be “moderately transmissible” [Riley et al. 2003]. Lau et al. [2004] observed that for cases in Amoy Gardens Block E, the median duration between the symptoms in the index patient and the probable secondary case was much shorter than the other secondary infections in households in other locations. This support the suggestion of environmental contamination as a factor associated with the outbreak. Yu et al. [2004] and Li et al. [2004a] suggested a hypothesis that the virus was dispersed through the airflow transmission in the re-entrant light-well, due to

prevailing wind, to provide a possible account for the infected cases from flats 8, which suffered the highest risk of receiving polluted air, and suffered with the greatest hit of infected cases. However, Li et al. [2004a] did mention that their research paper that their study could not explain fully why the number of infected cases for flat 7 was also relatively higher than the others. For the Amoy Gardens outbreak, flats 7 in Block E were the second worst among the other flats.

6.2 Drainage Stack as a Hypothetic Route for Viral Transmission

Among the Amoy Gardens clusters a typical higher rate on the occurrence of diarrhea (73%, or 55 of 75 cases) was reported [Peiris et al. 2003], comparing with outbreak cases occurred in other buildings like hospital-acquired infection [Chiu et al. 2004]. The Hong Kong Department of Health reported in 2003 that the index patient was having diarrhea when he was visiting 16th floor of flat 7 of Block E and he used the toilet there [Hong Kong Department of Health 2003]. Shi et al. [2005] performed a pathological study on seven SARS autopsies and revealed that SARS coronavirus has the ability to infect the epithelial cells and the mucosal lymphoid tissues in the intestines, such that the gastrointestinal tract can be a target of SARS coronavirus infection in our human body. In addition, Peiris et al. [2003] reported that SARS

virus was isolated from the faeces and urine as well as the respiratory tract among the patients from Amoy Gardens, which suggests the infection was not confined to the respiratory tract, and the possibility of fecal transmission had to be considered [Peiris and Guan 2004]. On the survival of SARS virus in fecal matter, Wang et al. [2005] studied the survival time of SARS virus in sewage samples and found that the virus can survive for 2 days at 20°C. The fecal droplets containing SARS coronavirus remain infectious a prolonged survival for 4 days at room temperature after being spiked in diarrheal stool, with an alkaline pH, as suggested by Lai et al. [2005]. All these findings support the hypothesis that the drainage and sewer system of the Amoy Gardens building were associated with the SARS outbreak in this residential development.

Immediately after the SARS outbreak in Amoy Gardens in 2003, at the sixth week after the index case reported, the investigation team leaded by the World Health Organization conducted a tracer gas injection by using sulphur-hexafluoride (SF_6) to investigate the possibility of contamination and viral transmission from block E to the adjacent building blocks (block C and D) in the underground drainage system. Some minute traces of gas was observed to travel from one sewer access hole to the next but far less gas was registered than was injected [World Health Organization

2003b]. While the possibility of viral transmission from block E to the other blocks through the underground drainage and sewer systems was not substantial, the report did not mention the situation for the above - ground drainage system, which refers to all the pipeworks and fitments installed at the building above ground floor level. In particular, flats 7 at various height level in block E of the Amoy Gardens suffered most, if the drainage system is also a possible route of SARS viral transmission, since the index case was in flat 7 at the 16th floor level.

6.3 Investigation Methodology

A 37-storey height high-rise residential building, with a floor plan and drainage system configuration similar to the Amoy Gardens building, was selected to verify the risk of air contamination from a residential unit at the middle floor to the others, by conducting a tracer gas experiment. The use of particle tracer to determine the relative amount of bacterial air transfer, among different rooms within a building, was reported in studies by Williams and Harding [1969], Foord and Lidwell [1972], Lidwell [1972], Hambraeu and Sanderso [1972], Foord [1973], Laurell and Hambraeus [1973] and Hambraeus [1973], early between 1960s to 1970s. Furthermore, Lidwell [1960] introduced the concept of transfer index as a descriptive parameter to address the efficiency of an air ventilation system in protecting a given

location from exposure to air-carried contamination. However, the case for droplet nuclei and virus transmission is different. Wells and Wells [1936] suggested that when droplets are exposed to the air shall become smaller due to rapid evaporation effect, such that the size of the residues of droplets, after evaporation, become so small that the behaviour of the residue may be considered to float or drift with the slightest air movement and therefore to be in effect become a part of the atmosphere. Pawar et al. [2007] also suggested that the spread of virus particles was considered analogous to diffusion of a tracer gas. The use of gaseous tracer is more common as a marker for estimating the risk of indoor airborne viral or droplet infections. In addition to the study by Pawar et al [2007], other examples include the study conducted by Rudnick and Milton [2003]; and the National Institute for Occupational Safety and Health [NIOSH 1998] in the United States. Cermak and Melikov [2007] also used a gaseous tracer to estimate airborne infection transmission risk for various ventilation system design options in a full-scale indoor test room. On the SARS outbreak case, Yu et al. [2004] suggested that for the case in Block E of the Amoy Gardens outbreak in Hong Kong it was most likely that huge numbers of virus-laden aerosols were generated from the index case in unit 7 at the 16th floor. The virus-containing bio-aerosols were also modeled as a passive tracer (carbon dioxide gas CO_2) in studies conducted by Li et al. [2004a, 2004b] for both

the case in Amoy Gardens residential building in Hong Kong, and a hospital outbreak case in Hong Kong. In our analysis we also use gaseous tracer to determine the relative amount of room-to-room viral transmission. Instead of using carbon dioxide, in our study we use sulphur hexafluoride as a tracer gas, since the latter is normally absent in the ambient environment.

The floor plan layout is similar to the Amoy Gardens residential buildings, with a typical cruciform layout with re-entrant light-wells for toilets and kitchen ventilation, and the installation of drainage pipes and stacks, and at each floor there are eight residential flats. This configuration is typical for residential buildings in Hong Kong constructed by non-government private sector property developers. The case study building was recently built and unoccupied at the time of our experiment. In all the toilets and kitchen a propeller fan is installed for mechanical air exhaust purpose, while a window is also provided for natural ventilation purpose to fulfill the local legislative requirements for the construction of residential buildings [Buildings Department 1998]. The vertical drainage stack under test is a typical circular polyvinyl chloride (PVC) plastic pipe, with a cross-sectional diameter of 100mm. At each floor, a horizontal branch pipe, with a cross-sectional diameter of 40mm, is provided dedicatedly for the washing machine inside the room. At the time of our

experiment the pipework was installed while the washing machine was not provided yet. Along this horizontal pipe there are two openings: one is the removable cleansing eye and the other is a removable bottle trap at the end of this horizontal drainage pipe (figure 6.1 and 6.2). This provides sufficient access points for the injection and the monitoring of the tracer gas concentration.

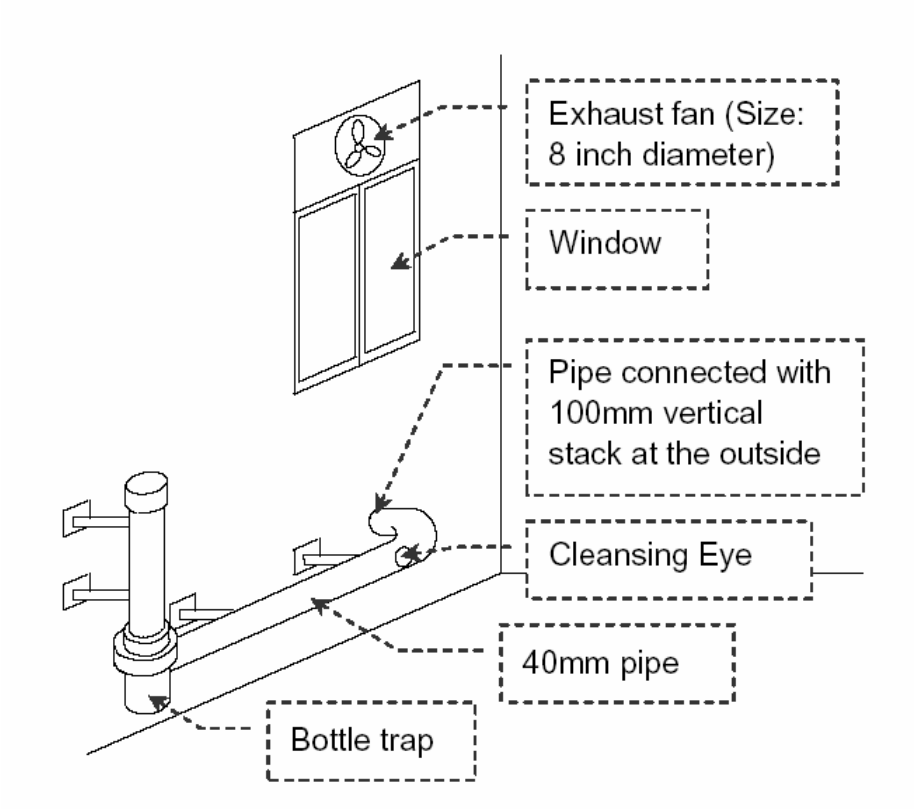


Figure 6.1 Drainage pipe installations in the investigated room

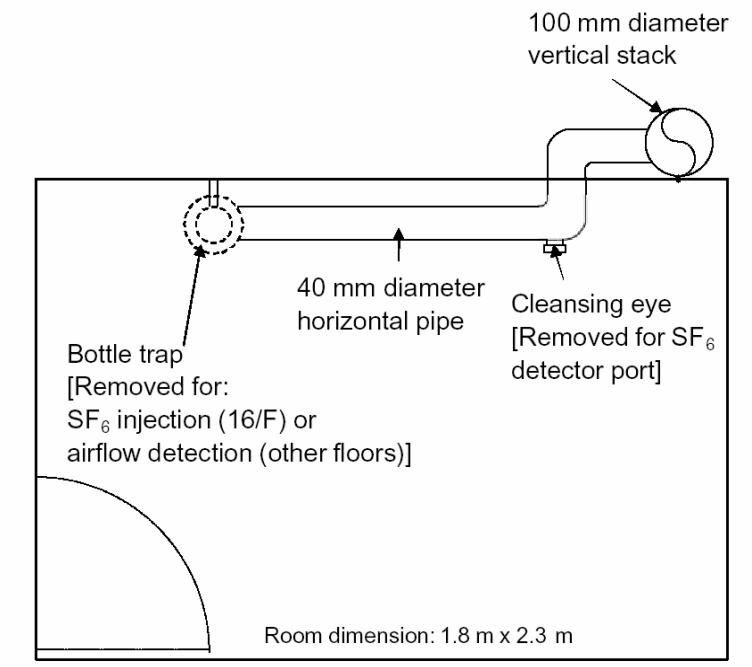


Figure 6.2 Floor plan and drainage pipe layout for the investigated room

Sulphur hexafluoride (SF_6) was selected as the tracer gas, since the gas is normally absent in the ambient environment. This ensures the elevated concentration of sulphur hexafluoride gas at the receiver location, if any, was solely caused by the air transported from our dedicated tracer gas injection source location. A calibrated gas analyzer, Bruel & Kjaer Gas Analyzer model 1302 and 1303 setup, adopting photoacoustic spectroscopy technique, was used to measure the concentration of SF_6 tracer gas. This analyzer was stayed at 16/F for all of the testing trials. Before conducting the experiment the ambient SF_6 concentration was measured to be lower than 0.1 ppm. The bottle trap at the horizontal drainage pipe at 16th floor (corresponding to the index floor in the Amoy Gardens outbreak) was removed, to

facilitate the injection of tracer gas. The cleansing eye of the horizontal pipe was also removed for the connection of the tracer gas sampling tube (figure 6.2 and 6.3), such that the tracer gas concentration inside the horizontal pipe can be monitored. Throughout the whole experiment, for all of the trials mentioned in the next paragraphs, the SF_6 gas concentration inside the 40mm diameter horizontal drainage pipe at 16th floor was controlled at a range between 797 to 867 ppm. The tracer gas is used to represent the quantity of the aerosolized infectious virus discharged into the drainage system. At the 16th floor, the door and windows were all closed, and the propeller exhaust fan was turned off during all of the testing trials mentioned below.

The flat at the 37th floor located above the index floor, served by the same vertical drainage stack, was investigated if SF_6 tracer gas was transmitted to the room. In the first trial, the circular propeller exhaust fan, with a local commercial size of 8 inch internal diameter, was switched on. The air exhaust flow rate was measured once it was switched on. The bottle trap at the end of horizontal pipe was removed, such that air movement (if any) was allowed to flow across the pipe to the room (figure 6.4), to evaluate the relative amount of foul air that can be transmitted from 16th floor to the upper floors. This represents the scenario that water seal was lost in the trap. All the other pipes, the vertical drainage stacks and sanitary fitments along the whole

building (except 16th floor) were unaltered. Simultaneously, at all the other floors the exhaust fans were switched off, and the windows and doors all the rooms were closed as well. The SF_6 concentration at the 37th receiver floor was measured by another calibrated Bruel & Kjaer Gas Analyzers model 1302 and 1303 set-up.

Three tests were conducted in the room at 37th floor, on different ventilation modes. In test 1 the exhaust fan was switched on and all the window and door closed, in other words, air exhaust was solely achieved by the mechanical system. In test 2 the window was opened, while the exhaust fan was switched off and the door was closed, in other words, air exhaust was solely achieved by natural ventilation. When test 1 was finished and switching to another ventilation mode, the drainage pipe was blocked, to allow the residue tracer gas in the room, if any, was exhausted through the fan. It was ensured that the tracer gas SF_6 concentration reading from the same B&K gas analyzer, measured in the room by the same gas analyzer was below 0.1ppm, before conducting test 2. This also ensured the residue SF_6 gas dosed to the gas analyzer during the previous test, if any, was also removed. When performing test 2, the exhaust fan was switched off. The measurement period for test 2 (and for all of the measurement trials and for all of the visited floors mentioned above and below) were at least 15 minutes.

To estimate the quantity of airflow at the drainage pipe opening, air velocity at the end of the 40mm horizontal pipe was measured by using an anemometer (TSI model 8388). For test 1 the air velocity at the suction side of the exhaust fan was also measured by the same anemometer for estimation of exhaust air flow rate, such that the airflow at the suction side of the drainage pipe and that of the exhaust fan can be compared. For test 2, the average air velocity flow across the window was measured.

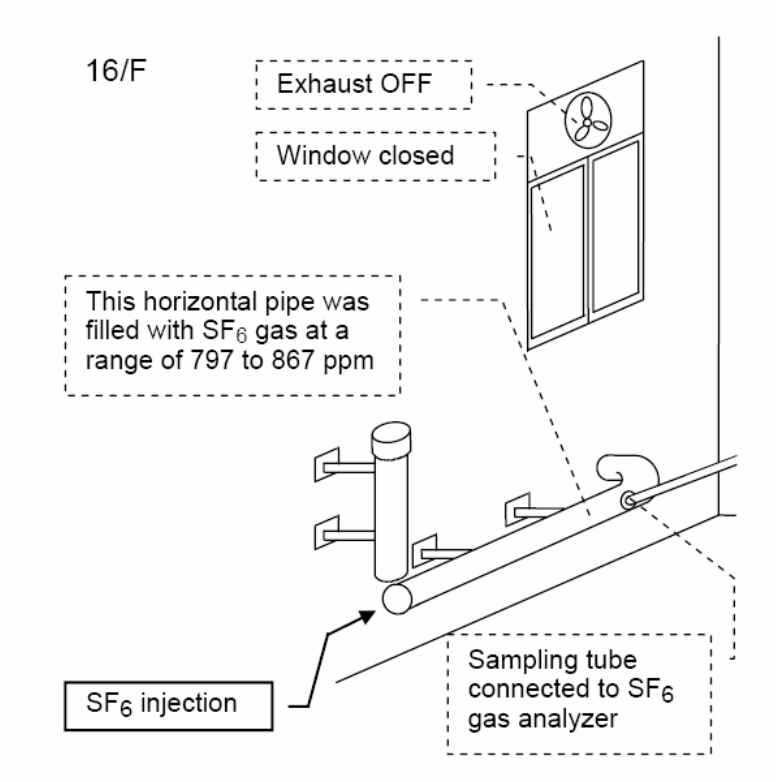


Figure 6.3 SF_6 tracer gas injection at 16th floor

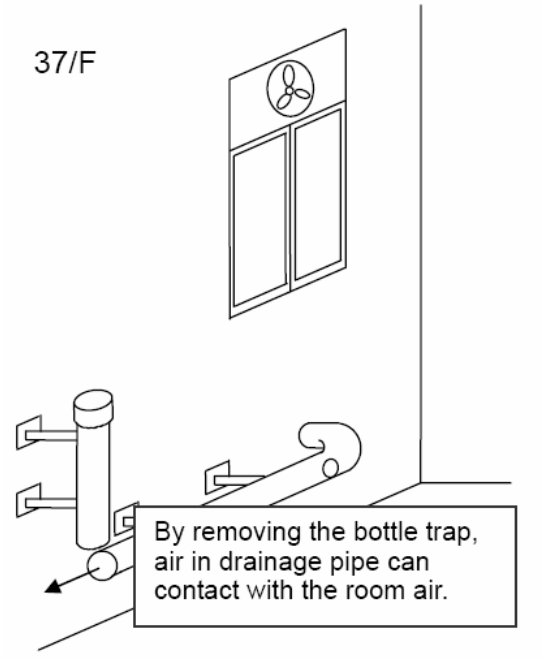


Figure 6.4 Bottle trap removed to represent the “trap seal lost” scenario

All the above testing procedures were repeated sequentially at 17th and 27th floors in the same manner. After finishing all the measurement trials at 37th floor, the cleansing eye and the bottle trap was restored back to the original locations, before leaving the room at 37th floor. Before starting a new trial of the experiment at the 17th floor, it was ensured that the SF_6 concentration measured in the room at the 17th floor was below 0.1 ppm. Again, this ensures both the room and the gas analyzer itself was not contaminated before starting a new trial at a new floor.

6.4 Measurement Results

Figure 6.5 shows the observation in test 1, at which the exhaust fan was turned ON, and all window and door were closed. Tracer gas was detected at 37th floor, after 3 minutes and 43 seconds (figure 6.5), showing an upward air flow direction in the drainage stack, if the building services system was operated in a same manner of our test. This agrees with the computational analysis on the airflow characteristic by simulation [Swaffield and Jack 2004, Jack et al. 2006, Douglas et al. 2005], and it is reported by Jack [2006] that the flats between the 17th floor and 33rd floor is susceptible for viral attack. Our study also confirms further that the highest floor of our test building, the 37th floor, was also susceptible. Our result may provide a possible explanation of why the 35th floor of flat 7, block E, was attacked. In test 2 only a trace amount of SF_6 was detected when the exhaust fan was switched OFF throughout a measuring period of 15 minutes. The amount of tracer gas detected in test 3, also lasting for a measurement period of 15 minutes, was also comparatively small when compared with test 1 (figure 6.6). Figures 6.7 to 6.8 show the test results for the 17th and 27th floors respectively. Figure 6.9 summarizes the observation.

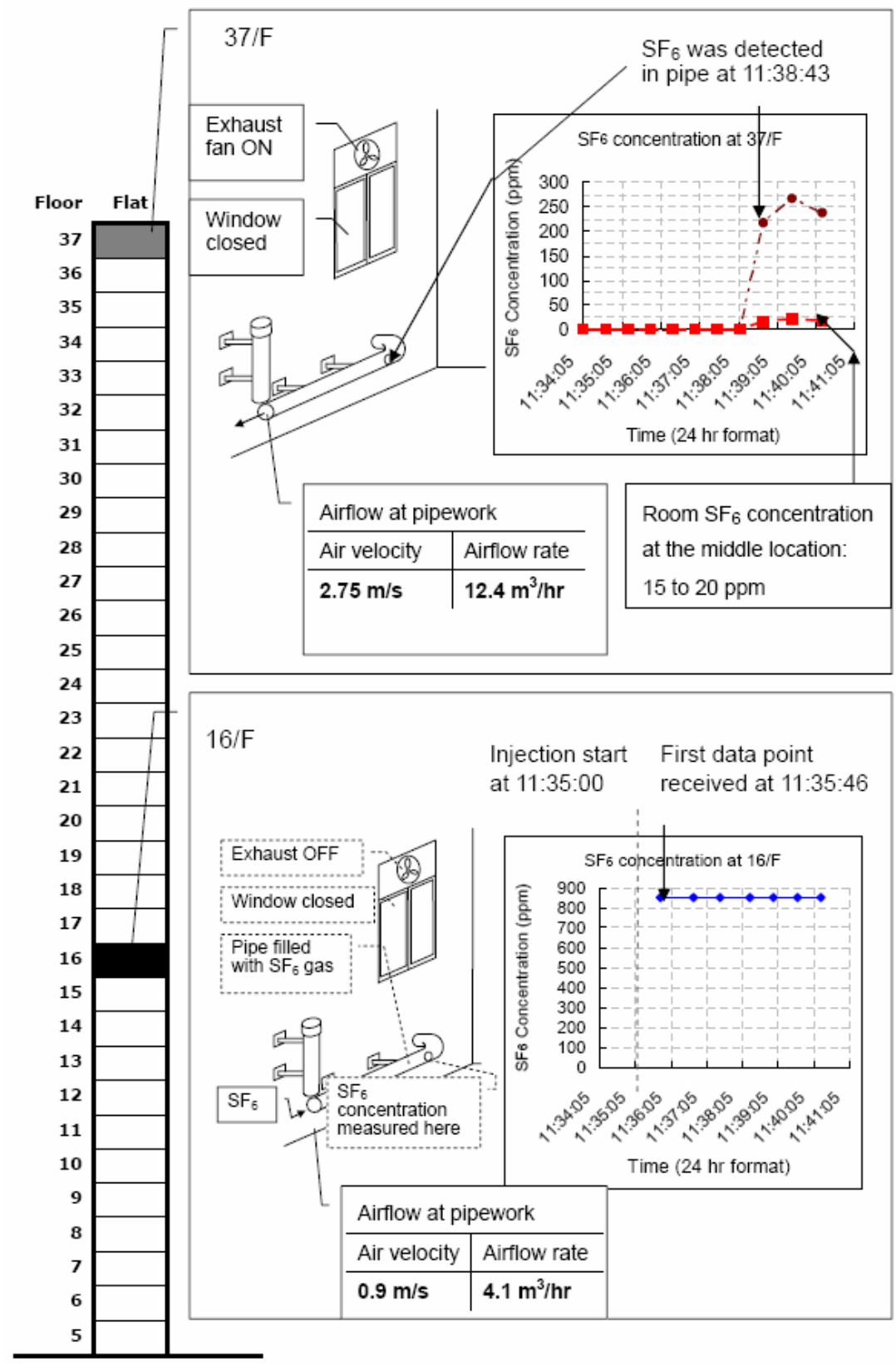


Figure 6.5 Concentration of tracer gas (SF_6) injected at 16th floor, and received at 37th floor

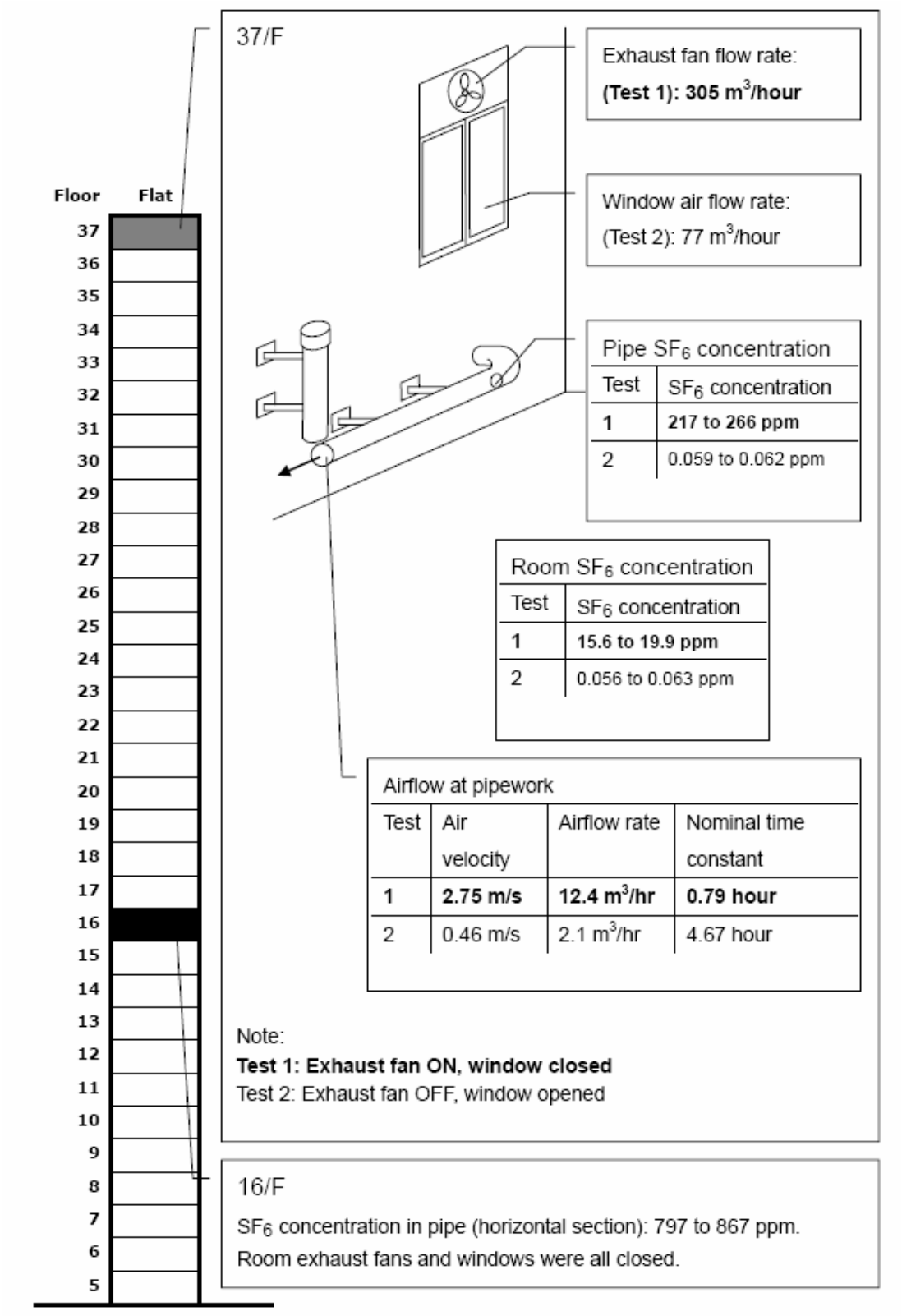


Figure 6.6 Quantity of tracer gas (SF_6) received at the 37th floor at different ventilation modes (mechanical exhaust fan vs. window natural ventilation vs. both)

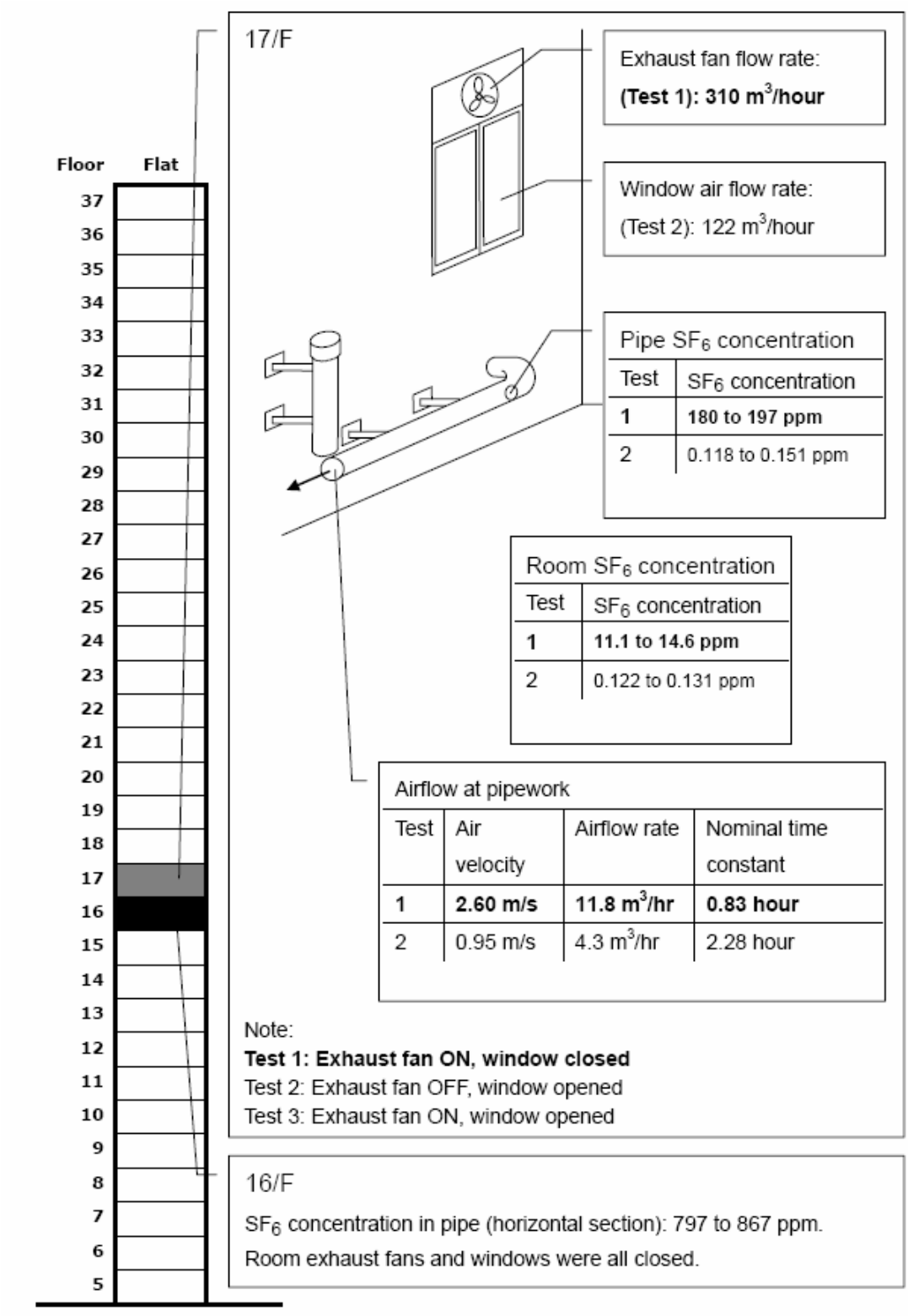


Figure 6.7 Quantity of tracer gas (SF_6) received at the 17th floor, at different ventilation modes (mechanical exhaust fan vs. window natural ventilation vs. both)

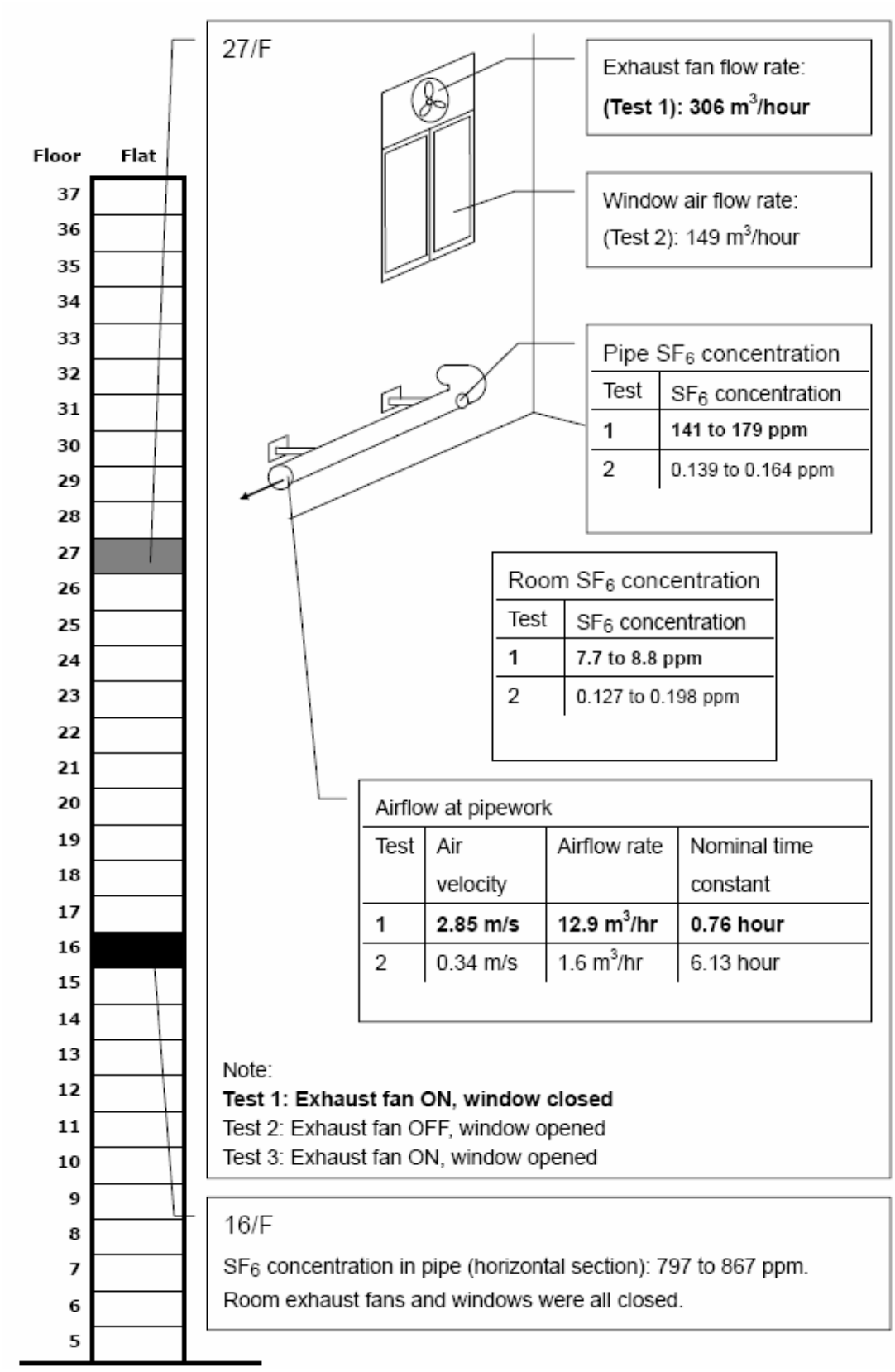
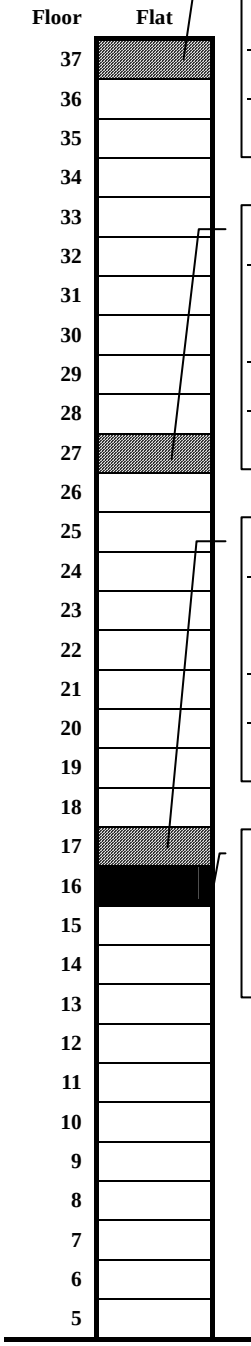


Figure 6.8 Quantity of tracer gas (SF_6) received at the 27th floor, at different ventilation modes (mechanical exhaust fan vs. window natural ventilation vs. both)



37/F

SF_6 conc.	**Exhaust fan ON** **Window closed**	Exhaust fan OFF Window opened
Pipe	**217 to 266 ppm**	0.059 to 0.062 ppm
Room	**15.6 to 19.9 ppm**	0.056 to 0.063 ppm

27/F

SF_6 conc.	**Exhaust fan ON** **Window closed**	Exhaust fan OFF Window opened
Pipe	**141 to 179 ppm**	0.139 to 0.164 ppm
Room	**7.7 to 8.8 ppm**	0.127 to 0.198 ppm

17/F

SF_6 conc.	**Exhaust fan ON** **Window closed**	Exhaust fan OFF Window opened
Pipe	**180 to 197 ppm**	0.118 to 0.151 ppm
Room	**11.1 to 14.6 ppm**	0.122 to 0.131 ppm

16/F

SF_6 concentration in pipe (horizontal section): 797 to 867 ppm.
Room exhaust fans and windows were all closed.

Figure 6.9 Tracer gas concentration measured at different floors

6.5 Risk Estimation by Wells-Riley Equation

To evaluate the relative risk of infection under different modes of exhaust system operation, the Wells-Riley model for airborne infection [Wells 1934, Riley et al. 1978] was applied. This mathematical model was developed to account for the statistical probability of escaping infection [Riley et al. 1978], with reference factors affecting the infection risk, including the number of "infectious quanta" generated to the room by the infector(s), the breathing rate and the time duration of exposure of a susceptible person, and the volumetric ventilation rate of the enclosed space [Nardell 2001, Ko 2001]. The model was postulated with the concept of quantum of infection. One "infectious quanta" was defined as being the number of infectious droplet nuclei required to infect $(1 - e^{-1})$ of susceptible person [Wells 1955, Beggs et al. 2003]. The number of infectious quanta generated per hour, q, may serve as an index indicating the relative infectiousness [Nardell 2001] and the quantity of infectious agent released in a particular outbreak. The general mathematical expression of the Wells-Riley Model of Airborne Infection is shown as equation 6.1.

$$C = S\ (1 - e^{-\frac{Iqpt}{Q}}) \qquad \{\text{Equation 6.1}\}$$

where

C is the number of new infections

S is the number of susceptible persons

I is the number of infected persons in the index case

Q is the number of infectious quanta per hour generated from an infected person.

Q is the room ventilation rate (m^3/hour)

$\frac{I\ q}{Q}$ represents the concentration of infectious agent in the room

I × q represents the total infectious quanta added to the air per hour (Riley et al. 1978, Wells 1955, Nardell et al. 1991)

p is the pulmonary ventilation rate of a susceptible person (m^3/hr)

t is the time duration stayed inside the room (in hour)

p × t is the volume of air breath by the susceptible person (in m^3)

The probability of infection P can be estimated by dividing C with S, such that,

$$P = \frac{C}{S} = (1 - e^{-\frac{Iqpt}{Q}}) \qquad \{\text{Equation 6.2}\}$$

In equation 6.2, it is assumed that the whole fraction the infectious particle inhaled by the susceptible can deposit in the alveoli region in the lung and successfully trigger an infection. Several assumptions are made when using this equation, as stated in section 1.7 in chapter 1 in this thesis, including: (1) difference in susceptibility among the susceptible persons are ignored. (2) The generation rate of quanta of infection from the infectious person is considered constant. (3) Droplet nuclei inside the room is evenly distributed and well-mixed inside the receiver room. (4) The rate of change for the number of infected persons is proportional to the number of encounters between susceptibles and quanta of infection. This term is modeled with the lass of mass action. The probability obtained from equation 6.2 can be used as an indicator for the relative risk of getting infected among the susceptible persons under different scenario. In previous epidemiological studies [Riley et al. 1978, Riley 1974, Gammaitoni and Nucci 1997a, 1997b], the quantity of “infectious quanta” generated by the infected person(s) was indirectly measured with the use of Riley, Murphy and Riley model [Riley et al. 1978]. On the quantum generation rate of the outbreaks of Severe Acute Respiratory Syndrome, Liao et al. [2005] reported an estimation of 28.77 quanta per hour for two Severe Acute Respiratory Syndrome (SARS) outbreak cases in Taiwan, one in an elementary school and the other in the National Taiwan University (NTWU) Hospital. In another paper, Chen et al. [2006]

reported an estimation of 28.94 qph for the National Taiwan University Hospital outbreak. While the actual quantum per hour produced in an outbreak should vary among different incidents, the qph index reported in the above-mentioned literature was adopted on the estimation the relative risk of infection under different ventilation rates in buildings [Nardell et al. 1991, Escombe et al. 2007].

The dose rate of infectious quanta at the receiver flats (17, 27 and 37th floors) at the drainage pipe was estimated with reference to the fraction (α) of SF_6 tracer gas detected at receiver rooms that is transferred from the 16th source room. Table 6.1 shows the fraction values at receiver rooms under different mode of ventilation. Based on the dose rate at the receiver room horizontal drainage pipe, and the ventilation rate due to exhaust fan operation or opened windows, the predicted well-mix steady state concentration inside the room can be calculated and listed in table 6.2.

Table 6.1 Fractions of SF_6 detected at receiver floors

Floor	Pipe flow rate (m^3/hour)	SF_6 conc. at pipe (mg/m^3)	Dose rate (mg/hour)	Fraction c/w. 16/F (α)
16/F	4.1	5263	21246	Source room
17/F (mode 1)	11.8	1093	12893	α_{17A}: 0.6
17/F (mode 2)	4.3	0.72	3.08	α_{17B}: 0.000144
27/F (mode 1)	12.9	856	11041	α_{27A}: 0.52
27/F (mode 2)	1.6	0.84	1.35	α_{27B}: 0.000063
37/F (mode 1)	12.4	1317	16334	α_{37A}: 0.76
37/F (mode 2)	2.1	0.36	0.75	α_{37B}: 0.000035

Mode 1: Exhaust fan switched ON, windows closed

Mode 2: Exhaust fan switched OFF, windows opened

Table 6.2 Mixing factor at different ventilation modes

Floor	Steady state, well-mixed room SF_6 conc. (mg/m^3)	Observed room SF_6 conc. (mg/m^3)	Mixing factor (m)
17/F (mode 1)	41.6	67.4	0.617
17/F (mode 2)	0.0252	0.74	0.034
27/F (mode 1)	36.1	46.7	0.772
27/F (mode 2)	0.0091	0.77	0.012
37/F (mode 1)	53.6	94.7	0.566
37/F (mode 2)	0.0098	0.36	0.027

The predicted steady state, well-mixed room SF_6 concentration (C_∞) is calculated by equation 6.3. As the observed room SF_6 concentration is larger than the

observed C_∞, a mixing factor *m* is introduced to account for the imperfect mixing, and in the calculation of risk using Wells-Riley equation, the measured ventilation rate is multiplied by the mixing factor, such that the equivalent ventilation rate is used in the risk estimation (equation 6.4).

In this case the infected person has not entered the receiver room (17/F, 27/F, 37/F), it is the vertical drainage stack which can propagate the infectious quanta from an infected person at the index floor to the receiver floors. The vertical drainage stack acts like an infected person to generate the infectious quanta inside the room. The fraction term α in table 6.1 can be interpreted as the equivalent "number of persons" inside the room. Thus in equation 6.1, the term *I*, the number of infected person, is replaced by the term α, and shown in equation 6.4. The fraction term α is multiplied with the quanta generation rate at 16th floor, to represent the expected quanta dose rate at the receiver floor.

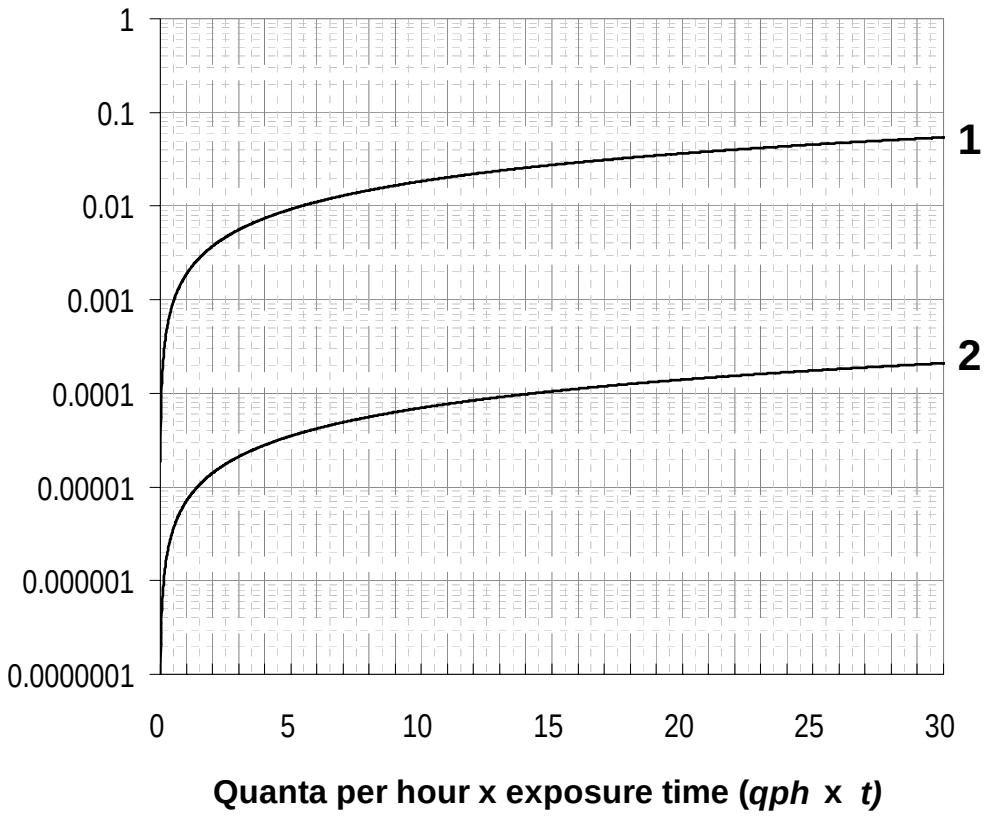
$$C_\infty = \frac{G}{Q_{\text{observed}}} \qquad \{\text{equation 6.3}\}$$

where G is the SF6 dose rate at the receiver floor, measured at the horizontal drainage pipe, Q_{observed} is the measured air flow rate at the exhaust fan or the

window.

$$\text{Probability of infection at receiver room} = 1 - e^{-\frac{\alpha qpt}{mQ}} \quad \{\text{equation 6.4}\}$$

where q is the quanta generation rate at the 16th floor source room, and m is the mixing factor as shown in table 6.2. Using equation 6.4, the predicted probability of infection can be estimated. To compare the effect of the mode of ventilation on the risk of infection, the risk of infection is plotted against the product $q \times t$, for a person stays inside the room for a time of exposure t (in hours), in figures 6.10 to 6.12, as the quantity and infectivity of a disease outbreak as represented by the index q, the number of infectious quanta produced from the index person, can vary among different cases. The quanta generation rate reported in Taiwan hospital outbreak (28.77 quanta per hour) is adopted as an example reference value for probability calculation. The pulmonary inhalation rate p is assumed to be 0.42 m^3/hour for a typical person.



1: $\text{Risk} = (1 - e^{-0.00186qt})$ {Equation 6.5}

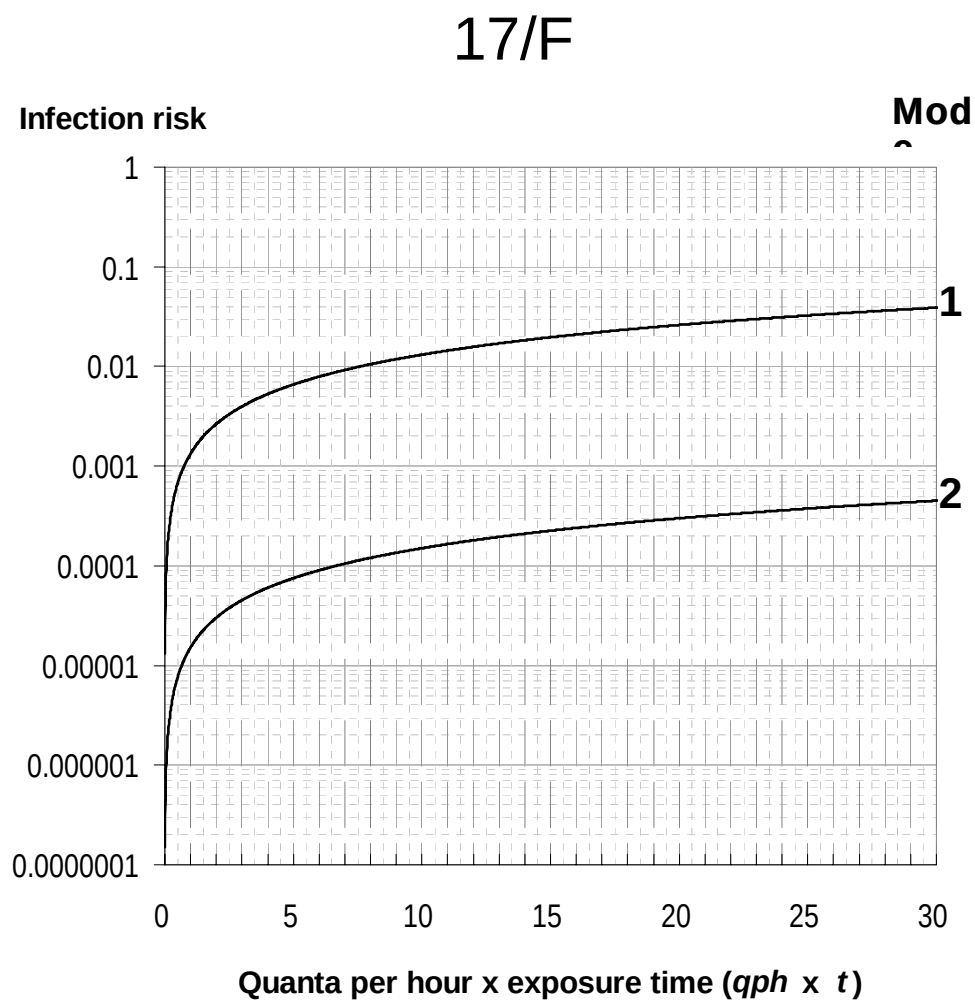
2: $\text{Risk} = (1 - e^{-0.000007qt})$ {Equation 6.6}

Mode 1: Exhaust Fan ON, Window closed. (α_{37A} = 0.76)

Mode 2: Exhaust Fan OFF, Window opened. (α_{37B} = 0.000035)

Risk	q = 28.77, exposure 15 minutes	q = 28.77, exposure 1 hour
Mode 1	0.0133	0.052
Mode 2	0.00005	0.0002

Figure 6.10 Risk of infection, 37th floor.



1: $\text{Risk} = (1 - e^{-0.00132qt})$ {Equation 6.7}

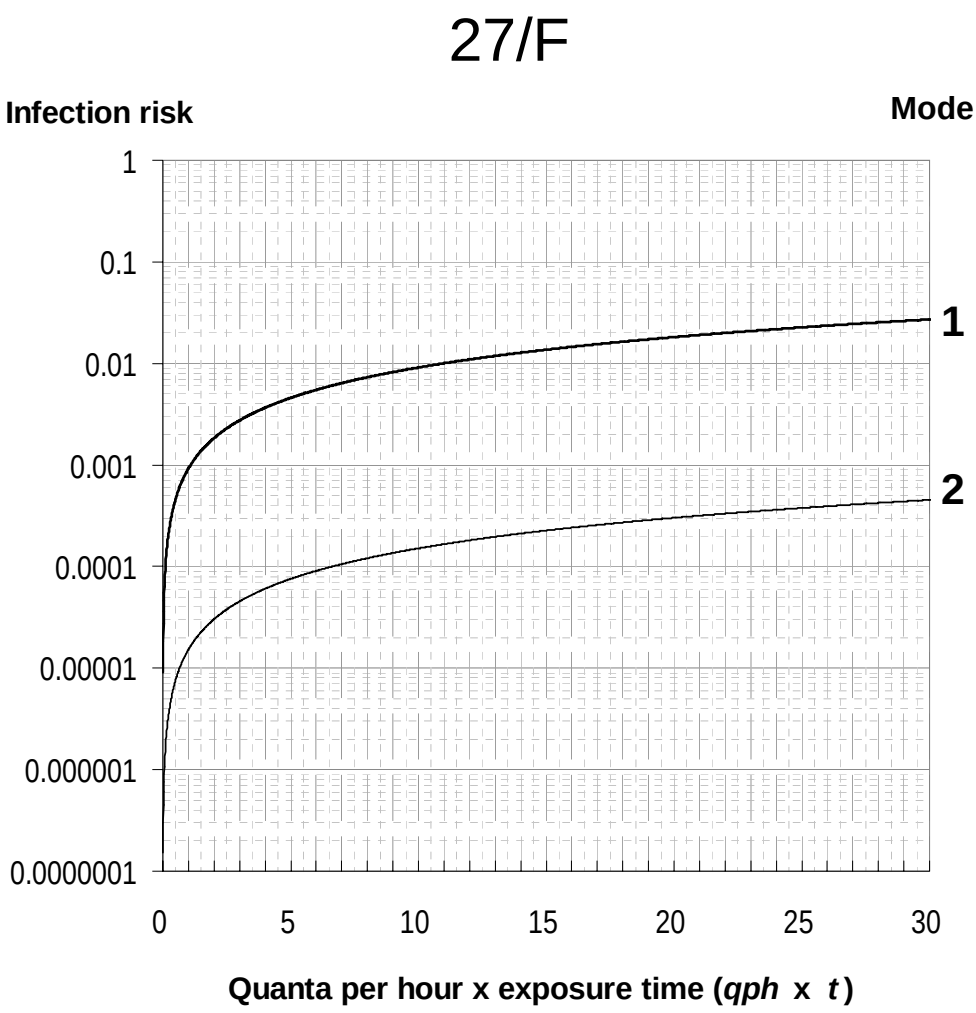
2: $\text{Risk} = (1 - e^{-0.000015qt})$ {Equation 6.8}

Mode 1: Exhaust Fan ON, Window closed. (α_{37A} = 0.60)

Mode 2: Exhaust Fan OFF, Window opened. (α_{37B} = 0.000144)

Risk	q = 28.77, exposure 15 minutes	q = 28.77, exposure 1 hour
Mode 1	0.0095	0.0373
Mode 2	0.00011	0.00043

Figure 6.11 Risk of infection, 17th floor.



1: $\text{Risk} = (1 - e^{-0.00092qt})$ {Equation 6.9}

2: $\text{Risk} = (1 - e^{-0.000015qt})$ {Equation 6.10}

Mode 1: Exhaust Fan ON, Window closed. (α_{37A} = 0.52)

Mode 2: Exhaust Fan OFF, Window opened. (α_{37B} = 0.000063)

Risk	q = 28.77, exposure 15 minutes	q = 28.77, exposure 1 hour
Mode 1	0.0066	0.0264
Mode 2	0.00011	0.00043

Figure 6.12 Risk of infection, 27th floor.

6.6 Microbiological Hazard in Household Toilets

In this study the tracer gas injected to the drainage pipe represents the case that the index infected person used the toilet, such that a flush of a toilet generates huge numbers of aerosols by the hydraulic action in vertical soil stacks [Yu et al. 2004]. Early in 1975, Gerba et al. [1975] commented that there is a possibility for a person to acquire an infection from an aerosol produced by a toilet, in their study on the microbiological hazard in a household toilet. Experiment conducted by Lam [2004] shown that a minimum concentration of 40000 aerosol particles (within the particle size range of 0.3 to 0.4 μm) per litre of air can be observed during a flush of water-closet. In addition, with reference to a relative long survival period of the SARS virus reported by the World Health Organization [2003a, 2003c], and the suggestion made by Anderson et al. [2004] that viral transmission could occur via faecel or urine contamination of surfaces, we adopted the continuous injection test, and not considering an impulse injection. The World Health Organization (WHO) reported that the SARS coronavirus was shown to survive on plastic surface for up to 48 hours, up to 1 to 2 days in urine, and up to 2 days in stool, and up to 4 days with diarrhea [WHO 2003a, Rabenaus et al. 2005, Yassi et al. 2005, Louie 2006]. For a typical indoor environment, the survival time for the human coronavirus 229E in

experimental aerosol could persist and retain viability for as long as 6 days at 20°C and 50% relative humidity, a typical indoor condition. The SARS coronavirus is expected to have similar airborne survival characteristics, given that these viruses are in the same family and have broadly similar physicochemical properties [Ijaz et al. 1985, Booth et al. 2005, Tan et al. 2005]. Lai et al. [2005] also suggested that the SARS coronavirus (strain GVU6109) can remain infectious in respiratory specimens for 7 days or longer at room temperature.

6.7 Comparison with the Case Clusters

Our measurement reveals that the operation of exhaust fan at the upper floor causes a significance increase in the risk of infection, while if the window is opened, a much lower air transfer index was obtained from our observation, thus the quantity of infectious agent discharged from the drainage pipe decrease significantly. The dried-up trap at the sanitary fitment attached to a drainage system is also a necessary condition for the air to enter the room from the drainage pipe. When comparing our findings with the cluster distribution of the Amoy Gardens outbreak (Hong Kong Department of Health 2003) in figure 6.15, it is not surprising that not all the floors at flat 7, above 16th floor, were attacked if the drainage stack is responsible for the viral transmission for flats 7 at block E, since some of the floors were protected by

the water trap seal, or the occupants did not use the exhaust fan even if the trap seal was absent, leading to a significant decrease on the quantity of viral contaminated air transferred from the drainage system to the susceptible room, as verified in our test. Generally speaking, the habit of the operation of exhaust system, and the maintenance of sanitary fitments and the water seal in the trap among the occupants is not related to the height level of the room, possibly random in nature. Based on this hypothesis, it is not surprised to find a scattered, or in other words, a random distribution of infected case at the upper floors above the 24th floor at flat 7 (figure 6.13), if the drainage pipe is considered to take a role of SARS virus transmission, and responsible for the infection cases along flats 7 above the index case.

Floor	Flat 1	Flat 2	Flat 3	Flat 4	Flat 5	Flat 6	Flat 7	Flat 8
36				1		1		1
35							1	3
34	1							
33					1			
32		1	1					2
31			1	1			1	3
30		3						1
29			1					4
28		1	1				2	1
27								2
26				1				4
25	1		1					3
24							1	2
23	1			1			1	
22			1				1	4
21				3				3
20	1			2			1	2
19		1		1			2	2
18		2	1				5	3
17	1					1	2	2
16				2			3	3
15	1	3				1	2	
14	1					1	3	3
13		1				1	1	3
12								2
11								1
10		1			1			1
9								2
8								
7								
6	1							
5		1						
4								

*The number indicates no. of infected persons inside that particular flat.

**Index flat: 16/F flat 7

Figure 6.13 SARS infected cases in block E, Amoy Gardens [Hong Kong Department of Health 2003]

While an upward flow of air, and most likely the same case for aerosolized viral particle, was observed in our study; this does not exclude the possibility that a few floors lower than the index flat, may also get infected due to air transfer from the contaminated drainage stack if the water trap seal was emptied, since it is not

impossible that the urine, faecel and diarrhea matter would fall downward and contaminated the internal surface [Anderson et al. 2004] inside the vertical drainage stack, at the location of a few floors below and near the index flat. In addition, for searching an explanation of why some of the floors for flat 7, below 16th index floor, were also attacked in the outbreak, the other suspected transmission routes should not be excluded, and further research is needed. In case of surface contamination, building users should be aware of the importance of thorough disinfection of the infected area [Chau and Yip 2003].

6.8 Safe Operation of the Ventilation and Drainage System

While opening the window can reduce the risk of air extraction from the drainage system, by opening the window facing the re-entrant light-well, in typical high-rise residential buildings in Hong Kong, it means to allow a transfer of contaminated air from flat to flat, and the risk of infection is still exist, as demonstrated in studies by Yu et al. [2004] and Li et al. [2004a], and in chapter 7 in this thesis. As a result, instead of avoiding the use of air exhaust system, the most effective way to reduce the infection risk is to ensure the air ventilation path to flow from the clean side to the less-clean area like the re-entrant (figure 6.14). The doors of kitchen and

bathrooms that are facing re-entrant, and the windows inside, shall be closed. In addition, it is more important to ensure the water trap seal connected to the drainage system is always exist, before switching on the mechanical air exhaust fan.

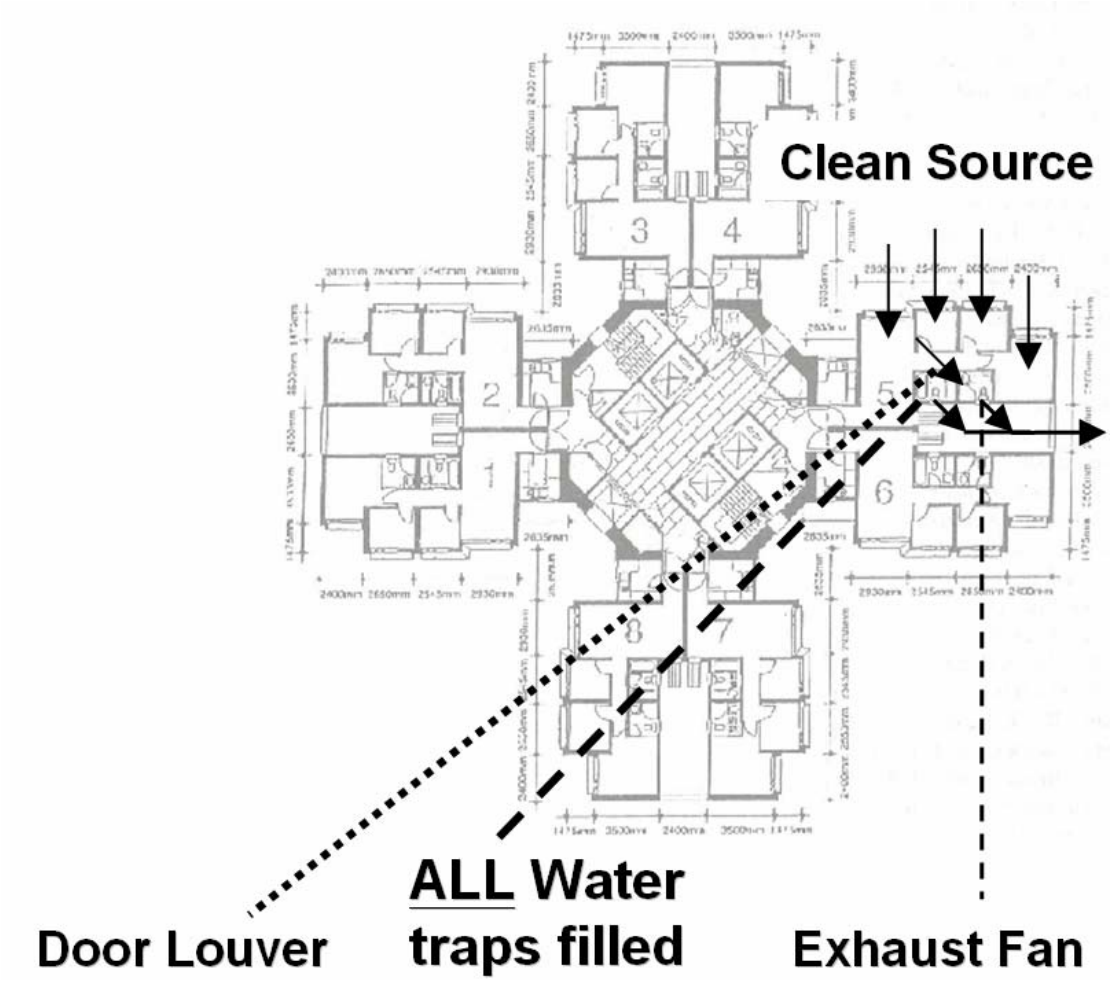


Figure 6.14 Recommended ventilation path for typical residential building in HK.

6.9 Chapter Summary

The research finding in this study verifies that the upward airflow direction along the vertical drainage stack is possible if a mechanical exhaust fan is operated at one of the upper floor above the index case, with all the windows and door closed inside the room, and under the condition of an absence of water trap seal in any one of the sanitary drainage fitment. In such case the vertical drainage stack acts as an infected person to generate the infectious matter to the upper floors above the index floor. While a comparatively higher risk of airborne infection is estimated with the sole use of exhaust fan which may extract the foul air from drainage system, the building users should be cautious on the maintenance of the water trap seal in all sanitary drainage fitments, to protect themselves by preventing foul air to enter the occupied space, rather than avoiding the using of mechanical exhaust fan when it is necessary. The rule of “clean source, clean path” on air ventilation in residential (and for all buildings) should be observed to prevent the transfer of air from the contaminated side. In addition, further research on the appropriate design practice and sizing of the mechanical exhaust system and fans, for waste air disposal from building in a safe manner, shall be necessary. The risk of airborne transmission of infection via the vertical drainage stack is studied in this chapter, assuming the infective aerosol particles behave like gas molecule. In this sense the risk value is not an absolute

value, and the methodology adopted in this chapter is only applicable to airborne species which are still viable in tiny droplet nuclei. Even so, the result is still useful to compare the relative risks for different operating scenarios of building services system. The drainage route study result compare with the other hypothetical routes, e.g. the re-entrant light-well route the investigation is reported in chapter 7. The result from this chapter can be compared with the re-entrant light-well route study in chapter 7.

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CHAPTER 7: ASSESSING VENTILATION PERFORMANCE AND AIRBORNE INFECTION RISK IN RESIDENTIAL BUILDING

In chapter 6, the potential risk of cross-contamination from flats to flats in a high-rise residential building is discussed, in particular for the situation of empty water trap in drainage system, and the operation of mechanical fan which can induce a suction of air from the middle floor to the upper floors in a building. The finding in chapter 6 leads to a recommendation on the maintenance of water trap seal in drainage system, and a safe operating mode for ventilation system to ensure adequate ventilation and avoid air intake from a contaminated source, for both the foul air from drainage system and the foul air from the semi-enclosed light-well (re-entrant) should be avoided. This chapter continues to investigate the ventilation performance of typical high-rise residential buildings in Hong Kong, and the possibility of cross-contamination of air from flats to flats through the re-entrant of a building.

7.1 Air Ventilation Rate and Respiratory Infection Risk

As described in chapter 1, a theoretical model, named as the Wells-Riley equation, is available from the literature to relate the risk of airborne infection as a function of

outdoor air ventilation rate delivered to the indoor environment. On the role of ventilation in controlling the spread of airborne infectious diseases, Billings [1893] had complied statistics on the death rates of men in well-ventilated versus unventilated barracks, ships and prisons. It was proposed that numerous diseases, including tuberculosis, were caused by or exacerbated by insufficient ventilation (as mentioned by [Addington 2001]), and recommended a ventilation rate of 60 ft^3/min (28.3 L/s) per persons was necessary to avoid cross infection in medical ward for patients with tuberculosis. Li et al. [2007] conducted a systematic review on the role of ventilation in airborne transmission of infectious agents in a built environment. Numerous reporting studies were conducted by Menzies et al. [2000] and Hoge et al. [1994], and other 38 studies were reviewed in an attempt to establish a specification and quantification of minimum ventilation requirements to minimize the transmission of airborne infectious diseases based on modern studies. Menzies et al. [2000] conducted an investigation on the risk of tuberculosis infection among healthcare workers in hospitals and reported that the infection risk is higher for those working in non-isolation rooms with ventilation rate of less than two air changes per hour. In another study, Hoge et al. [1994] found that an epidemic of pneumococcal disease in a jail (location), the cell blocks with the lowest ventilation rate and a smallest living space per person suffered the highest attack rate of disease. The

attack rate in a cell block with a ventilation rate of 4.2 ft^3/min (or 1.98 L/s) per person was 7.3 cases per 1000 inmates, while for cell blocks with higher ventilation rates of 7.1 (or 3.35 L/s) and 8.0 ft^3/min (or 3.78 L/s) per person, the attack rates were reduced to 4.4 and 3.1 cases per 1000 inmates respectively. While these studies provide evidence on the association between air ventilation rate in built environment and the risk of infectious disease, it is not sufficient to rely solely on the above observations to support a specification or a quantification of the minimum ventilation requirements in relation to the spread of airborne infectious diseases. While it is not possible to establish benchmarks from the literature to assess ventilation performance in buildings on the basis for prevention of airborne infectious disease, several legislative requirements may be adopted to serve as a benchmark.

7.2 Legislative Requirement on Ventilation for Residential Buildings in Hong Kong

Ventilation requirements for residential buildings in Hong Kong are specified in the Building (Planning) Regulation Chapter 123F, regulation 29 to 37. The regulations mainly specify the definitions of “open air” are the size of windows (facing open air) in the rooms, and the maximum degree of obstruction allowed outside such window.

Regulations 29 to 33 outline the requirements on windows: size and the maximum degree of obstruction allowed outside the window. The first is that the aggregate superficial area of glass in the window should not be less than one-tenth of the room floor area, and the windows can be opened, to an extent of, at least equal to the aggregate to one-sixteenth of the room floor area. Due to the reason of maximum allowable obstruction angle of window enacted in the Building Ordinance since 1962 [Butterworths 2002], the obstruction angle of window is 71.5 degrees for habitable rooms and 76 degree for kitchens. The above requirements apply to “rooms for habitation”, which exclude kitchens, staircases, staircase halls, lift landings, the space used in providing the water-closet fitments, urinals and lavatory basins, according to the interpretation stated in Building (Standards of sanitary fitments, plumbing, drainage works and latrines) Regulation. While the requirements on kitchen windows are stated in addition to “habitable rooms”, in Building (Planning) Regulation Chapter 123F, Regulations 29 to 33, there is no account on the requirements for toilet window. Instead, the requirements on windows provision for washrooms and toilets in residential flats are specified in Regulation 36. In this regulation, the requirements on size of opening is specified in a similar manner with Regulations 29 to 33 (the aggregate superficial area of glass therein is not less than the equivalent of one-tenth of the area of the floor of the room; and a part thereof,

not less in area than the equivalent of one-sixteenth of the area of the floor of the room, can be opened directly into the open air). There is no requirement on the obstructions to the windows, but by the definition for “open air”, in which a window must be vertically uncovered, unobstructed in not less, in any horizontal dimension, than 1.5 m. This can be interpreted as “a minimum requirement” on the width of re-entrant gap. If a washroom window is located opposite to it, a horizontal distance of 1.5 m must be available to fulfill the requirement in CAP123F, Regulation 36. These are the prescriptive requirements for ventilation design. In this study the “open air” definition described in the Building Regulation is regarded as a “pseudo” open air, and the term “true” open air is used to distinguish the windows that are not affected by re-entrant by any means.

In 2003 the Practice Notes for Authorized Persons, or PNAP no. 278 was issued. This practice note specifies a required air change rate, if a performance-based ventilation design is adopted in the residential building design. In the Practice Notes, an air change rate of 1.5 ACH (by natural means) is required for habitable rooms and an air change rate of 1.5 Air Change per Hour (ACH) (by natural means) plus 5 ACH (by mechanical means) is required for kitchens. By fulfilling the requirements in PNAP 278, applications to modify the prescriptive requirements set out in Building

(Planning) Regulations 30, 31 and 32 would be accepted during building design process [PNAP no. 278, revised version June 2005]. Similar arrangement is also established for toilets and bathrooms, which is documented in another Practice Notes no. 219, issued in year 2000. Application for modification of the requirement stated in Building (Planning) Regulation 36 would be accepted, if the requirements in PNAP 219 are fulfilled. Designers may consider artificial lighting system and mechanical ventilation, which is capable to achieve 5 ACH, as an alternative.

7.3 Overseas Ventilation Codes and Standards for Residential Buildings

In section 7.2, the legislative requirement on ventilation in residential buildings is discussed. The prescriptive requirement is based on the window size and the obstruction of window, while the performance-based requirement specifies the air change rate in habitable rooms, kitchen and toilet. The requirement as stated in the ventilation codes and standards in overseas countries is presented in table 7.1 for comparison. In New Zealand, Norway and United Kingdom, the ventilation requirements in living rooms and bedrooms are based on window (or ventilation opening) size, while in other European countries the ventilation rate is specified.

Table 7.1a Ventilation in dwellings [For overseas countries, information obtained from Concannon 2002, McWilliams and Sherman 2005]

Country	Whole building requirement	Living room	Bedroom	Kitchen	Bathroom + WC	Toilet only
Hong Kong		Openable area of window not less than 1/16 of floor area. (prescriptive) or 1.5 Air changes per hour (ACH) (performance based)		Openable area of window not less than 1/16 of floor area. (prescriptive) or 1.5 ACH by natural ventilation and 5 ACH by mechanical means	Openable area of window not less than 1/16 of floor area. (prescriptive) or 5 ACH by mechanical ventilation	
Belgium (NBNB62-003)	0.7 – 1.0 ACH 20 – 30 m^3/h/p		1.0 $dm^3/s/m^2$ floor area	50 – 75 m^3/s	14 dm^3/s	7 dm^3/s
Canada (CSA F361-M1989, ASHRAE 62-1989)	> 0.3 ACH 5 L/s/p			Exhaust 50 L/s (inter.) 30 L/s (cont.)	Exhaust 25 L/s (inter.) 15 L/s (cont.)	
Denmark (DS 418)		0.4 – 0.6 ACH		0.7 ACH	0.7 ACH	
Finland (NBC – D2)		0.5 L/s/m^2	4.0 L/s/p 0.7 L/s/m^2 floor area	Exhaust 20 L/s	Exhaust 15 L/s	

Table 7.1b Ventilation in dwellings [For overseas countries, information obtained from Concannon 2002, McWilliams and Sherman 2005]

Country	Whole building requirement	Living room	Bedroom	Kitchen	Bathroom + WC	Toilet only
Hong Kong		Openable area of window not less than 1/16 of floor area. (prescriptive) or 1.5 Air changes per hour (ACH) (performance based)		Openable area of window not less than 1/16 of floor area. (prescriptive) or 1.5 ACH by natural ventilation and 5 ACH by mechanical means	Openable area of window not less than 1/16 of floor area. (prescriptive) or 5 ACH by mechanical ventilation	
France (Arrete 24.03.82)				20 – 135 m^3/h	15 – 30 m^3/h	15 – 30 m^3/h
Germany (Din 18017, Din 1946, VDI 2088)		Min 60 – 120 m^3/h Max 60 – 180 m^3/h		Min 40 m^3/h Max 60 m^3/h	Min 40 m^3/h Max 60 m^3/h	Min 20 m^3/h Max 30 m^3/h
Italy (MD 05.07.75)	0.3 – 0.5 ACH	15 m^3/h/p		1.0 ACH	1.0 – 2.0 ACH	
Netherlands (NEN 1087)		1.0 $dm^3/s/m^2$ floor area	1.0 $dm^3/s/m^2$ floor area	21 dm^3/s	14 dm^3/s	7 dm^3/s

Table 7.1c Ventilation in dwellings [For overseas countries, information obtained from Concannon 2002, McWilliams and Sherman 2005]

Country	Whole building requirement	Living room	Bedroom	Kitchen	Bathroom + WC	Toilet only
Hong Kong		Openable area of window not less than 1/16 of floor area. (prescriptive) or 1.5 Air changes per hour (ACH) (performance based)		Openable area of window not less than 1/16 of floor area. (prescriptive) or 1.5 ACH by natural ventilation and 5 ACH by mechanical means	Openable area of window not less than 1/16 of floor area. (prescriptive) or 5 ACH by mechanical ventilation	
New Zealand (ASHRAE 62-1989)	Openable window to 5% of floor area in each room				25 L/s per room (inter.) 10 L/s per room (cont.)	
Norway (NBC ch47-1987)		Supply: openable window or inlet bigger than 100 cm^2 in external wall.	Supply: openable window or inlet bigger than 100 cm^2 in external wall.	Mech. Extract 60 m^3/h or by natural extract at least 150 cm^2 duct above roof.	Mech. Extract 60 m^3/h or by natural extract at least 150 cm^2 duct above roof.	Mech. Extract 40 m^3/h or by natural extract at least 100 cm^2 duct above roof.

Table 7.1d Ventilation in dwellings [For overseas countries, information obtained from Concannon 2002, McWilliams and Sherman 2005]

Country	Whole building requirement	Living room	Bedroom	Kitchen	Bathroom + WC	Toilet only
Hong Kong		Openable area of window not less than 1/16 of floor area. (prescriptive) or 1.5 Air changes per hour (ACH) (performance based)		Openable area of window not less than 1/16 of floor area. (prescriptive) or 1.5 ACH by natural ventilation and 5 ACH by mechanical means	Openable area of window not less than 1/16 of floor area. (prescriptive) or 5 ACH by mechanical ventilation	
Sweden (BFS 18ch4.1)	Supply: min. 0.35 l/s/m^2 floor area	Supply: 0.35 l/s/m^2 floor area	Supply: 4.0 L/s/p	Extract: 10 L/s per room	Extract 10-30 L/s	Extract: 10 L/s
Switzerland (SIA 384/2, SIA 382/1)			80 – 120 m^3/h		30 – 60 m^3/h	
United Kingdom (BS 5720-1979, BS 5925-1991, Building Reg. approved doc. F)	Rec 12 – 18 L/s/p Min. 8 – 12 L/s/p	Vent openings with at least 1/20 floor area, total area not less than 4000 mm^2.	Vent openings with at least 1/20 floor area, total area not less than 4000 mm^2.	Mech Supply 60 L/s (inter) or 30 L/s cooker hood & natural vent. Openings with total area not less than 134000 mm^2.	15 L/s (inter.)	Openings not less than 1/20 floor area or 3 ACH intermittent with overrun.

Table 7.1e Ventilation in dwellings [For overseas countries, information obtained from Concannon 2002, McWilliams and Sherman 2005]

Country	Whole building requirement	Living room	Bedroom	Kitchen	Bathroom + WC	Toilet only
Hong Kong		Openable area of window not less than 1/16 of floor area. (prescriptive) or 1.5 Air changes per hour (ACH) (performance based)		Openable area of window not less than 1/16 of floor area. (prescriptive) or 1.5 ACH by natural ventilation and 5 ACH by mechanical means	Openable area of window not less than 1/16 of floor area. (prescriptive) or 5 ACH by mechanical ventilation	
USA (ASHRAE 62 - 1989)	0.35 ACH but not less than 7.5 L/s/p			50 L/s (inter.) or 12 L/s (cont.) or openable windows	25 L/s (inter.) or 10 L/s (cont.) per room or openable windows	
USA (ASHRAE 62.2 - 2003)	0.05 x (total floor area) + 3.5 L/s/p			50 L/s (inter.) or 5 ACH (cont.) or openable windows	24 L/s (inter.) or 5 ACH (cont.) or openable windows	
Finland (NBC-D2, 2003)		0.5 L/s/m^2	6.0 L/s/p, or 0.35 L/s/m^2 floor area	Exhaust 8 L/s (cont.) 25 L/s (boost)	Exhaust 10 L/s (cont.) 15 L/s (boost)	Exhaust 7 L/s (cont.) 10 L/s (boost)

The performance-based requirement in Hong Kong (1.5 air changes per hour), is higher than some of the countries listed in the table, for example in Denmark (0.4 – 0.7 air change per hour), Belgium (whole building requirement of 0.7 – 1.0 ACH) and Italy (whole building requirement of 0.3 – 0.5 ACH).

7.4 Contemporary Ventilation Design in Private-sector Residential Buildings in Hong Kong

The plot ratio, site coverage and the accountable gross floor area controls stated in Building (Planning) Regulation resulting for the widespread development of point cruciform blocks, in response to the request of high spatial efficiency from developers [Ng 1998]. Before the implementation of Practice Notes 219 and 278, residential buildings built by private sector developers adopt cruciform design, to maximize the façade area for window provision in response to the prescriptive requirements on windows specified in the Building (Planning) Regulation. The windows in living rooms and bedrooms are typically open to the side with sufficient daylight and sky view. As a result, the kitchens and bathrooms are typically located at the internal façade of a flat, with windows facing re-entrants (figure 7.1).

The width of re-entrant gap can be as narrow as 1.5m to fulfill the requirement of “open air” in the Building (Planning) Regulation. As the floor plans are designed for spatial efficiency, the lift lobbies and corridors are squeezed to a minimum, and surrounded by dwelling units at all side. There may have no window for ventilating in the lift lobby. According to a window tunnel study by Ng [1998], the prevalent cruciform plan has the lowest ventilation coefficient when compared with alternative

residential design plan forms.

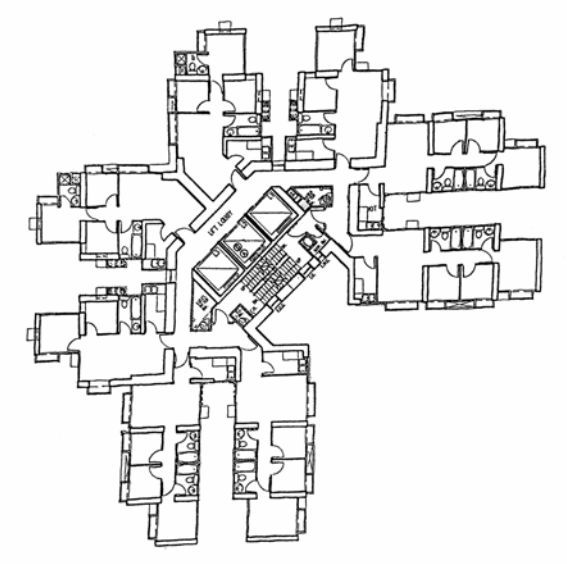

Figure 7.1 Cruciform layout of a typical private sector residential building

7.5 Ventilation in Cruciform Building in Hong Kong

7.5.1 Risk of Contamination via the Re-entrant

In 2003, the Severe Acute Respiratory Syndrome (SARS) outbreak in Amoy Gardens in Hong Kong triggered a concern on the ventilation performance in residential flats with re-entrant design, as the re-entrant light-well was proposed to be a hypothetic route for the transmission of SARS virus [Yu et al. 2004, Li et al. 2004].

A tracer gas experiment was conducted in a cruciform residential building to investigate if it is possible for a contaminant to travel from one flat to another through the air flow within the re-entrant. Sulphur hexafluoride (SF6) was used as a tracer. Two sets of Multi-gas monitors (Bruel and Kjaer model 1302) adopting photo-acoustic infra-red detection method were used. The building under

investigation is located at a private housing estate in Tseng Kwan O, as shown in figure 7.2. Basically, there are 8 flats at a single floor (figure 7.3), despite for upper floors on and above 24/F there are only 6 flats. Thus two of the flats (flats B and G as labeled in figure 7.2 and 7.3) are free from obstruction at both sides of the flat, without facing re-entrant at the upper floors (figure 7.4). Below road A (according to the orientation shown in fig. 7.2) is a hillside. There is no obstruction for at least 10 metres measured from the building to the hillside direction. Flat B of the residential block was selected as the main flat in the case study. The re-entrant size is 2.2 m width and 6.2 m depth as indicated in the figure 7.3.

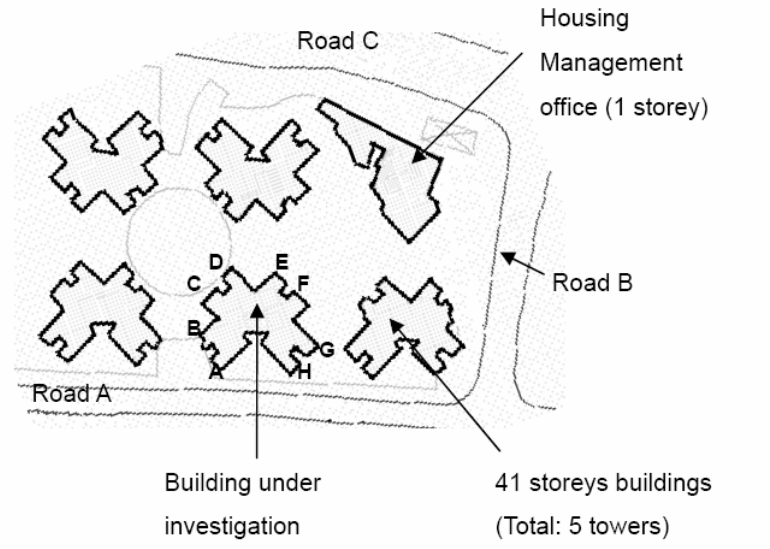

Figure 7.2 Housing Estates under Investigation

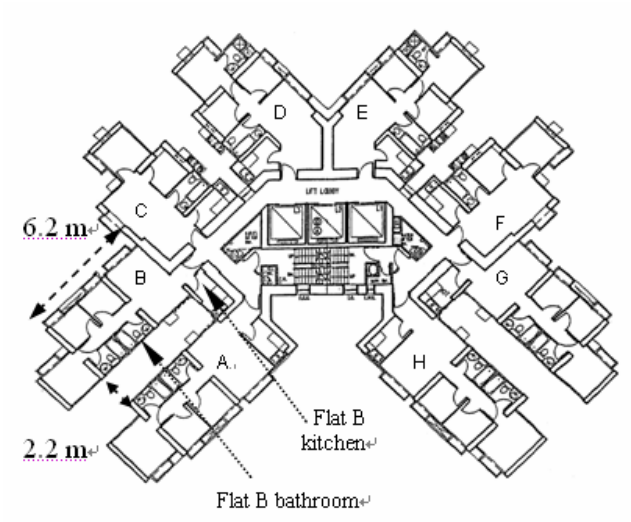

Figure 7.3 Floor plan for the building tower (1 to 23/F)

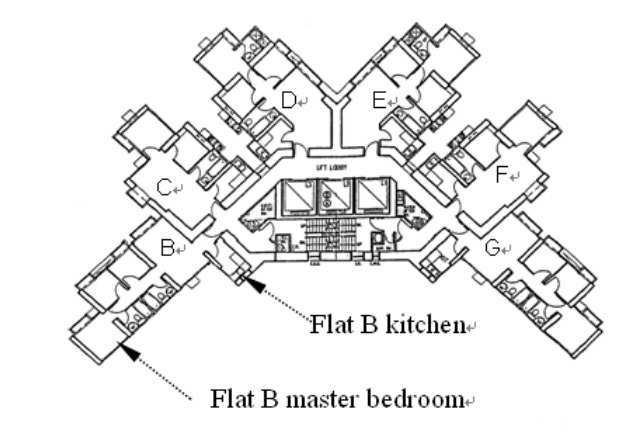

Figure 7.4 Floor plan for the building tower (24/F and above)

The kitchen in flat B at the second floor (2/F) as shown in figure 7.3 was selected as the source room. Window size for this kitchen is 0.6 m x 0.8 m (i.e. 0.48 m^2), and the kitchen floor area was 4.5 m^2, which means the window size was just fulfilling the minimum requirement, which is 1/10 of the floor area. Window-mounted axial fan (6 inch internal diameter) is installed, serving as exhaust fan inside the kitchen. Before the test, the infiltration rate of the room and the ventilation rate achieved by the

exhaust fan were evaluated. The infiltration rate was estimated by observing the tracer gas decay when the window was closed and the exhaust fan was turned OFF. Equations 7.1 and 7.2 are used for the calculation.

$$C = C_0 \, e^{-A t}$$ {equation 7.1}

Where C is the concentration of tracer gas at time t, C_0 is the tracer gas concentration at time t = 0, A is the air change rate and t is the time. Re-arranging the above equation yields the following equation:

$$A = (\ln C_0 - \ln C) / t$$

$$\ln C = -A t + \ln C_0$$ {equation 7.2}

The decay profile was shown in figure 7.5 and 7.6 and the infiltration rate was 0.27 air changes per hour.

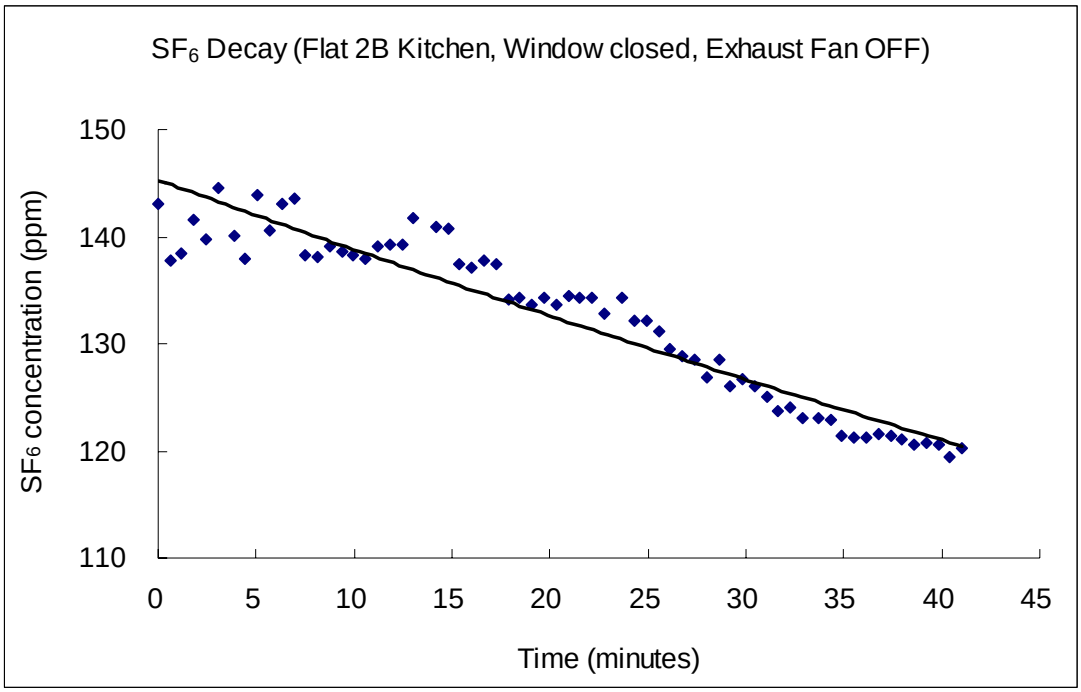

Figure 7.5 Decay profile for window closed and exhaust fan OFF in 2/F kitchen

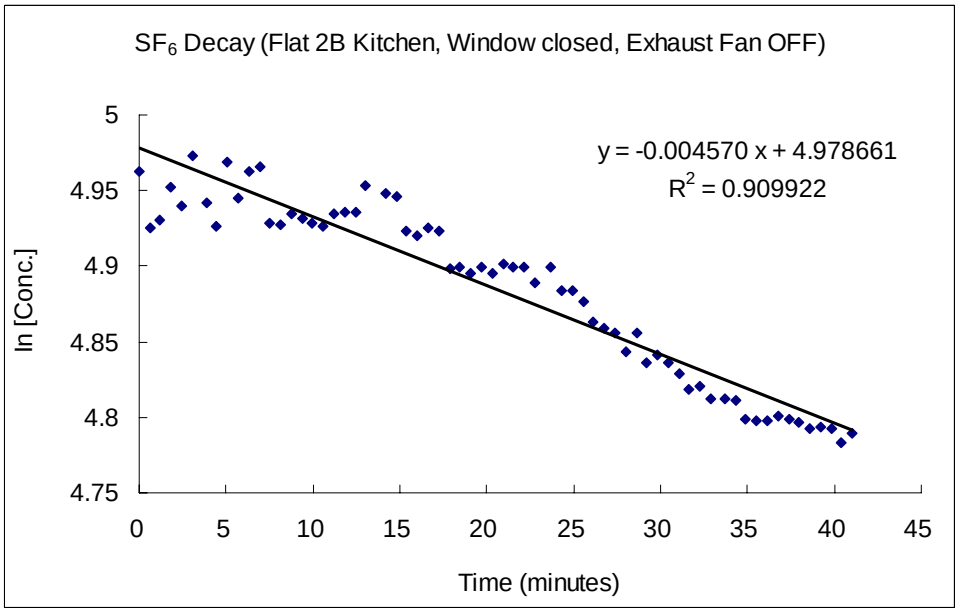

Fig 7.6 Log curve for window closed and exhaust fan OFF in 2/F kitchen

The air change rate achieved by the exhaust fan was evaluated by repeating the tracer gas experiment, with window closed and the exhaust fan turned ON. The exhaust

rate was 9.14 air changes per hour (figure 7.7 and 7.8).

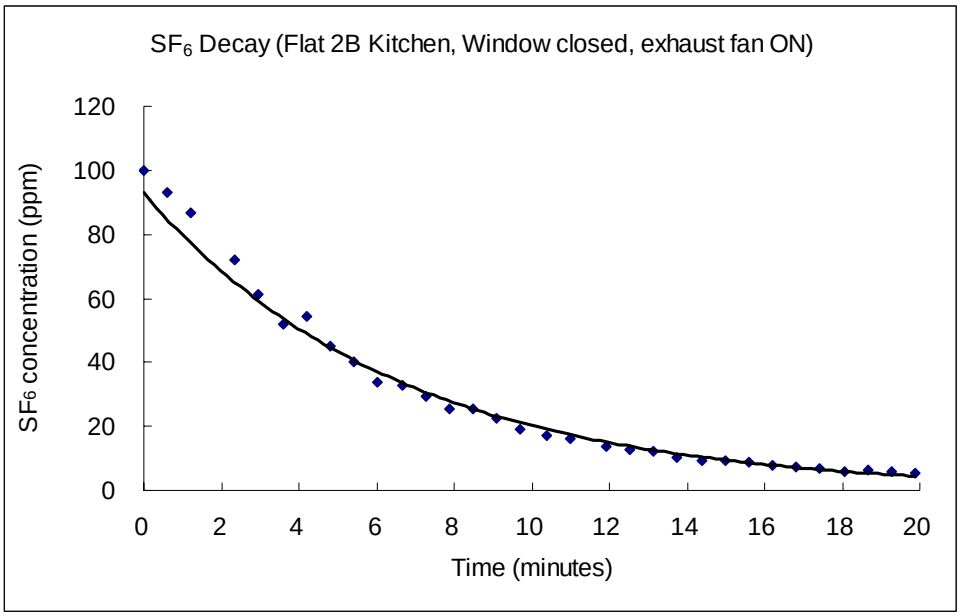

Figure 7.7 Decay profile for window closed and exhaust fan ON in 2/F kitchen

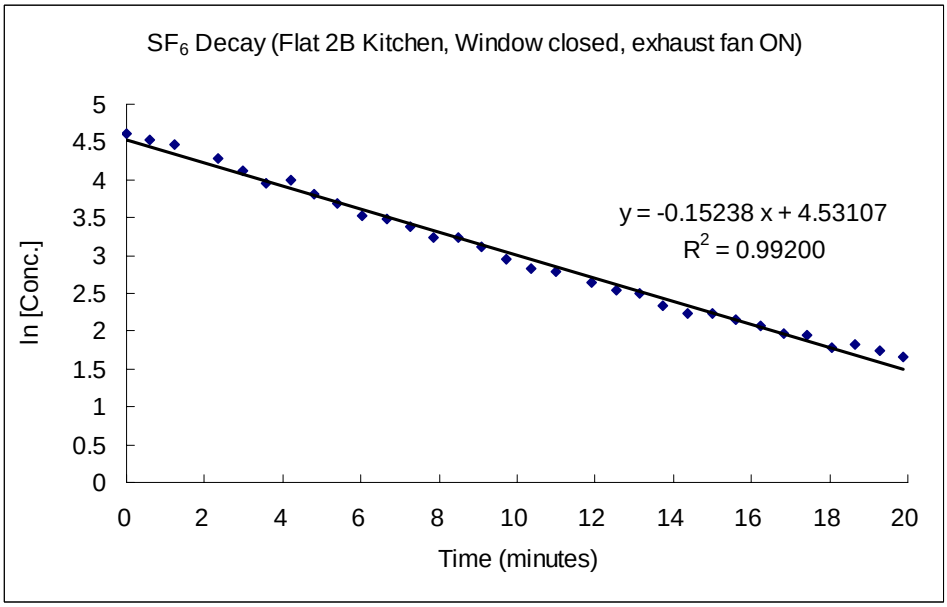

Figure 7.8 Log curve for window closed and exhaust fan ON in 2/F kitchen

In the third trial, tracer gas was injected in the kitchen located at 2/F SF_6 at an initial

concentration of 156 ppm. The window was closed and the exhaust fan was turned ON. In the 3/F kitchen, the window was opened with the exhaust fan turned ON to observe for whether there was any SF_6 tracer gas detected at the 3/F. The SF_6 decay profile at 2/F kitchen is shown in figure 7.9 and 7.10. The air change rate at 2/F kitchen in this test was 21.89 air changes per hour. The higher air change rate (21.89 vs. 9.14 ACH) could be explained by the operation of both the 2/F and 3/F exhaust fan.

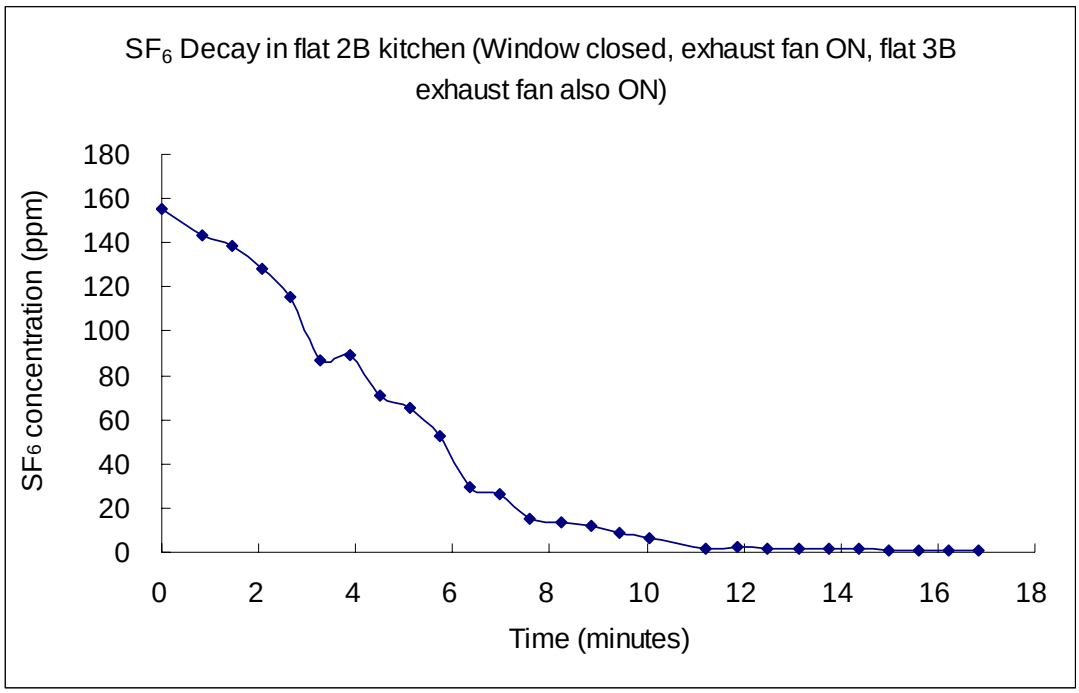

Figure 7.9 Decay profile for window closed and exhaust fan ON in 2/F and 3/F kitchen

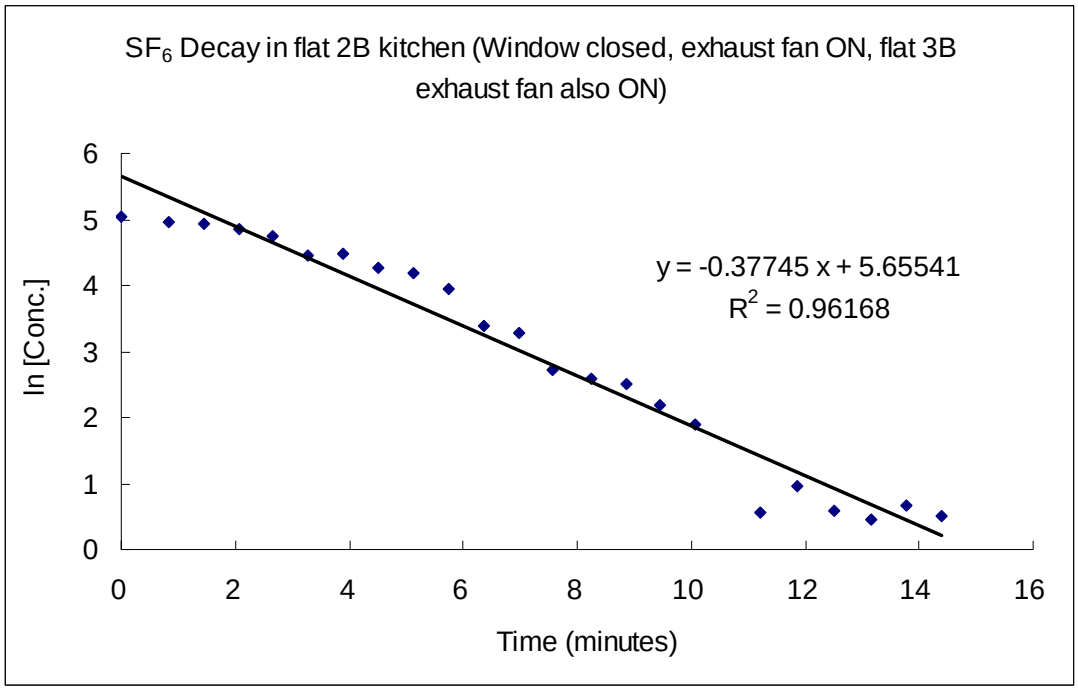

Figure 7.10 Log curve for window closed and exhaust fan ON in 2/F and 3/F kitchen

Figure 7.11 showed the concentration of SF_6 detected in 3/F kitchen when the window was opened to allow for air to enter from the 2/F exhaust fan via the re-entrant with the exhaust fan at 3/F turned ON. The room dimension, window size and exhaust fan installation inside the kitchen at 3/F is the same as the 2/F kitchen. Under this condition, the SF_6 concentration at 3/F was measured in the centre of the kitchen at a height of 1.1m above the floor. The maximum SF_6 concentration detected in the 3/F receiver room was 0.5 ppm, the concentration fraction (compare with the initial concentration in source room) is 0.003. This concentration is much lower than the concentration fraction of 0.019 obtained in the tracer gas test at the vertical drainage stack as described in chapter 6. Figure 7.12 shows the result obtained in chapter 6 for comparison. Despite this, the possibility of contaminant transmission via re-entrant light-well still exists, and the best way to avoid contamination is to keep the window facing re-entrant closed.

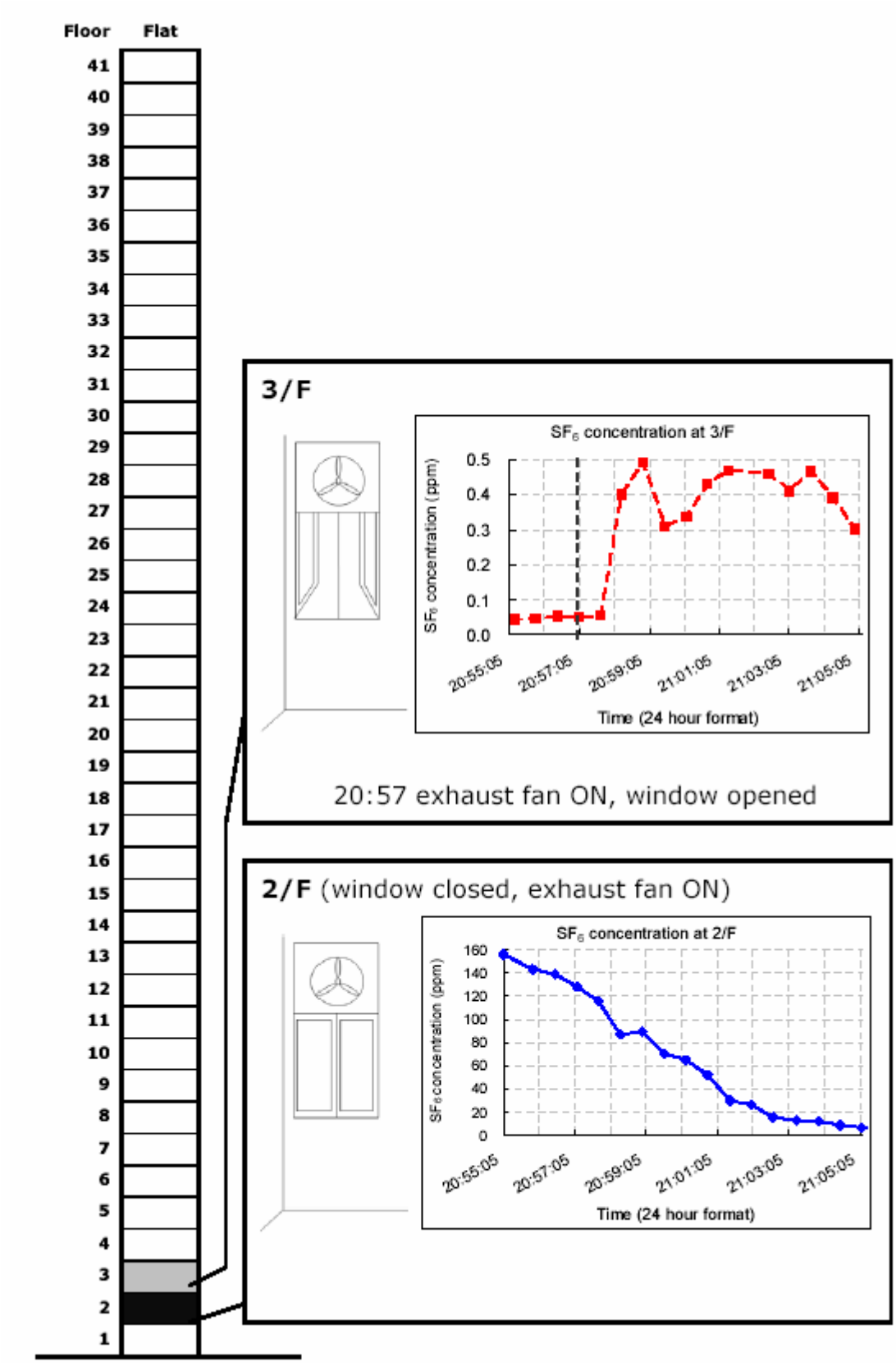

Figure 7.11 Concentration of tracer gas (SF_6) injected at 2nd floor and received at 3rd floor

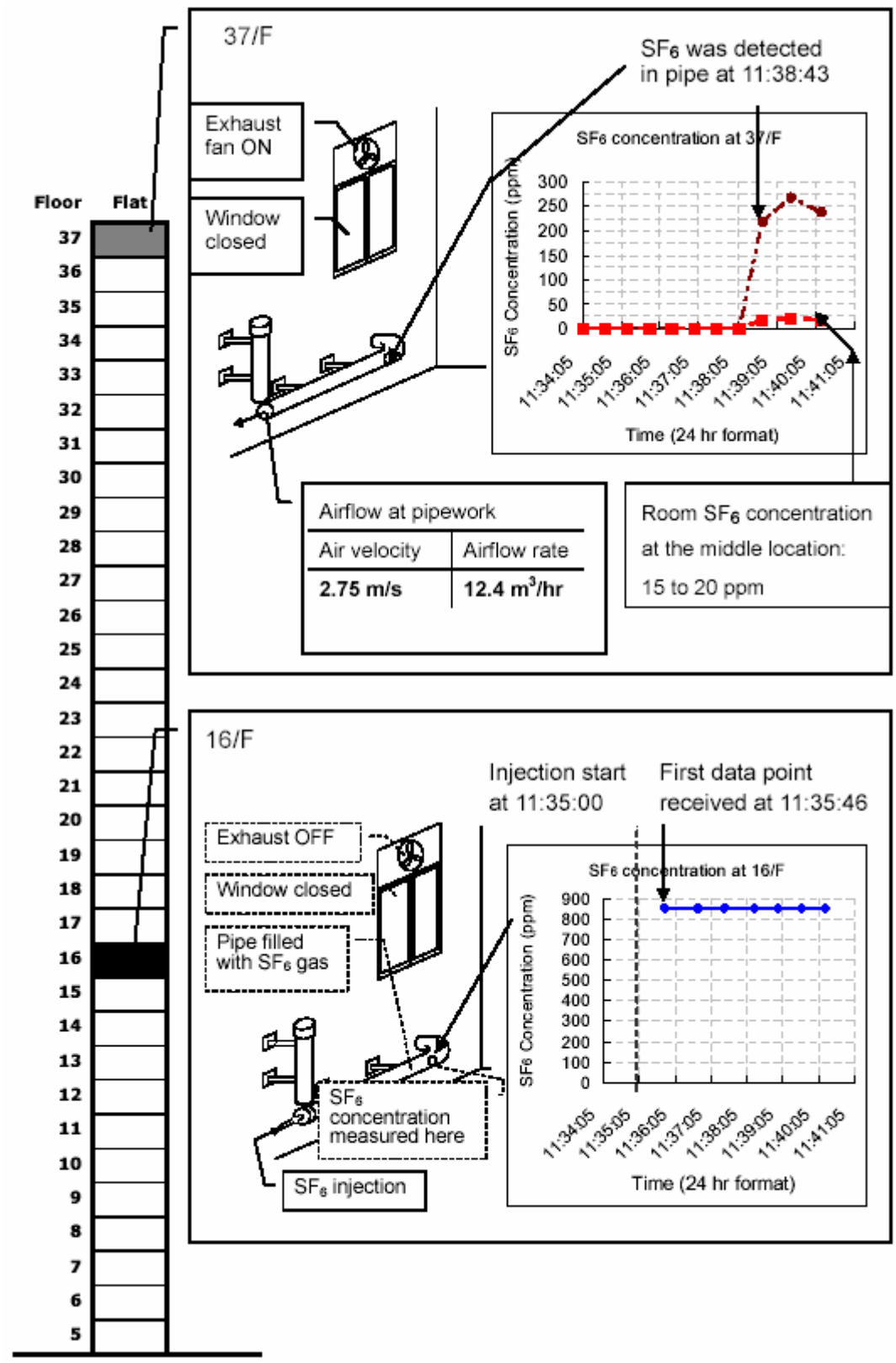

Figure 7.12 Concentration of tracer gas (SF_6) measured for the drainage route investigation in chapter 6.

7.5.2 Ventilation in a Bedroom

Ventilation rates for a bedroom in flat B at 36/F (as shown in figure 7.4), under two operating modes of ventilation, were estimated by tracer gas experiment. The floor area of this bedroom is 8 m^2, and with a height of 2.8m, such that the volume of the room is 22.4m^3. The size of openable window inside the bedroom is 0.8 m^2. Two operation modes were defined: (1) windows closed, room air-conditioner switch ON, and the fresh air louver at room air-conditioner opened (air-conditioning mode), (2) all windows opened (natural ventilation mode). The first trial (air-conditioning mode) was conducted at 1:23 pm to 3:25 pm in 5 December 2003, and the second trial (natural ventilation mode) was conducted at 4:36 pm to 4:51 pm in 5 December 2003. Figure 7.13 to 7.16 show SF_6 decay profile. Table 7.2 shows the ventilation rate of flat 36B bedroom under two different ventilation operation modes

Table 7.2 Ventilation rate in 36/F flat B bedroom

Operation mode	door	windows	Air-conditioner	ACH	Ventilation rate
Air-conditioning	closed	closed	ON	1.28 hr^{-1}	28.8 m^3/hr
Natural vent.	closed	opened	OFF	22.3 hr^{-1}	501.8 m^3/hr

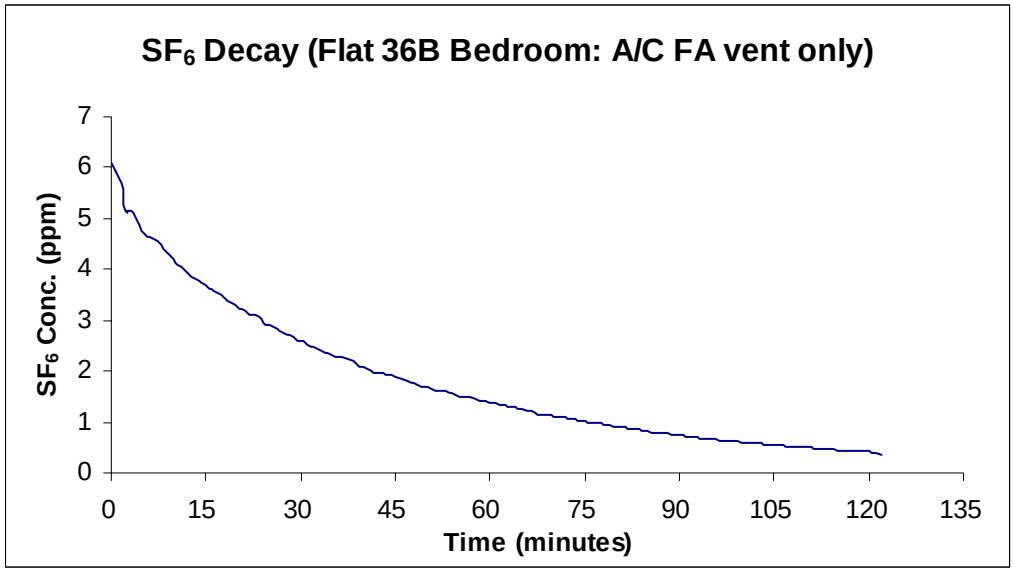

Figure 7.13 SF_6 decay for 36/F flat B bedroom, air-conditioning mode

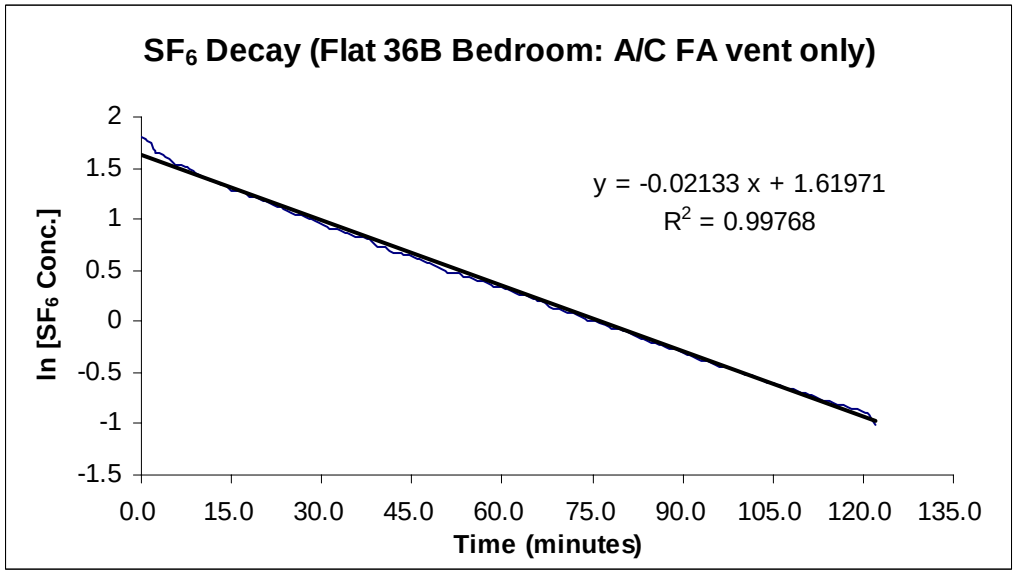

Figure 7.14 Log curve for 36/F flat B bedroom, air-conditioning mode

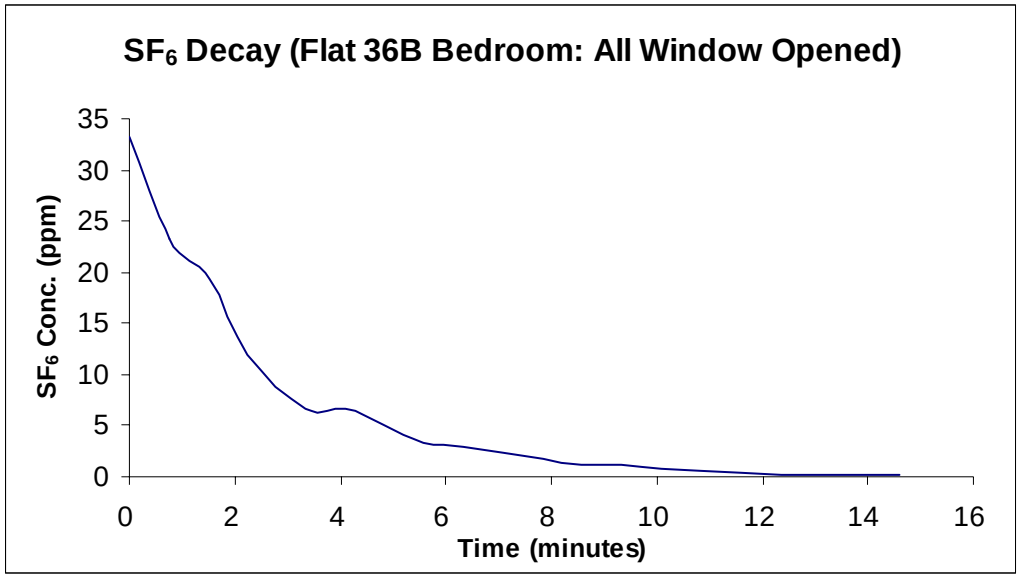

Figure 7.15 SF_6 decay for 36/F flat B bedroom, natural ventilation mode

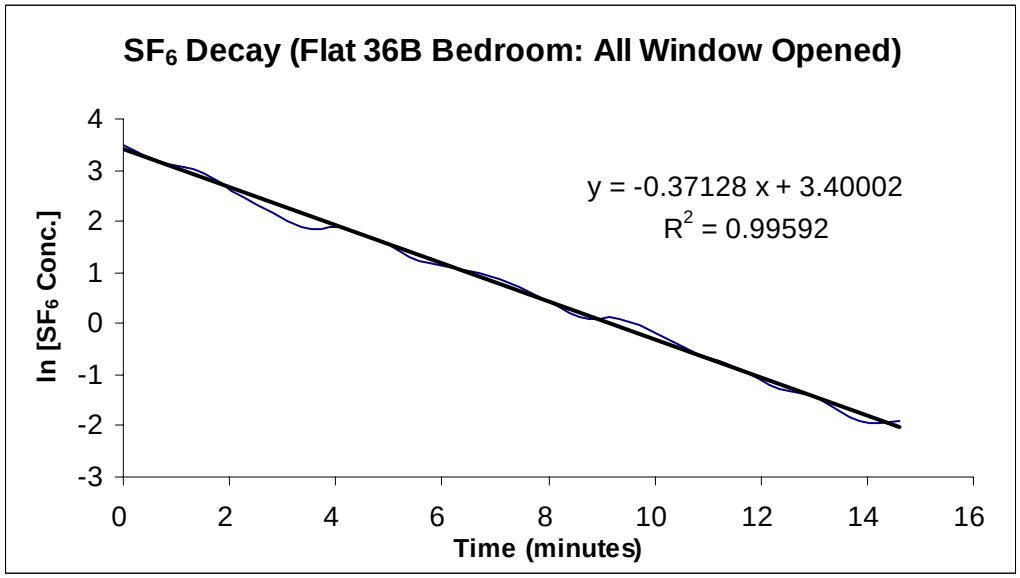

Figure 7.16 Log curve for 36/F flat B bedroom, natural ventilation mode

7.6 Predicting Risk of Infection in a Bedroom

Based on the ventilation measurement result in section 7.5.2, the probability of infection for a hypothetical case can be predicted using the Wells-Riley equation.

The equation is proposed by Riley et al. [1978] and Wells [1934], providing a simple Poisson model for indoor airborne infection that appears to provide a reasonable explanation for observed epidemiological data. The details and the assumptions made on the use of Wells-Riley equation is discussed in section 1.7 in chapter 1 in this thesis. Consider a single person infected with tuberculosis, while unaware of getting infected, sleeps with another uninfected person together in the same bedroom for 8 hours, using the 36/F flat B bedroom for illustration. The room air-conditioner was switched ON and the fresh air louver was opened such that the ventilation rate was 19.1 m^3/hour. The infected person generates 12.7 quanta per hour of tuberculosis droplet nuclei. The particle size is ranged from 2.1 to 3.3 μm diameter (in this study the size of 2.7 μm diameter is used as the typical size for prediction), according to the measurement of size distribution of the airborne particles containing *Mycobacterium tuberculosis* conducted by Fennelly et al. [2004]. The air-conditioner was equipped with a typical coarse filter with the Clean Air Delivery Rate same as the one tested in chapter 5 (see section 5.2.5), for particle size range between 2.0 to 3.0 μm the filtration rate of coarse filter was 3.85 m^3/hour. The probability for the room-mate to be infected can be calculated by equation 7.3.

$$\text{Probability of infection} = 1 - e^{-\frac{I q p t}{\lambda_V + \lambda_{fc}}} \qquad \{\text{equation 7.3}\}$$

Where I is the number of infected person (1 person), q is the quanta generation rate which is 12.7 per hour, p is the pulmonary air inhalation rate which is 0.42 m^3/hr, t is the exposure time (1 hour), λ_V is the ventilation rate inside the room (28.8 m^3/hour)

and λ_{fc} is the particle filtration rate of the coarse filter (3.85 m^3/hour). The probability of infection in this scenario was 0.151.

If an electrostatic air filter with higher filtration rate was used, the protection to the susceptible person can be enhanced. In this second scenario the probability of getting infection is shown in equation 7.4 and the protection factor is defined in equation 7.6.

$$\text{Probability of infection} = 1 - e^{-\frac{I q p t}{\lambda_V + \lambda_{fe}}} \quad \{\text{equation 7.4}\}$$

$$P = 1 - e^{-\frac{(\lambda_V + \lambda_{fc})}{(\lambda_V + \lambda_{fe})} \times \frac{Iqpt}{(\lambda_V + \lambda_{fc})}} \quad \{\text{equation 7.5}\}$$

Or $$P = 1 - e^{-f \times \frac{Iqpt}{(\lambda_V + \lambda_{fc})}} \quad \{\text{equation 7.6}\}$$

where f is the protection factor when electrostatic filter is used,

$f_{fe} = (\lambda_V + \lambda_{fc})/(\lambda_V + \lambda_{fe})$ and λ_{fe} is the particle filtration rate of the electrostatic filter (4.25 m^3/hour).

The protection factor achieved when using electrostatic filter is 0.988, which means

that the quanta concentration is reduced to 98.8% of which when coarse air filter is used. The probability for the room-mate to get infected is reduced to 0.149. The protection in this case is not obvious as the filtration rate is only increased by 0.4 m^3/hour.

If natural ventilation (open all windows) is adopted instead, the probability function becomes equation 7.7,

$$P = 1 - e^{-\frac{(\lambda_{VAC}+\lambda_{fe})}{\lambda_{NV}} \times \frac{Iqpt}{(\lambda_{VAC}+\lambda_{fe})}} \quad \text{\{equation 7.7\}}$$

Where λ_{VAC} is the ventilation rate achieved by opening the fresh air louver at the air-conditioner (room windows all closed), and λ_{NV} is the ventilation rate achieved by natural ventilation. If the outdoor available wind can create a ventilation rate as high as 333 m^3/hour as measured in our "snap-shot" tracer gas measurement, the protection factor, $f_{NV} = (\lambda_{VAC} + \lambda_{fe})/\lambda_{NV}$ can reach 0.066 (compare with mechanical ventilation by air-conditioner plus the use of electrostatic filter), or a reduction of 93.4% of the infectious quanta concentration in the room, resulting a probability of infection of 0.011 (for one hour exposure of quanta generation rate of 12.7 per hour), which largely reduce the risk. The protection factor and the probability of infection under natural ventilation depend on the outdoor available wind.

7.7 Simulation of Natural Ventilation in a Residential Quarter

7.7.1 Simulation model for natural ventilation

To account for the effect of different wind speed and directions on the ventilation rate of an apartment, Computational Fluid Dynamics (CFD) coupled with multi-zone modeling was applied on the analysis of the wind driven natural ventilation rate of each apartments on the residential block as shown in figure 7.2. Commercial software ANSYS® FLUENT for CFD and a freeware CONTAM for multi zone modeling were used. CFD was applied to solve the mass, momentum, and energy equations in a finite volume procedure in a staggered grid system of the outdoor environment. By knowing the dynamic pressure of each window, the ventilation rate in each apartment can be calculated by using multi zone modeling. Both indoor and outdoor simulation can be done by either CFD or multi zone modeling. Done in this way is due to the optimization of time and preciseness.

Modeling equations of natural ventilation are adopted to calculate the wind pressure difference between exterior building surface and local ambient atmospheric pressure at same elevation in undisturbed approach wind.

$$p_v = \frac{\rho_a U_H^2}{2} \qquad \{\text{equation 7.8}\}$$

$$U_H = U_{met}\left(\frac{\delta_{met}}{H_{met}}\right)^{a_{met}}\left(\frac{H}{\delta}\right)^{a} \qquad \{\text{equation 7.9}\}$$

$$p_s = C_p p_v \qquad \{\text{equation 7.10}\}$$

where,

a = exponent in power law wing speed profile for local building terrain, dimensionless

a_{met} = exponent a for the meteorological station, dimensionless

C_p = local wind pressure coefficient, dimensionless

H = wall height above ground on upwind building face, m

H_{met} = height of anemometer at the meteorological station, m

p_s = wind pressure difference between exterior building surface and local ambient atmospheric pressure at same elevation in undisturbed approach wind, Pa

p_v =wind velocity pressure at roof level, Pa

δ = fully developed atmospheric boundary layer thickness, m

δ_{met} = atmospheric boundary layer thickness at meteorological station, m

7.7.2 Governing equations of multi-zone model

The basic equation for the air flow rate from zone j to zone I $F_{j,i}$ (kg/s) is a function of the pressure drop along the flow path, $P_j = P_i$ [Walton and Dols 2008]

$$F_{j,i} = f\left(P_i - P_j\right) \qquad \{\text{equation 7.11}\}$$

By ideal gas law, the mass of air in zone i, m_i is:

$$m_i = \rho_i V_i = \frac{P_i V_i}{R T_i} \qquad \{\text{equation 7.12}\}$$

Where

V_i = zone volume (m^3)

P_i = zone pressure (Pa)

T_i = zone ttemperature (K)

R = gas constant (287.055 (J/Kg.K)

By the conservation of mass in s snapshot of time,

$$\frac{\partial m_i}{\partial t} = \rho_i \frac{\partial V_i}{\partial t} + V_i \frac{\partial \rho_i}{\partial t} = \sum_j F_{ji} + F_i \approx \frac{1}{\Delta t}\left[\left(\frac{P_i V_i}{R T_i}\right) - \left(m_i\right)_{t-\Delta t}\right] \quad \{\text{equation 7.13}\}$$

Where

m_i = mass of air in zone i

F_i = non-flow processes that could add or remove significant quantities of air from the zone

7.7.3 Governing equations and configurations for the CFD simulation

The following conservation equations for mass and momentum have been used to solve the steady flow problem. The equation for conservation of mass can be written as

$$\frac{\partial}{\partial x_i}\left(\rho u_i\right) = S_m \quad \{\text{equation 7.14}\}$$

The above equation is valid for incompressible as well as compressible flows. The

sources S_m is the mass added to the continuous phase from the dispersed second phase (e.g. due to the vaporization of liquid droplets) and by any other user-defined source.

Conservation of momentum for the *i*th direction in an inertial reference frame is written as

$$\frac{\partial}{\partial x_i}\left(\rho u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial s_j} + \rho g_i + F_i \qquad \text{\{equation 7.15\}}$$

where τ_{ij} is the shear stress tensor which is given by

$$\tau_{ij} = \left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] - \frac{2}{3}\mu\frac{\partial u_i}{\partial x_j}\delta_{ij} \qquad \text{\{equation 7.16\}}$$

The second term on the right hand side is the effect of volume dilation or calculating the pressure. This method is derived from the SIMPLE algorithm of Patankar and Spalding [Patankar and Spalding 1972].

For turbulent flow, the flow variables are decomposed into mean and fluctuating components and substituted in the above instantaneous equation. Taking the time average yields the averaged momentum equation as

$$\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_j}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right) \qquad \text{\{equation 7.17\}}$$

The continuity equation remains the same.

An addition term, $\left(-\rho\overline{u_i'u_j'}\right)$ appear that represent the effect of turbulence and needs to be modeled in order to get closer solutions [Wilcox 2000].

Traditionally, the simulation of the outdoor air flow applied the large eddy simulation (LES) because of its ability to handle the unsteadiness and intermittency of the flow. However, in this study, RNG $k-\varepsilon$ model was adopted as it can keep an acceptable accuracy while needing less computational time which is also widely applied in industrial and engineering practice. [Gao et al. 2008]

In turbulent flows, small, high frequency fluctuations are present even in a steady flow, and to account for these, time-averaging procedure is employed, which results in additional terms. These additional terms need to be expressed as calculable quantities for closure solution. The standard $k-\varepsilon$ model will be used in the simulation of most indoor air flow simulation a semi-empirical model based on model transport equations for the turbulent kinetic energy 'k' and its dissipation rate 'ε'. The standard $k-\varepsilon$ model is as follows:

Kinematic eddy viscosity:

$$\nu_T = \frac{C_\mu k^2}{\varepsilon} \qquad \{\text{equation 7.18}\}$$

Turbulent kinetic energy:

$$\frac{\partial k}{\partial t} + u_j \frac{\partial k}{\partial x_j} = \tau_{ij} \frac{\partial u_i}{\partial x_j} - \varepsilon + \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_T}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] \qquad \{\text{equation 7.19}\}$$

Dissipation rate:

$$\frac{\partial \varepsilon}{\partial t} + u_j \frac{\partial \varepsilon}{\partial x_j} = C_{\varepsilon 1} \frac{\varepsilon}{k} \tau_{ij} \frac{\partial u_i}{\partial x_j} - C_{\varepsilon 2} \frac{\varepsilon^2}{k} + \frac{\partial}{\partial x_j} \left[\left(\nu + \frac{\nu_T}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] \qquad \{\text{equation 7.20}\}$$

Closure coefficients and auxiliary relations:

$C_{\varepsilon 1}$=1.44, $C_{\varepsilon 2}$=1.92, C_μ=0.09, σ_ε=1.3, σ_k=1.0,

$\omega = \frac{\varepsilon}{C_\mu k}$, and $\qquad \{\text{equation 7.21}\}$

$$\ell = \frac{C_\mu k^{\frac{3}{2}}}{\varepsilon} \qquad \{\text{equation 7.22}\}$$

The RNG $k-\varepsilon$ model was developed by Yakhot and Orszag [1986]. The equation for the eddy viscosity still uses those in the standard $k-\varepsilon$ model, but applies a modified coefficient, $C_{\varepsilon 2}$, which is:

$$C_{\varepsilon 2} \equiv \tilde{C}_{\varepsilon 2} + \frac{C_\mu \lambda^3 \left(\frac{1-\lambda}{\lambda} \right)}{1+\beta \lambda^3} \qquad \{\text{equation 7.23}\}$$

$$\lambda \equiv \frac{k}{\varepsilon} \sqrt{2 S_{ij} S_{ji}} \qquad \{\text{equation 7.24}\}$$

RNG has different closure coefficients as the standard, they are:

$C_{\varepsilon 1}$=1.42, $C_{\varepsilon 2}$=1.68, C_{μ}=0.085, σ_{ε}=0.72, σ_{k}=0.72, β=0.012, λ_{o}=4.38.

For the near-wall treatment, non-equilibrium wall functions are adopted here as the Reynolds number is low to the near wall region. On the other hand, RNG only works under a high Reynolds number. The non-equilibrium wall function is different from the standard wall function in two ways: the treatment of the mean velocity, which is sensitized to the pressure gradient, and the two-layer based concept for turbulence kinetic energy ($\overline{G_k}$, $\bar{\varepsilon}$) calculation.

y_v is the dimensionless thickness of the viscous sub layer

$$y_v \equiv \frac{\mu y_v^*}{\rho C_\mu^{1/4} k_p^{1/2}}, \quad y_v^* = 11.225 \qquad \{\text{equation 7.25}\}$$

The mean velocity is calculates as:

$$\frac{\hat{U} C_\mu^{1/4} k_p^{1/2}}{\tau_\omega / \rho} = \frac{1}{0.4187} \ln\left(9.793 \frac{\rho C_\mu^{1/4} k_p^{1/2} y_p}{\mu} \right) \qquad \{\text{equation 7.26}\}$$

where

$$\hat{U} = U - \frac{1}{2}\frac{dp}{dx}\left[\frac{y_v}{\rho\kappa\sqrt{k}} \ln\left(\frac{y}{y_v} \right) + \frac{y - y_v}{\rho\kappa\sqrt{k}} + \frac{y_v^{\,2}}{\mu} \right] \qquad \{\text{equation 7.27}\}$$

As mentioned before, the non-equilibrium wall function divided the region into 2 sub-layers, when $y \prec y_v$, $\tau_t = 0$, $k = \left(\frac{y}{y_v}\right)^2 kp$ and $\varepsilon = \frac{2\nu k}{y^2}$, on the other hand, when $y > y_v$, $\tau_t = \tau_w, k = kp, \varepsilon = \frac{k^{3/2}}{C_l y}$

$$\overline{G_k} \equiv \frac{1}{y_n}\int_0^{y_n} \tau_t \frac{\partial U}{\partial y} dy = \frac{1}{\kappa y_n} \frac{\tau_\omega^2}{\rho C_\mu^{1/4} k_p^{1/2}} \ln\left(\frac{y_n}{y_v}\right) \quad \{\text{equation 7.28}\}$$

$$\overline{\varepsilon} \equiv \frac{1}{y_n}\int_0^{y_n} \varepsilon dy = \frac{1}{y_n}\left[\frac{2\nu}{y_v} + \frac{k_p^{1/2}}{C_l}\ln\left(\frac{y_n}{y_v}\right)\right] k_p \quad \{\text{equation 7.29}\}$$

7.7.3.1 Discretization method

For calculating pressure, the SIMPLE algorithm is adopted, while for the others, second-order upwind is applied. The basic steps for the SIMPLE (semi-implicit method got pressure-linked equations) are shown in the following flow chart (figure 7.17).

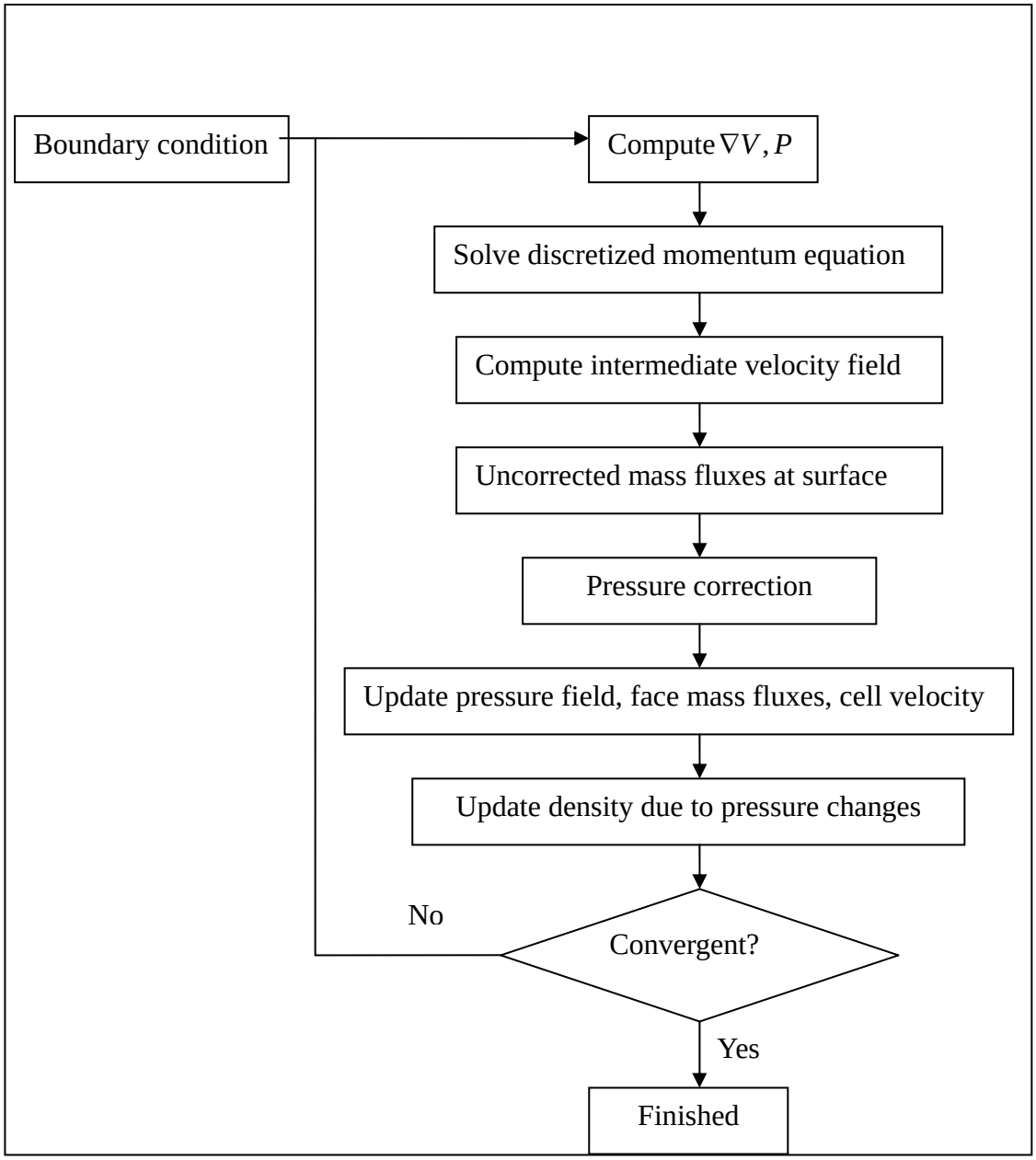

Figure 7.17 Calculation procedure of SIMPLE algorithm

Second-order upwind first calculates the average of the parameter ϕ between two adjacent cells, then uses the two cell average ($\tilde{\phi}_f$) to calculate the gradient of the parameters to the upstream cell, $\nabla\phi$ by taking volume average of the $\tilde{\phi}_f$:

$$\nabla\phi = \frac{1}{V}\sum_{f}^{N_{face}} \tilde{\phi}_f \vec{A} \qquad \text{\{equation 7.30\}}$$

Then the new face value is calculated by the summation of the old value ϕ plus the gradient times the displacement of the centroids ($\nabla\vec{s}$).

$$\phi_f = \phi + \nabla\phi \cdot \nabla\vec{s} \qquad \text{\{equation 7.31\}}$$

Unlike first-order upwind and power-law scheme, the second-order upwind takes more cell values into consideration, and thus a higher accuracy is expected. When compared to the QUICK scheme, second-order upwind can save computational time. Consequently, this scheme provides an optimum between computational time and accuracy level.

7.7.4 The CFD Model

The simulation case consisted of 4320174 tetrahedral meshes. For critical locations, for example, the window of the studied block, smaller grids were applied. The grid actually divided the space into tiny little volume and after generating it, discrete algebraic equations were solved with the boundary condition settings. After initialization of the simulation, iterations were carried out until the convergence criteria were met. The convergence criteria was set to be 10^{-3} of sum of the absolute residual for the x,y,z momentum, continuity of mass, kinetic energy of turbulence and the dissipation rate of turbulence energy.

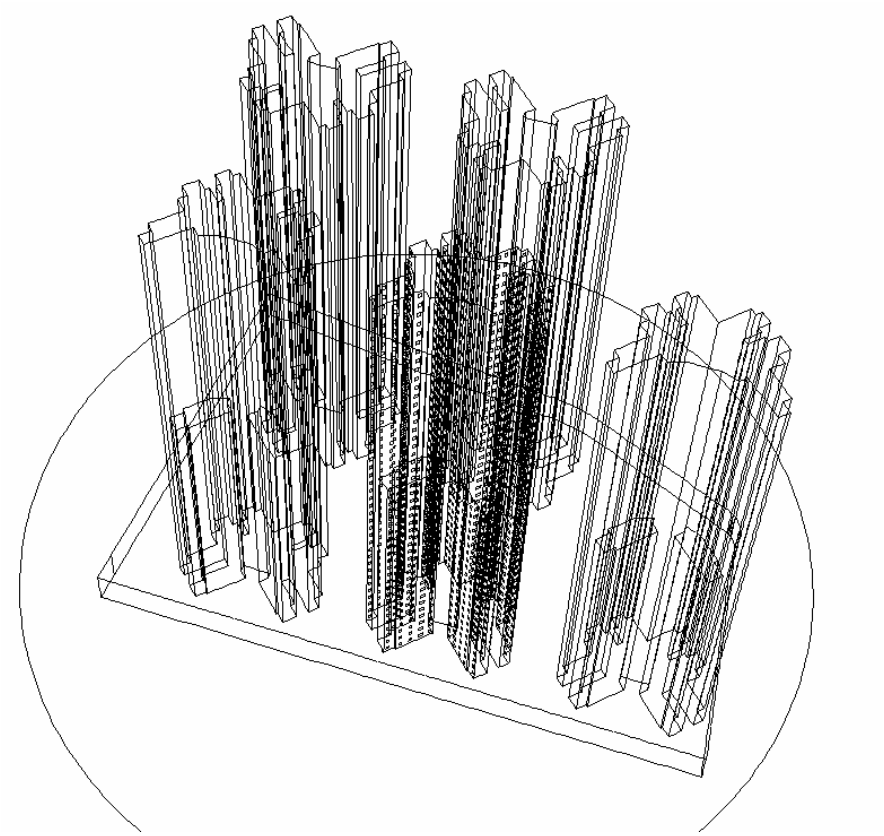

Figure 7.18 Simulation model

7.7.5 Simulation Analysis

36 cases representing all prevailing wind direction are simulated to calculate the pressure coefficient of all the windows of block 2 with respect of the freestream wind above the building. By using the pressure coefficient at a window as the input parameter for multizone airflow simulation program CONTAM, the airflow rate to a particular room inside a flat can be estimated.

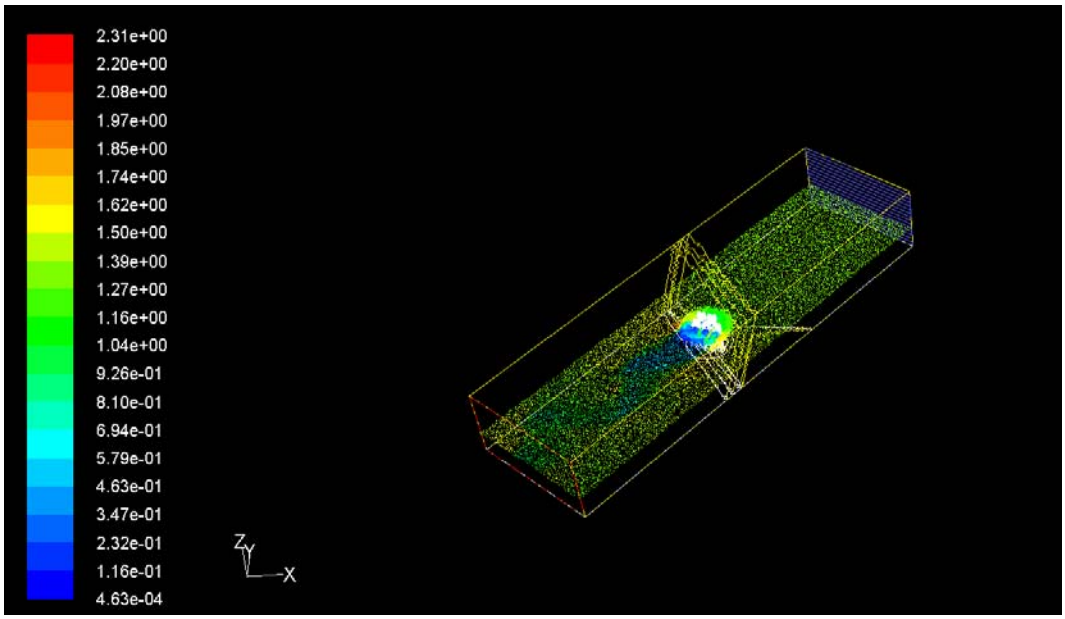

Figure 7.19 Velocity vector of the whole study area at height of 70m above ground with prevailing wind of 40^{o}

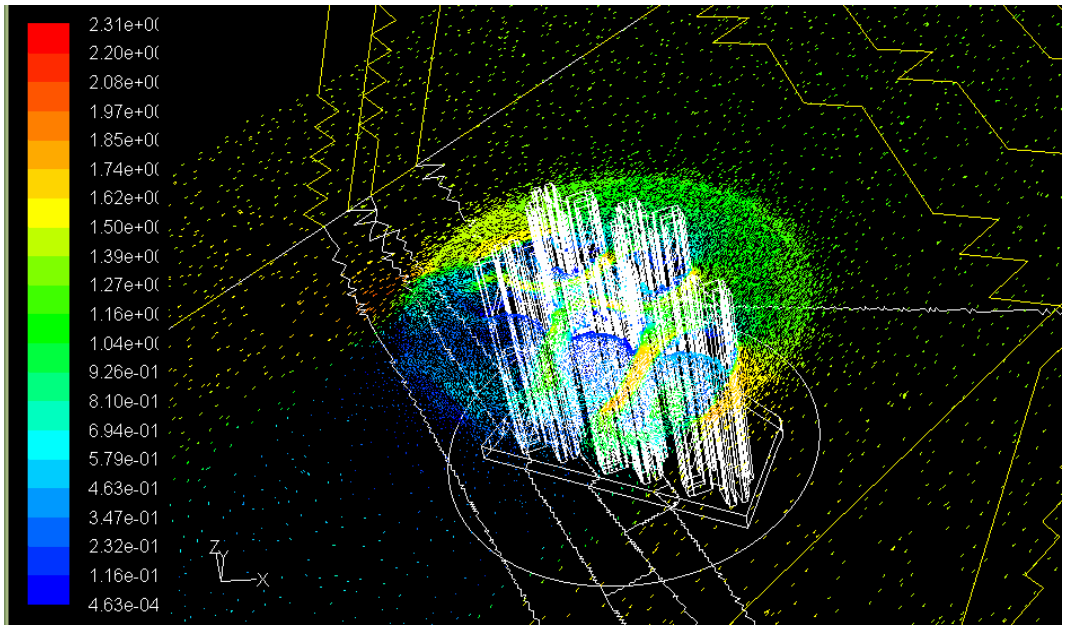

Figure 7.20 Velocity vector near the studied zone with prevailing wind of 40^{o}

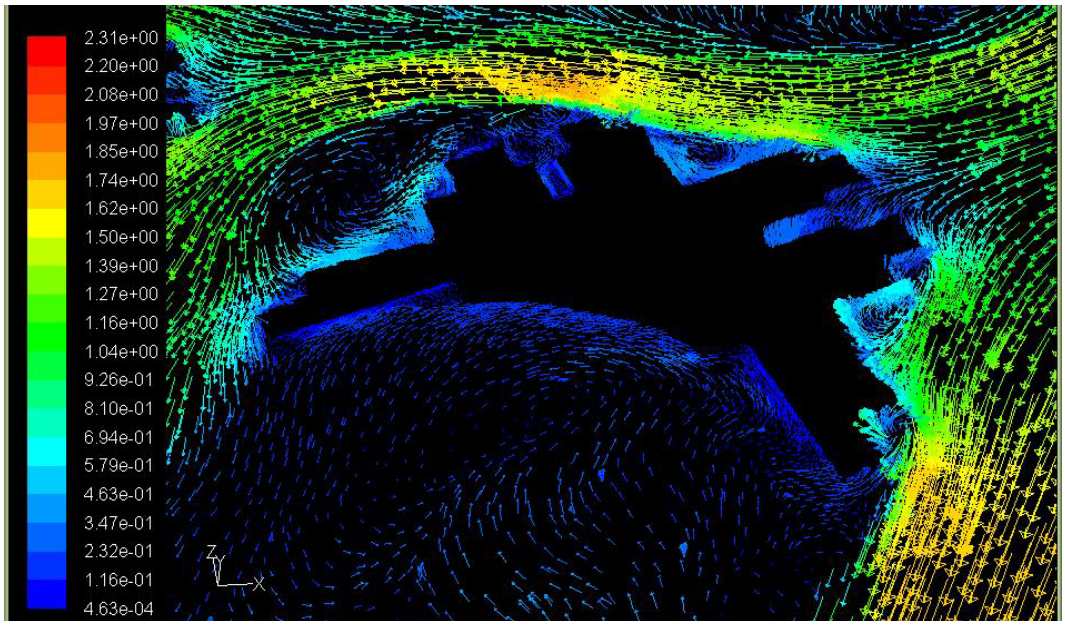

Figure 7.21 Velocity vector near the studies block (block 2) with prevailing wind of 40^{o}

By using the weather data from Hong Kong Observatory (figure 7.22), the availability of the natural ventilation is expressed as a probability density distribution function taking into account of the annual wind rose showing the frequencies of annual wind direction. Figure 7.23 and 7.24 show the percentage of time in wind direction in Tseung Kwan O district for 5 years from 2003 to 2007.

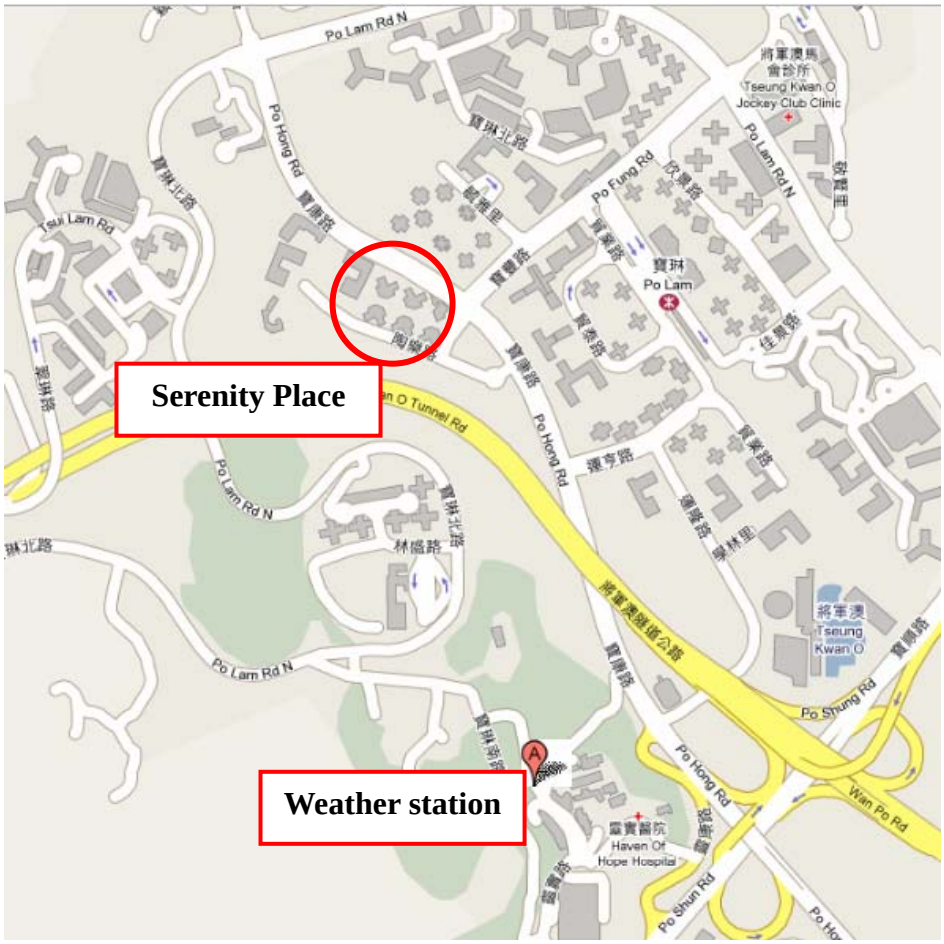

Figure 7.22 Location of Hong Kong Observatory weather station

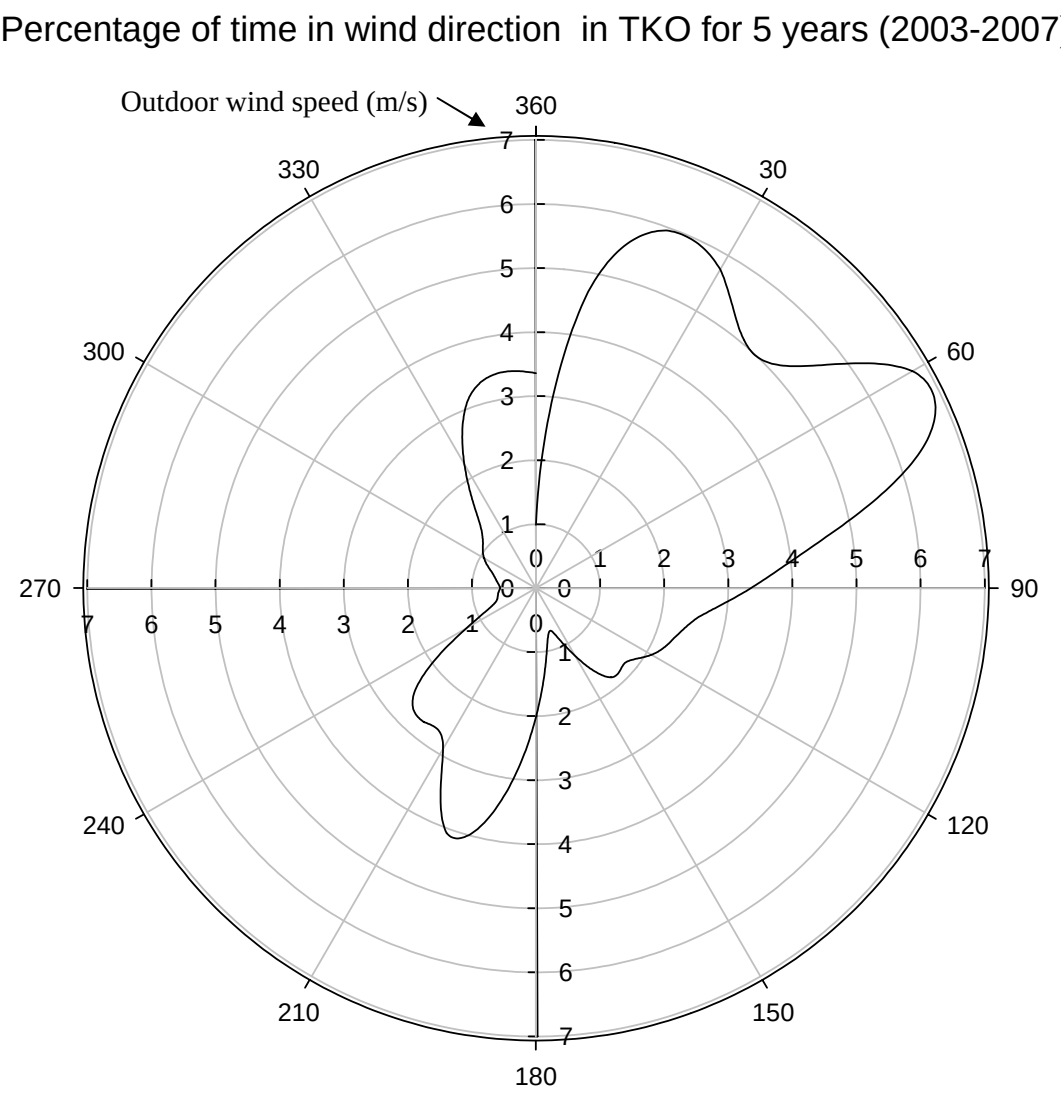

Figure 7.23 Wind rose diagram for Tseng Kwan O

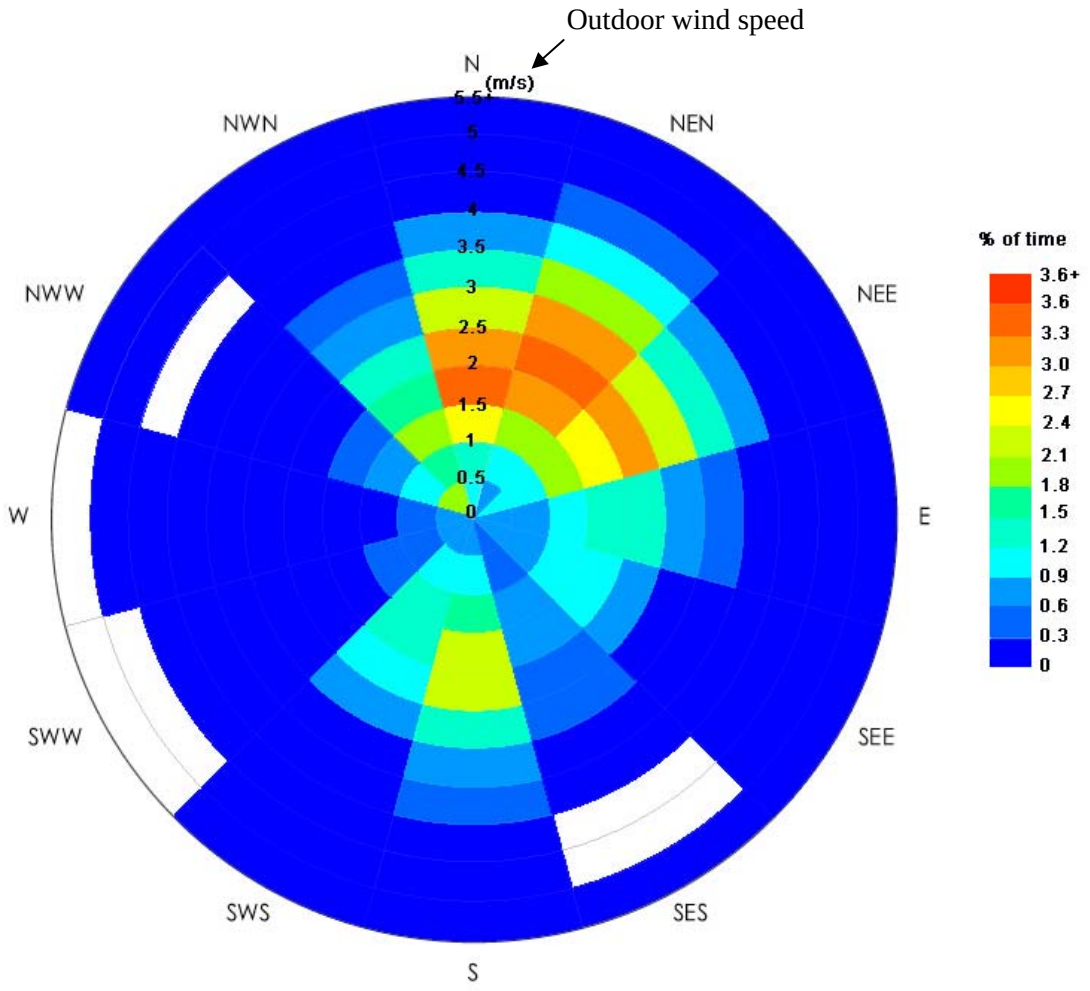

Figure 7.24 Percentage of time in wind direction in Tseng Kwan O

7.7.6 Ventilation rate and predicted infection risk at 36/F flat B master bedroom

In section 7.5.2 a “snap-shot” ventilation rate of master bedroom at 36/F flat B during 4:36 p.m. to 4:51 p.m. in 5 December 2003 is reported. The door was closed and all the windows were fully opened. According to the hourly wind data from The Hong Kong Observatory Tseng Kwan O weather station, at 4:00 p.m. the outdoor wind speed is 2.5 m/s and the window direction is 40° (north-east-north), while at

5:00 p.m. the outdoor wind speed decreased to 1.1 m/s and the wind direction was changed to 80° (east). By using CFD and CONTAM simulation the ventilation rate is estimated to be 0.397 m^3/s (or 1428 m^3/hour) based on the wind data at 4:00 p.m., while for using 5:00 p.m. wind data the ventilation rate obtained from CFD and CONTAM simulation is 0.046 m^3/s (165 m^3/hour). According to tracer gas experiment the result ventilation rate 0.093 m^3/s (333 m^3/hour).

The use of CFD and CONTAM simulation allows the estimation of ventilation rate at different outdoor wind direction and velocity. Over a five year period from 2003 to 2007, the weighted average of ventilation rate over the period is estimated to be 0.314 m^3/s for the master bedroom in 36/F flat B. The cumulative frequency curve on the airflow rate at the master bedroom is shown figure 7.25.

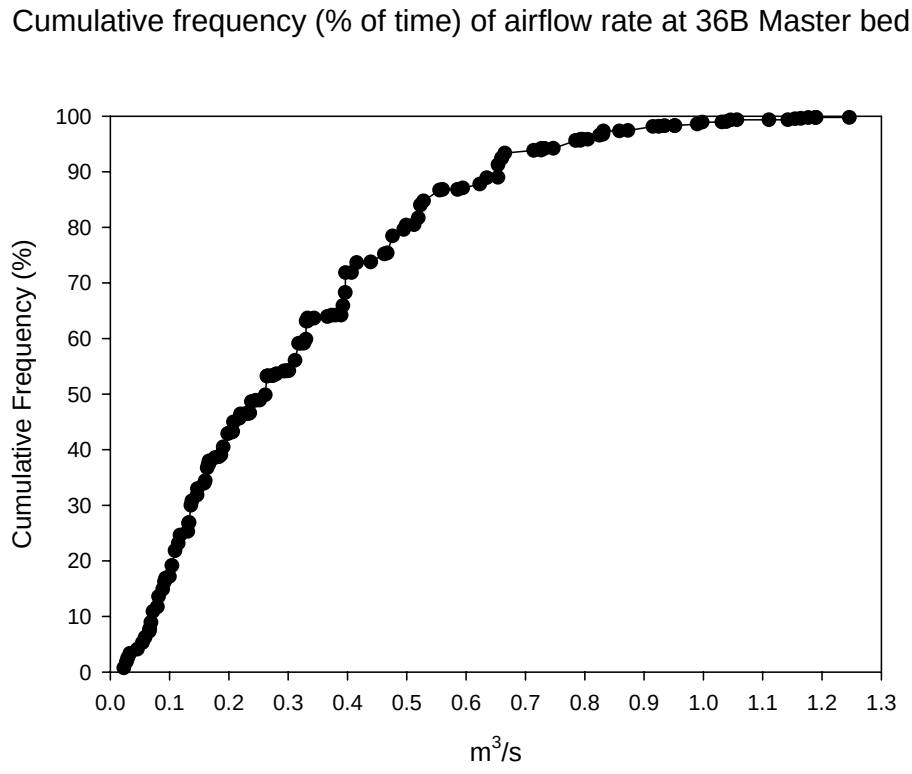

Figure 7.25 Cumulative frequency curve on the airflow rate at master bedroom

The percentage of time on various outdoor airflow rate achieved by natural ventilation is shown in figure 7.26.

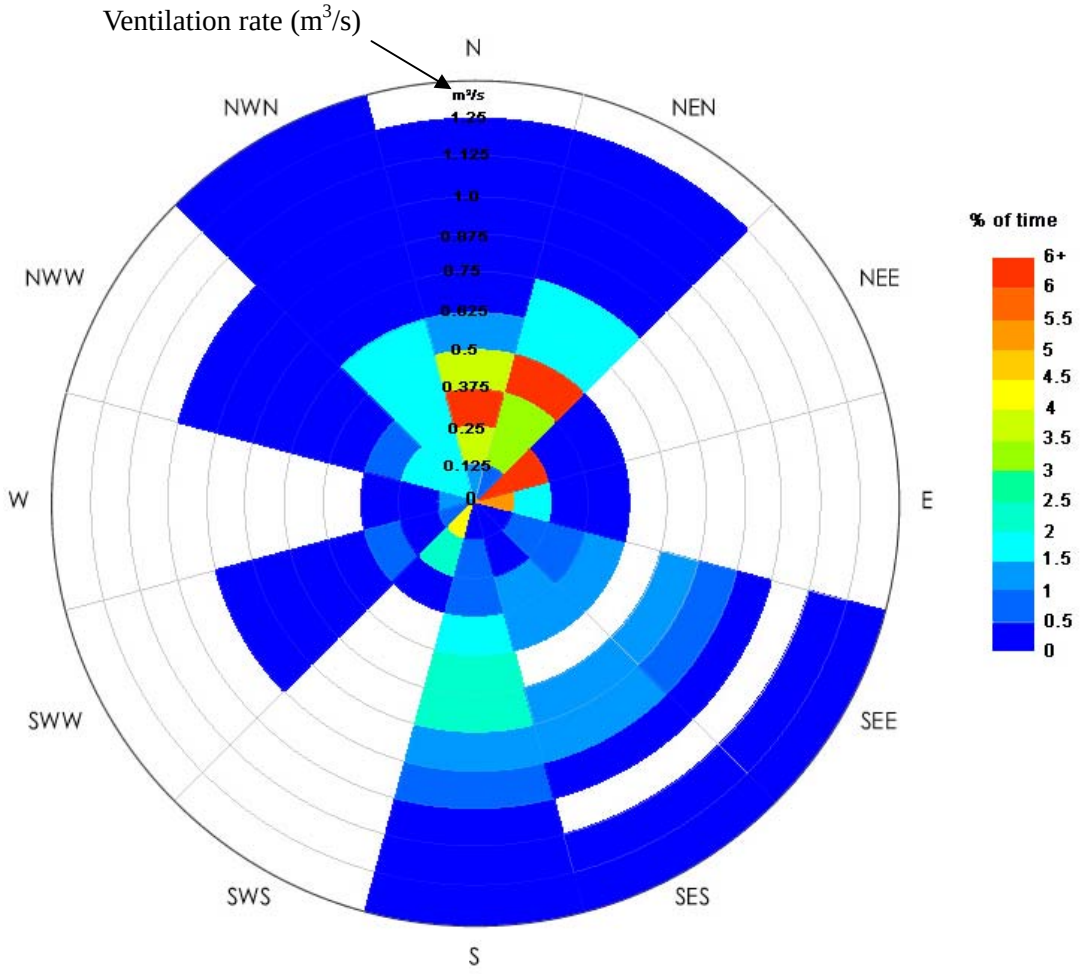

Figure 7.26 Percentage of time for various outdoor airflow rate to the bedroom by natural ventilation

For 80% of time over the period of 1 January 2003 to 31 December 2007, the airflow rate at the bedroom is at least 0.1 m^3/s or more, and for 90% of time over the five-year period bewteen 2003 to 2007, the airflow rate at the bedroom is at least

0.07 m^3/s, corresponding to an infection risk of 0.021 estimated by the Wells-Riley equation, for one hour exposure at a quanta generation rate of 12.7 per hour. By the worst case the minimum ventilation rate achieved by natural ventilation is 0.0229 m^3/s (or 82.4 m^3/hour), which is still larger than the ventilation rate of 28.8 m^3/hr when using window-type air-conditioner and window closed, as reported in table 7.2 in section 7.5.2. When the outdoor air flow rate is 82.4 m^3/hour, the infection risk is 0.063 for one hour exposure at a quanta generation rate of 12.7 per hour. On the infection risk estimated by Wells-Riley equation, figure 7.27 and 7.28 show the cumulative frequency curve, for different per hour quanta generation rates.

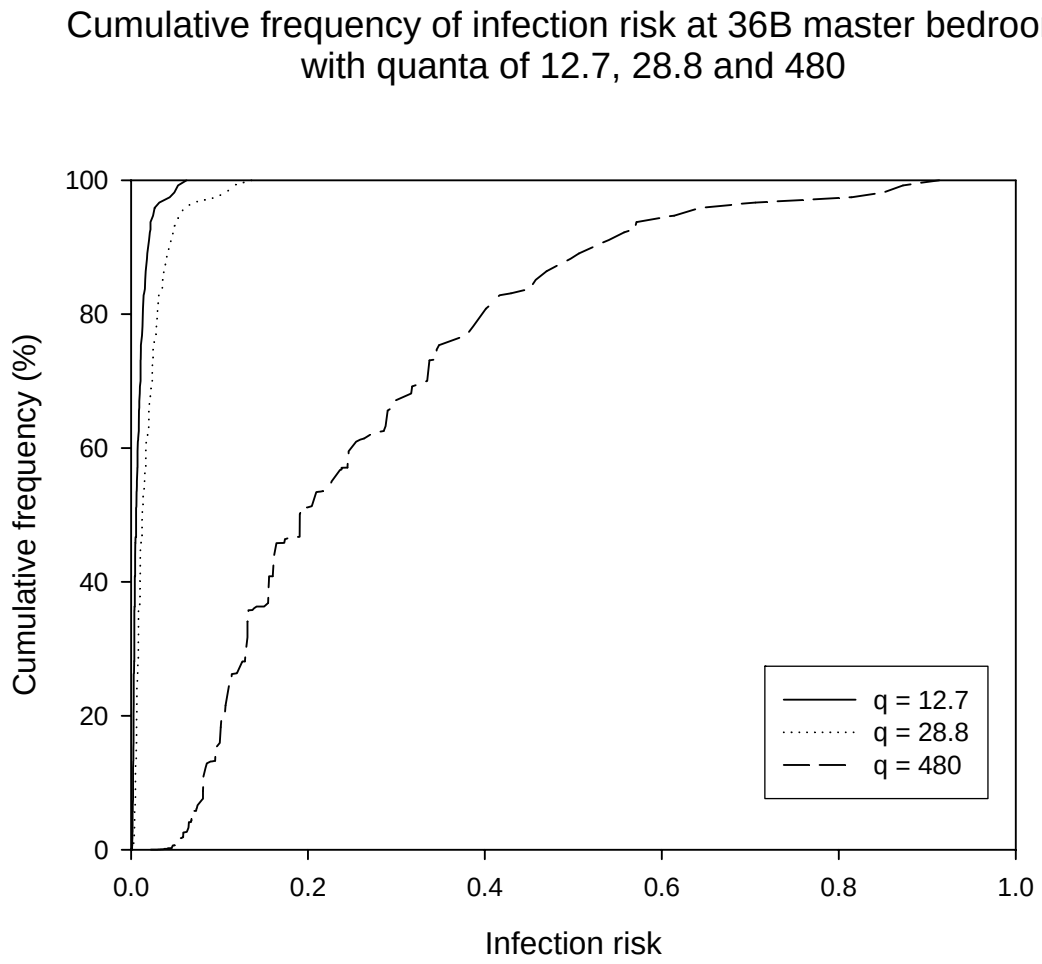

Figure 7.27 Cumulative frequency curve on estimated infection risk

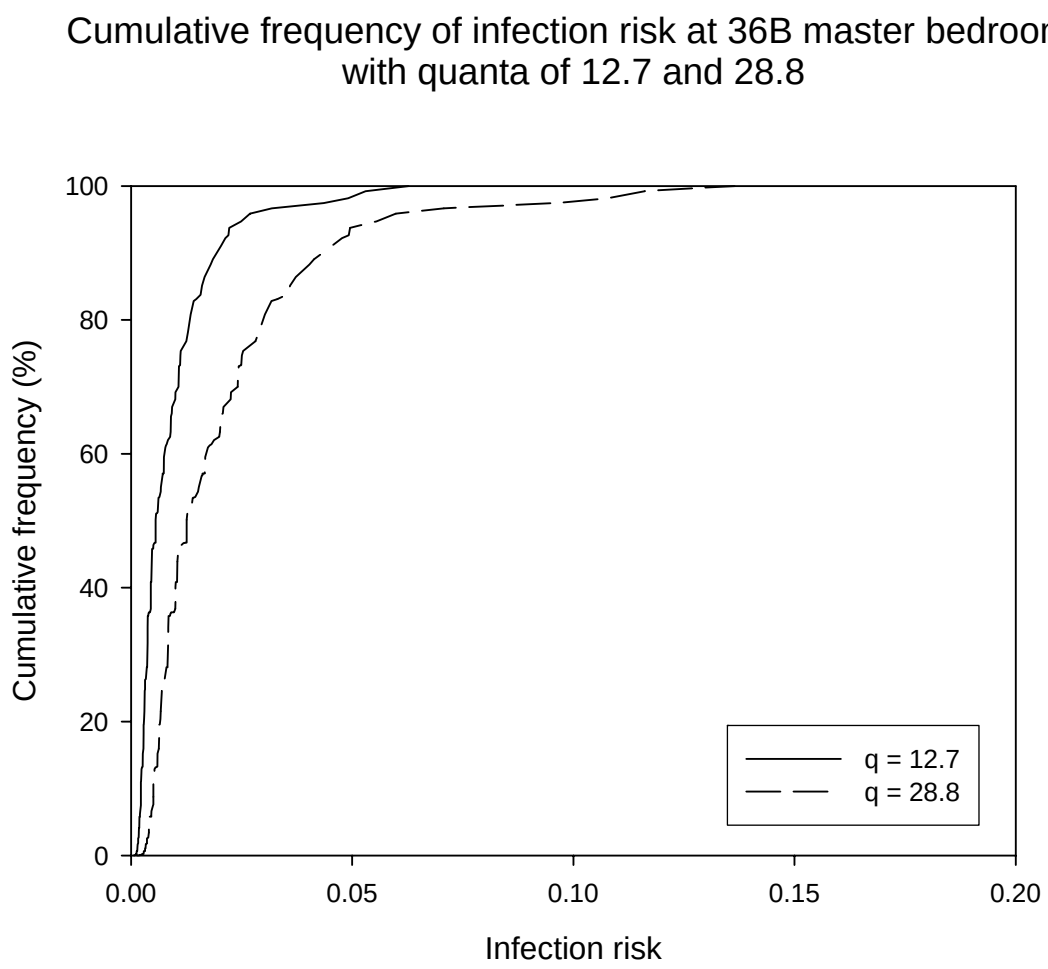

Figure 7.28 Cumulative frequency curve on infection risk (q=480 not shown)

The quanta generation rates of 12.7 per hour corresponds to a Tuberculosis outbreak in an office reported by Nardell et al. [1991], the quanta generation rate of 28.8 per hour corresponds to a SARS outbreak case in hospitals in Taiwan [Liao et al. 2005], and the quanta generation rate of 480 per hour corresponds to a measles outbreak in an elementary school [Riley et al. 1978]. Figure 7.29 to 7.31 show the infection risk predicted by Wells-Riley equation for one hour exposure in 36/F flat B master bedroom at different outdoor wind direction and speed.

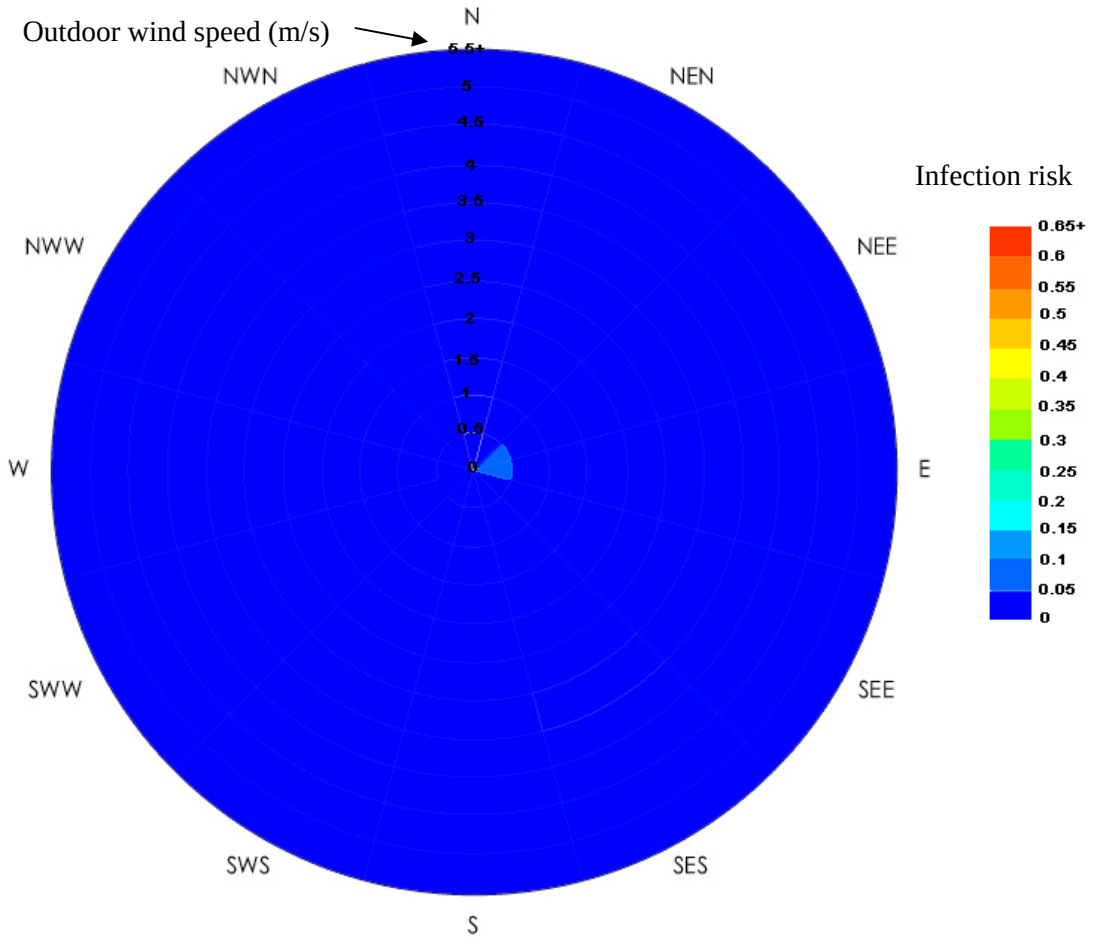

Figure 7.29 Predicted infection risk (q=12.7 per hour) under various outdoor wind direction and speed.

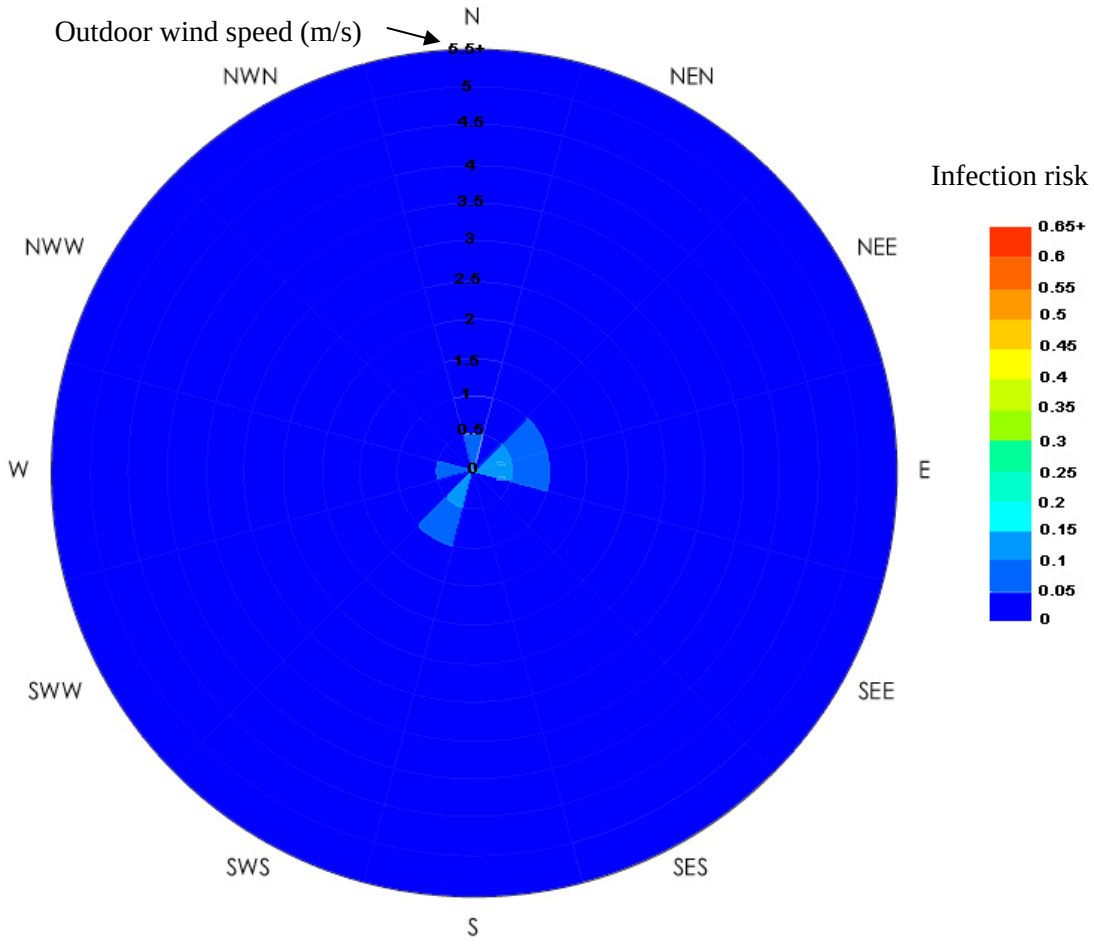

Figure 7.30 Predicted infection risk (q=28.8 per hour) under various outdoor wind direction and speed.

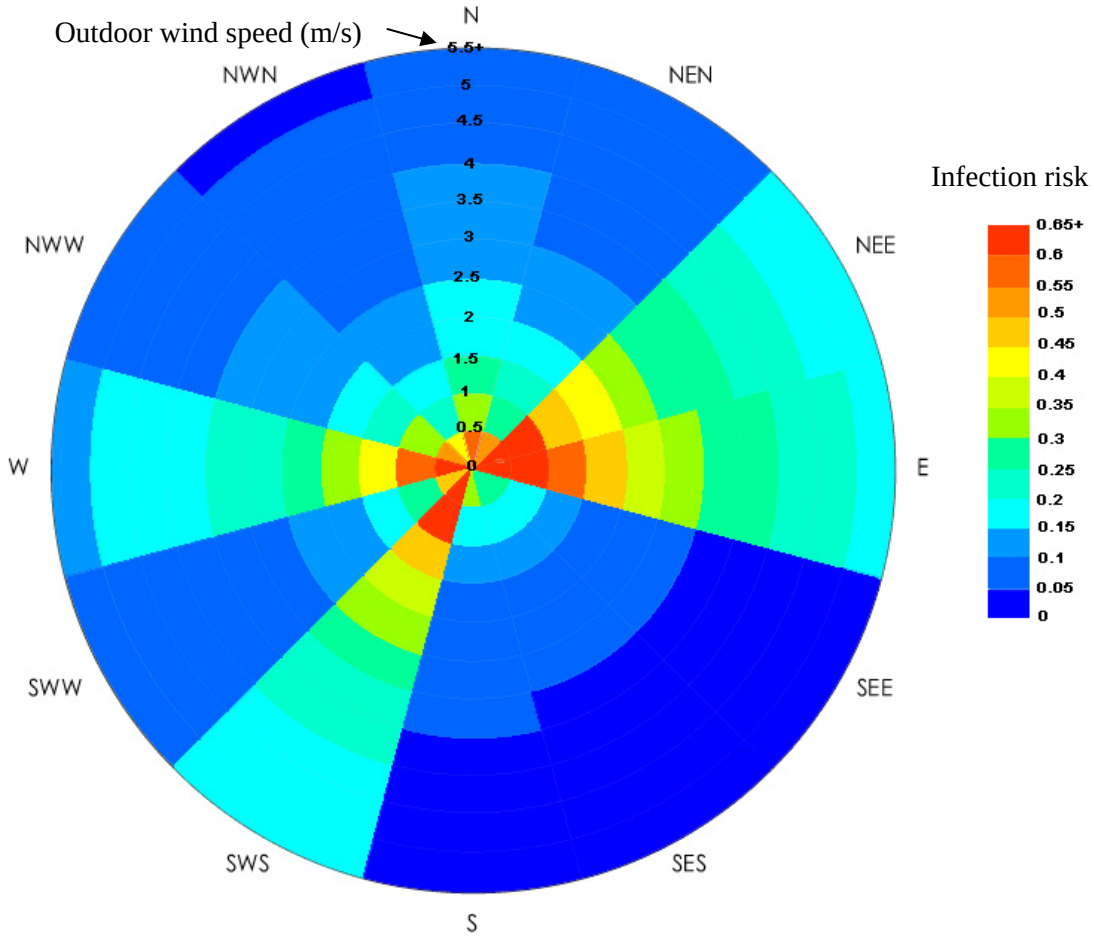

Figure 7.31 Predicted infection risk (q=480 per hour) under various outdoor wind direction and speed.

The above figures show that, if natural ventilation is adopted for the master bedroom under investigation, the estimated 1-hour exposure maximum risk is 0.063 for a generation rate of 12.7 quanta per hour; the maximum risk for a generation rate of 28.8 quanta per hour is 0.136; and for a generation rate of 480 quanta per hour, the maximum risk is 0.914. For 90% of time within 1 January 2003 to 31 December 2007, the estimated risk is shown in table 7.3. For a highly infectious airborne disease like measles, the infection risk is much higher even under a higher ventilation rate achieved by natural ventilation.

Table 7.3 Predicted infection risk for different quanta generation scenario

Quanta generation rate	Predicted infection risk	
	Maximum	For 90% of time the risk is lower than:
12.7 quanta per hour	0.063	0.020
28.8 quanta per hour	0.136	0.045
480 quanta per hour	0.914	0.54

7.8 Chapter Summary

In this chapter the review of the ventilation requirement for minimizing the risk airborne infectious diseases shows a trend that higher outdoor air ventilation rate can reduce the risk of infectious disease, while the cases reported in the literature were found to be inadequate for a definite quantification of the minimum ventilation requirements in relation to the spread of airborne infectious diseases. Ventilation requirements in residential buildings documented in codes and standards from various countries are then reviewed and serve as benchmark in the evaluation of ventilation performance in typical cruciform residential buildings in Hong Kong.

The ventilation rate achieved by fully opened window natural ventilation in a bedroom inside a residential flat is compared with the operation mode of closed window and using the outdoor air louver in the window type air-conditioner. The tracer gas experiment provides an estimation of “snap-shot” ventilation rate at a particular outdoor wind speed and direction. To account for the ventilation rate achieved at different outdoor wind speed and direction, Computational Fluid

Dynamics (CFD) coupled with multi-zone modeling is applied on the analysis of the wind driven natural ventilation rate. By using the Wells-Riley equation which relates the infection risk with air ventilation rate, together with the air filter efficiency information reported in chapter 5, it is predicted that the infection risk can be reduced significantly at the natural ventilation mode by fully opening the window.

The risk of vertical transmission of contaminant through the air via re-entrant is evaluated by the injection of SF_6 tracer gas. The SF_6 concentration detected in the receiver room is 0.5 ppm, a ratio of 0.003 to 0.005 compared with the source concentration. While this ratio is much lower than the vertical drainage stack route as reported in chapter 6, the test result for the re-entrant light-well route shows the possibility of contaminant transmission via re-entrant light-well exists and it is recommended to keep the doors and windows for bathrooms and kitchen facing re-entrant should be closed with the use of exhaust fan for ventilation purpose.

In this study, the expiratory aerosols were modeled as gas molecules. While the concept of droplet nuclei, as proposed by Wells W.F., assumes that the size of droplet nuclei is tiny that settling rate is negligible (as mentioned in chapter 1), the use of gas molecule for modeling may still lead to some discrepancy when the estimated risk is considered as an “absolute” risk. In addition, a portion of tiny infective particles can still deposit on surfaces, thus the estimated risk value solely consider the airborne transmission mechanism. The transmission risk of airborne infective particles through indirect contact can increase the “overall” risk if one is interested on obtaining an “absolute” value of risk.

The use of Wells-Riley model assumes perfect mixing of the air in the indoor space, such that the estimated risk is a single zone average. In typical ventilation phenomenon, the airflow direction in an indoor space fluctuates, and the absolute risk value in different locations (or in other words, exact points) inside the room varies from the single zone average value. The major aim of this study is to compare how the degree of change on relative risk under various ventilation scenarios. More sophisticated model is needed when a search of “absolute” risk value is found to be necessary.

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CHAPTER 8: ASSESSING RISK OF AIRBORNE INFECTION EPIDEMIC IN OFFICE BUILDING

Inside a building with safe indoor environment the occupants would be ideally immune from airborne infection. This management objective can be achieved by minimization of pathogenic or infective micro-organisms such as fungi, bacteria or viruses in the indoor environment. In the previous chapters the engineering performance of air cleaners and filters was evaluated in residential setting. The air cleaning rate of air cleaner under test is less than 1 air change per hour, which is much less than the air change rate achieved by ventilation. As a result, when the case for mechanically ventilated office building is studied in this chapter, the outdoor air ventilation and air filtration are considered to be the major engineering control methods for reducing the risk of airborne disease outbreak. The widely adopted susceptible – infected - removed (SIR) model in epidemiological study is applied analysis of safeness of the indoor environment, using the basic reproductive number (R_0) as an index for assessment, as discussed in section 8.1. The prediction on theoretical risk of epidemic outbreak in an office building is presented in section 8.2.

8.1 Model for Epidemiological Studies

8.1.1 The law of mass action and the SIR model

Assume the process of epidemic outbreak follows the law of mass action, which suggested that the rate at which an infection passes in a population is proportional jointly to the product of the number of persons I who are infectious and the number of persons S who are susceptible to the infection, the rate of infection $C_{infection}$, according to the law of mass action, can be expressed mathematically as

$$C_{infection} = \frac{dI}{dt} = r\,I\,S \qquad \{\text{equation 8.1}\}$$

Where r is the contact rate between infected person(s) and susceptible persons, I is the number of infectious persons and S is the number of susceptible persons. This assumes infectious persons and susceptible persons are mixed uniformly.

Within a population N, when the number of infected person I increase, the number of susceptible persons S decrease, and the rate of change of susceptibles can be expressed as,

$$\frac{dS}{dt} = -C_{infection} = -r\,I\,S \qquad \{equation\ 8.2\}$$

Considering a number of infected person is recovered and becomes immune, (or removed away from the population) at a recovery (or removal) rate $1/d$ (d is the effective infectious duration) [Giesecke 1994]. Equation 8.1 becomes,

$$\frac{dI}{dt} = r\,I\,S - \frac{I}{d} \qquad \{equation\ 8.3\}$$

The recovered / removal rate becomes

$$\frac{dR}{dt} = \frac{I}{d} \qquad \{equation\ 8.4\}$$

and the total population size N is,

$$N = S + I + R \qquad \{equation\ 8.5\}$$

The above mentioned equations describe the basic form of model for Susceptible – Infected – Removed (SIR model), which describes the dynamics of an epidemic disease outbreak.

8.1.2 The Basic Reproductive Number R_0

For a total population of N with homogenous mixing where each individual produces on average $r N$ offspring per unit of time for an effective infectious duration (d), then the basic reproductive number, defined as the expected number of new cases of an infection caused by a typical infected individual in a population consisting of susceptible only, becomes

$$R_0 = r N d \qquad \{\text{equation 8.6}\}$$

The basic reproductive number (R_0) is an important epidemiological threshold. It is the expected number of secondary individuals infected by a single infected individual during his or her infectious period, in a population which is entirely susceptible. For in-host dynamics, R_0 gives the number of newly infected cells produced by one infected cell during its lifetime, assuming all other cells are susceptible. By this definition, the threshold criterion states that when $R_0 < 1$ each infected individual produces, on average, less than one new infected individual and it is expected that the infection will be cleared from the population. If $R_0 > 1$, the pathogen is able to invade the susceptible population. The magnitude of reproductive number is also used to gauge the risk of an epidemic in merging infectious disease

[Heffernan et al. 2005]. For the management of safe indoor environment to protect the occupants against airborne diseases, one can determine which engineering control measures, such as outdoor air dilution ventilation, air filtration and air disinfection, and at what magnitude, would be effective in reducing the basic reproductive number R_0 below one. Noakes et al. [2006] have adopted the Basic Reproductive Number analysis to conduct a theoretical study on the epidemic potential under various occupancy density and air change rate in a hospital. In this thesis a mass-balance analysis for the concentration of infectious quanta is performed and linked with the SIR model to predict the theoretical epidemic potential in an office, based on observed occupancy data, air filter specification, and measured outdoor air supply flow rate of the ventilation system inside the building.

8.1.3 Mass balance on infectious quanta concentration in a room

Considering a mass balance on the concentration of infectious quanta *C* inside a room volume *V*,

$$\frac{\mathrm{d}VC}{\mathrm{d}t} = G - Q_o C - \eta_f Q_f C \text{ , or}$$

$$V\frac{\mathrm{d}C}{\mathrm{d}t} = q - (Q_o + \eta_f Q_f)C \qquad \{\text{equation 8.7}\}$$

Where V is the volume of room (m^3), C is the concentration of infectious quanta, $G = q$ is the quanta generation rate by the infected person, Q_o is the outdoor air ventilation rate, η_f is the particle size efficiency of air filter and Q_f is the volumetric air flow rate across the air filter.

The steady state average concentration of infectious quanta can be obtained when $\frac{\mathrm{d}C}{\mathrm{d}t} = 0$,

i.e. $q = (Q_o + \eta_f Q_f)\,C$, or

$$C = \frac{q}{Q_o + \eta_f Q_f} \qquad \{\text{equation 8.8}\}$$

As the contact of airborne infectious disease between the susceptible persons and the infected person can be considered as the inhalation of the infectious quanta produced by the infectors, the contact rate r becomes

$$r = p \times \frac{q}{Q_o + \eta_f Q_f}, \text{ or}$$

$$r = \frac{pq}{Q_o + \eta_f Q_f} \qquad \{\text{equation 8.9}\}$$

where p is the pulmonary inhalation rate of the susceptible persons.

Substitute equation 8.6 to equation 8.5 forms the equations,

$$\frac{\mathrm{d}S}{\mathrm{d}t} = -\frac{pq}{(Q_o + \eta_f Q_f)} IS \qquad \{\text{equation 8.10}\}$$

$$\frac{\mathrm{d}I}{\mathrm{d}t} = \frac{pq}{(Q_o + \eta_f Q_f)} IS - \frac{I}{d} \qquad \{\text{equation 8.11}\}$$

$$\frac{\mathrm{d}R}{\mathrm{d}t} = \frac{I}{d} \qquad \{\text{equation 8.12}\}$$

The reproductive number R_0 equation, as stated in equation 8.6, becomes

$$R_0 = \frac{pq}{(Q_o + \eta_f Q_f)} \times N \times d \qquad \{\text{equation 8.13}\}$$

By using equation 8.13, it is assumed that the generation rate of infectious quanta added to the air by the infectious person is constant, the droplet nuclei dispersed to the room is evenly distributed and the removal of droplet nuclei by outdoor air ventilation, and air filtration is at a rate proportioned to the amount present. Equation

8.13 provides a mean to predict the potential of epidemic outbreak based on the quantity and the strength of infectious quanta, the volume of space, room ventilation and the efficiency of air filters on the removal of infectious particles. Once the infectious quanta generated in typical airborne disease outbreak is known, one can determine the quantity of outdoor air and the efficiency of air filtration system required to prevent an epidemic outbreak by keeping the reproductive number R_0 (in equation 8.13) below one. In this study, the estimated the quanta generation rates for typical airborne infectious diseases reported in the literature are adopted. The quanta generation rate can be regarded as the possible "loading" of infectious matter on the indoor environment. After load estimation one can determine the requirement on ventilation and filtration system in a building in order to minimize the risk of disease outbreak in the indoor environment.

8.1.4 Reproductive number in real outbreak cases

Before using equation 8.13 to predict the potential of infectious disease epidemic in hypothetical cases, the equation is first tested using the data from previous occurred disease outbreaks as reported in the literature. If the reproductive number calculated by equation 8.13, which represents the expected number of secondary individuals infected by a single infected individual, matches with the actual number of persons

contracted with the disease among the susceptibles in real outbreak cases, the equation can be considered to be appropriate for the prediction of epidemic potential in hypothetical situation. Five outbreak cases reported in the literature are adopted to test the appropriateness of equation 8.13. The selected cases cover a wide range of quanta generation rate from 10 quanta per hour (Rhinovirus type 16) to 250 quanta per hour (bronchoscopy related tuberculosis), and a wide range of duration of infectious from 2.5 hours to 160 hours. Figure 8.1 and table 8.1 show the reproductive number calculated by equation 8.13, against the actual number of persons contracted the disease among susceptibles.

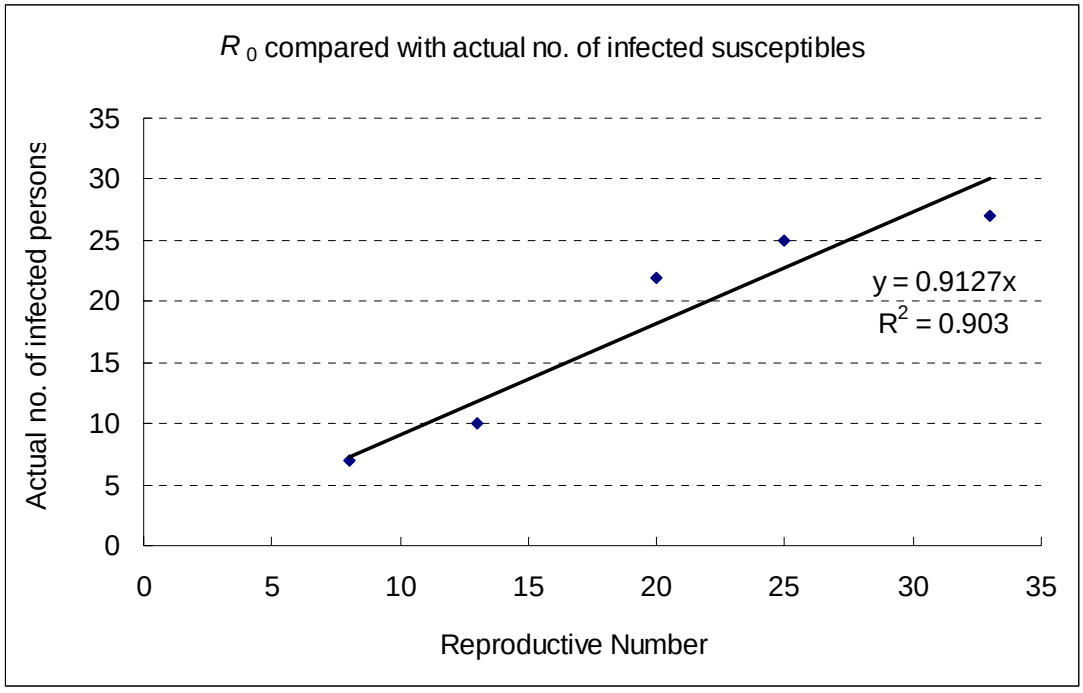

Figure 8.1 Reproductive number vs. actual no. of infected susceptibles

Table 8.1 Reproductive number vs. actual no. of infected susceptible in previously occurred disease outbreaks

Disease	Quanta generation rate per hour	Duration of infectiousness (hours)	No. of susceptibles	Reproductive number (by equation 8.13)	Actual number of infected susceptibles	Case reported in	Original source
Rhinovirus (type 16) case I	10	12	36	20	22	Rudnick and Milton [2003]	Dick et al. [1987]
Rhinovirus (type 16) case II	10	52	10	8	7	Meschievitz et al. [1984]	Meschievitz et al. [1984]
Tuberculosis (office)	12.7	160	67	33	27	Nardell et al. [1991]	Nardell et al. [1991]
Influenza	15	4.5	29	25	25	Rudnick and Milton [2003]	Moser et al. [1979]
Tuberculosis (bronchoscopy case)	250	2.5	13	13	10	Nardell et al. [1991]	Catanzaro [1982]

Figure 8.1 shows that the reproductive number is fairly close to the actual number of infected susceptibles. For the slight difference observed from the tuberculosis cases, one possible explanation for the slight over-estimation is that some people infected with *mycobacterium tuberculosis* bacteria would not immediately develop active disease [Heymann 2004], which is different to other pathogens which lead to develop active disease for almost all infected cases. One the whole,

8.2 Epidemic Risk Prediction on a 75 Storeys Office Building

8.2.1 Description on the building

The reproductive number equation is used to analyze the theoretical epidemic risk when an infected person enters one of the floors in an office building. On each floor the office occupied 1951 m^2, with a floor height of 2.8 metres. The outdoor air intakes are located at the mechanical floors at 5/F, 6/F, 44/F, 45/F, 71/F and 72/F. Constant volume air handling units are located at the mechanical floors to distribute the outdoor air to the fresh air louvers in air-conditioning plant room at office floors through vertical fresh air duct. The outdoor fresh air flow rate delivered to each floor can be estimated by measuring the face velocity at the fresh air louvers in the plant room. At each office floor a variable-air-volume (VAV) air-handling unit is housed in

the air-conditioning plant room. The maximum air handling capacity of the air-handling unit at each office floor is 13900 L/s (50000 m^3/hour) and the variable-pitch-in-motion vane-axial fan can throttle the air supply down to a 15% full capacity without the danger of surging. Room air from offices is mixed and recirculated to the plant room through return air louvers. Air filters with 85% dust spot efficiency are used for filtration of return air. By this system arrangement, if an infected person generates infectious pathogen in one of the office room at a floor, the air-handling system would spread the infectious pathogen to the entire floor. The infectious pathogen may be removed from the indoor air by filtration, or by deposition of infectious particles. The concentration of infectious matter in the room is diluted by outdoor fresh air supplied to each floor.

8.2.2 Survey of occupancy and outdoor fresh air quantity

A survey was conducted at selected office floors during working hours, to record the number of occupants at each floor. The outdoor fresh air supply flow rate at each selected floor is estimated by a 9-point average air velocity measurement at the outdoor fresh air louver in the air-conditioning plant room. Hot wire anemometer TSI VelociCAL meter is used. The measured quantity is compared with the recommended outdoor air supply flow rate recommended by the American Society

of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) Standard 62: Ventilation for Acceptable Indoor Air Quality. The 2001 edition of ASHRAE Standard 62 prescribed a rule of thumb of 10 L/s per persons for offices in the ventilation rate procedures. In the 2004 edition a different approach is mentioned, such that the quantity is based on both the number of occupants and the area of occupied space. For office, the requirement is 2.5 L/s per person + 0.3 L/s per m^2 x occupied area in m^2. Table 8.2 presents the data.

Table 8.2 No. of occupants and outdoor fresh air flow rate during survey

Floor	No. of occupants	Measured outdoor air flow rate		Recommended flow rate (m^3/hr) according to ASHRAE standard:	
		(m^3/hr)	Average L/s/person	62 [2001]	62 [2004]
41/F	11	2150	54	396	2207
57/F	18	2268	35	648	2268
68/F	24	5033	58	864	2322
33/F	28	757	7.5	1008	2358
40/F	28	2521	25	1008	2358
65/F	56	3624	18	2016	2610
56/F	65	341	1.5	2340	2693
25/F	66	1307	5.5	2376	2700
20/F	69	1853	7.5	2484	2729
26/F	76	145	0.5	2736	2790
59/F	87	2895	9	3132	2891

The selected floors shown in table 8.1 covers a wide range of occupancy level (from 11 persons at a floor to 87 persons at a floor), and a wide range of outdoor air supply flow rate (from 0.5 L/s per person to 54.3 L/s per persons). Observed from the data, the distribution of outdoor air was not properly balanced according to occupancy level, since at floors like 26/F and 56/F there was an obvious starvation of outdoor air but there was a surplus outdoor air flow at 68/F. The actual outdoor air supply to a particular floor does not match with the number of occupants on that floor during the time of investigation. It is expected that the theoretical epidemic risk at different floor in this building varies in according to the outdoor air flow.

8.2.3 Filtration of airborne micro-organisms

In the case study office building, air filters with 85% dust spot efficiency are installed inside the variable speed air handling units which recirculate the room air. The filter is equivalent to MERV 13 filter according to the rating suggested by ASHRAE standard 52.2 [2007]. The particle size efficiency for various particle size is shown in table 6.4. The particle size efficiency for a MERV 4 filter is also shown as information for typical aluminum-mesh filters used as pre-filters in air handling unit (or used in fan coil units).

Table 8.3 Particle size efficiency of MERV 13 and MERV 4 filters

MERV rating	Dust-spot efficiency (ASHRAE 52.1)	Particle size efficiency (ASHRAE 52.2)		
		0.3 – 1.0 μm	1.0 – 3.0 μm	3.0 – 10 μm
13	80% - 90%	$E_1 < 75\%$	$90\% \leq E_2$	$90\% \leq E_3$
4	< 20%	n/a	n/a	$E_3 < 20\%$

On the filtration efficiency for airborne microbes, Yanagi and Ikeda [2005] reported that for medium-efficiency filters installed in air-conditioning system the filtration efficiency of microbes was almost equal to the filtration efficiency over suspended particles. Kowalski [2006] also suggested that the filtration of micro-organisms nearly approximates the filtration of particles of identical size. Thus for a size of 2.7 μm diameter for infectious particle, the removal efficiency for MERV 13 filter is 90%, while for the MERV 4 pre-filter the removal efficiency is neligible. As the air recirculation rate of the VAV air handling unit can varies between 15% to 100% of full capacity, the recirculated germ-free air flow rate due to air filtration ($\eta_f Q_f$) becomes 6750, 22500 and 45000 m^3/hr respectively for 15%, 50% and 100% of AHU full capacity.

8.2.4 Prediction on epidemic potential

The reproductive number (R_0) derived in section 8.1.3 serves as an index of the risk of epidemic airborne infection to occur, when one infected person enters a room.

$$R_0 = \frac{pq}{(Q_o + \eta_f Q_f)} \times N \times d \qquad \{\text{equation 8.14}\}$$

For the pulmonary ventilation rate of susceptible persons, *p*, a range of 0.3 to 0.54 m^3/hour is reported in different literature [Riley 1979, Vander et al. 1994, ICRP 1994, Noakes et al. 2006]. The International Commission on Radiological Protection suggests that for a male adult the pulmonary ventilation rate is 0.54 m^3/hour when sitting, and for female the corresponding value is 0.39 m^3/hour. In this study the value recommended by Riley [1979] is adopted, i.e. 0.42 m^3/hour. The quanta generation rates, *q*, for various airborne infectious diseases are listed in chapter 1, table 1.3. For the duration of infectiousness, it is assumed that the infected person would seek medical assistance and not to enter the office building upon onset of symptoms. As a result, the duration of infectiousness adopted in the analysis only consider the time that the infected person is infectious while before onset of sick symptoms. For measles the period of communicability is from 1 day before the beginning of the prodromal period (usually about 4 days before rash onset)

[Heymann 2004]. For influenza the period of communicability is 1 day before onset of symptoms [Hawker et al. 2001]. For rhinovirus infection (common cold) the period of communicability is 24 hours before onset [Heymann 2004]. Thus the duration of infectiousness for the airborne infections in our analysis is defined as one working day, assuming 8 hours working inside the office, such that the infectious person is unaware of getting infected, and working in the office as usual. The outdoor air flow rate and the recirculated air flow rate are mentioned in section 8.2.2 and 8.2.3. With all parameters in equation 8.13 defined, the basic reproductive number R_0 can be estimated. Figure 8.2 to 8.6 shows the basic reproductive number for different occupancy status (with different average outdoor air flow rate per person). Figure 8.7 and 8.8 shows the change of basic reproductive number when the number of occupants at the floor is the same while the average outdoor air flow rate per person is different (7.5 L/s/p vs. 25 L/s/p). Figure 8.9 and 8.10 show the change of reproductive number when the average outdoor air flow rate per person is the same (7.5 L/s/p) while the number of occupants at the floor is different (28 persons vs. 69 persons). When $R_0 < 1$, it means that for each infected individual produces, on average, less than one new infected individual, and it is expected that, theoretically, epidemic of infection will not occur in the population. From figures 8.2 to 8.6, it can be observed that, for tuberculosis, rhinovirus and influenza (with quanta generation

rate q between 10 to 15 quanta per hour), and for SARS (with q = 28.77 quanta per hour), and for measles (for the case with q = 107 quanta per hour), when one infected person enter the population the reproductive number is below 1 for the situation when the air-handling unit is operated at 100% flow, at which the air filter filtrates 90% of the infectious particles (2.7 μm to 5 μm) in the re-circulated air and delivers 45000 m^3/hr of germ-free air to the occupied space.

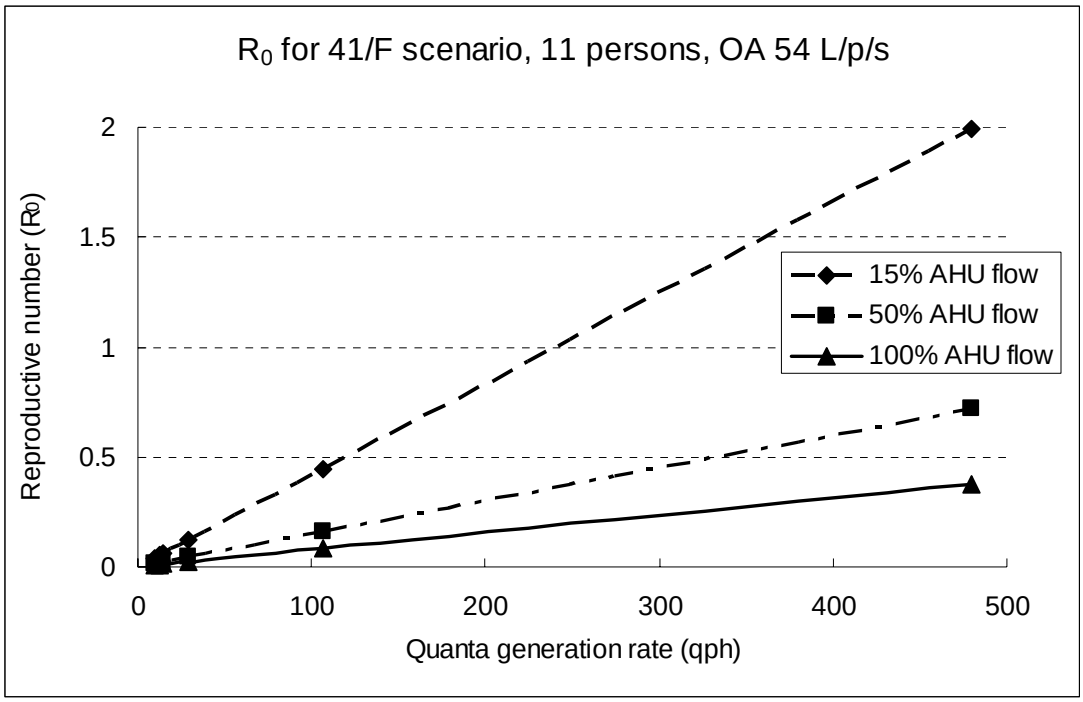

Figure 8.2 Reproductive number for 41/F scenario with outdoor air supply rate of 54 L/s per person

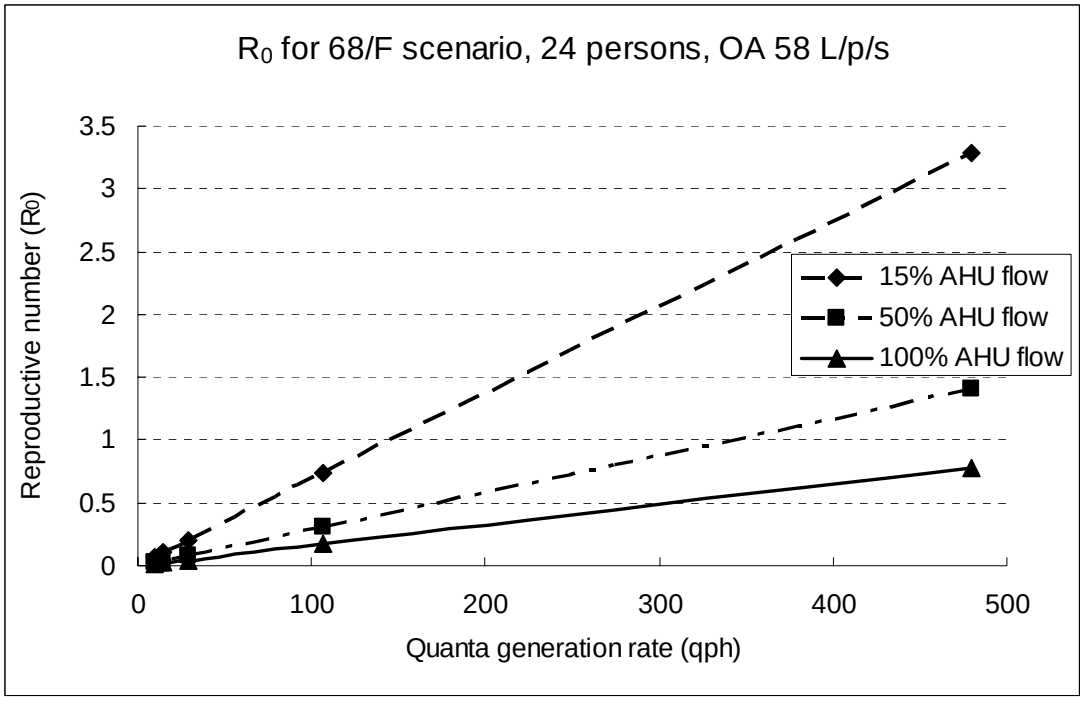

Figure 8.3 Reproductive number for 68/F scenario with outdoor air supply rate of 58 L/s per person

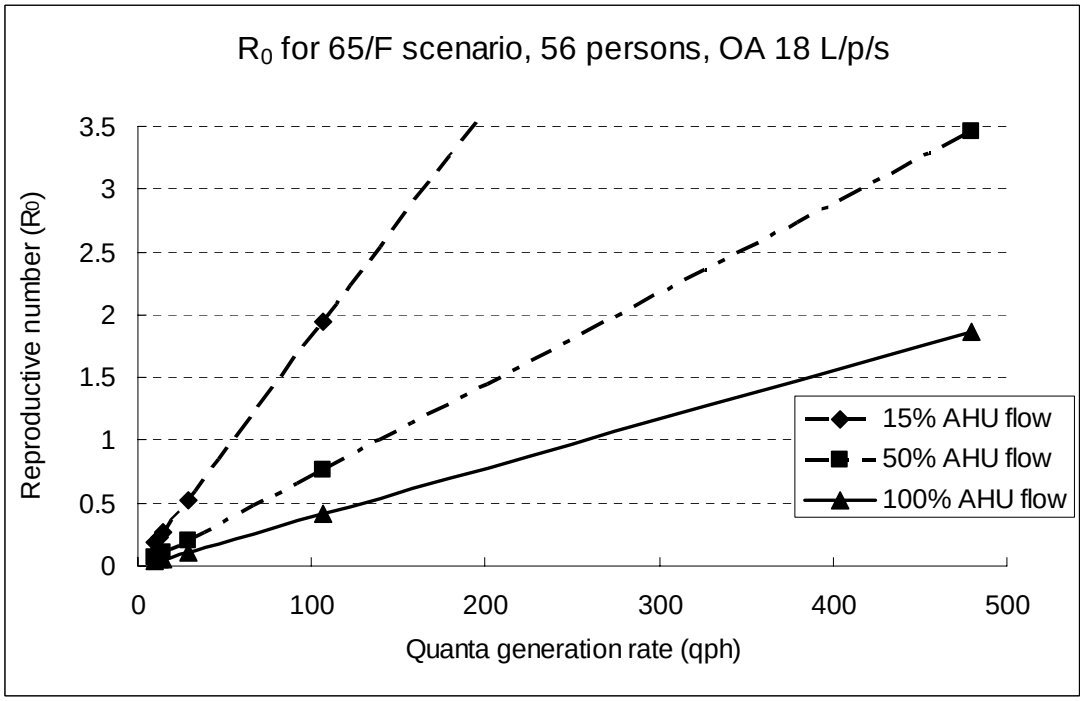

Figure 8.4 Reproductive number for 65/F scenario

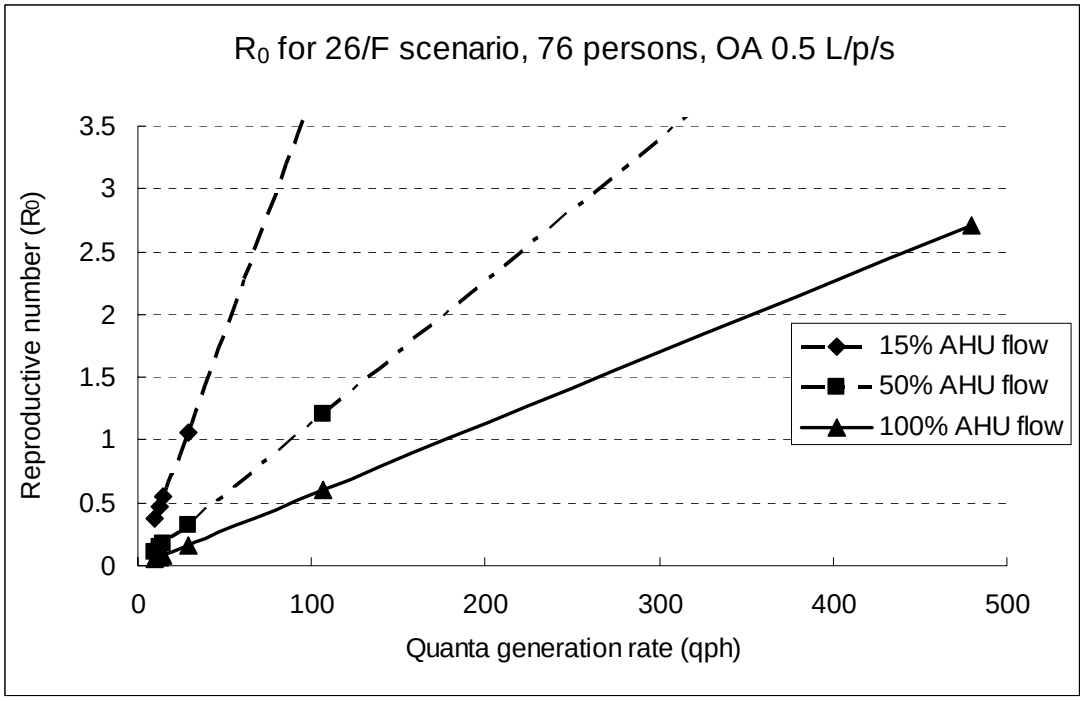

Figure 8.5 Reproductive number for 26/F scenario

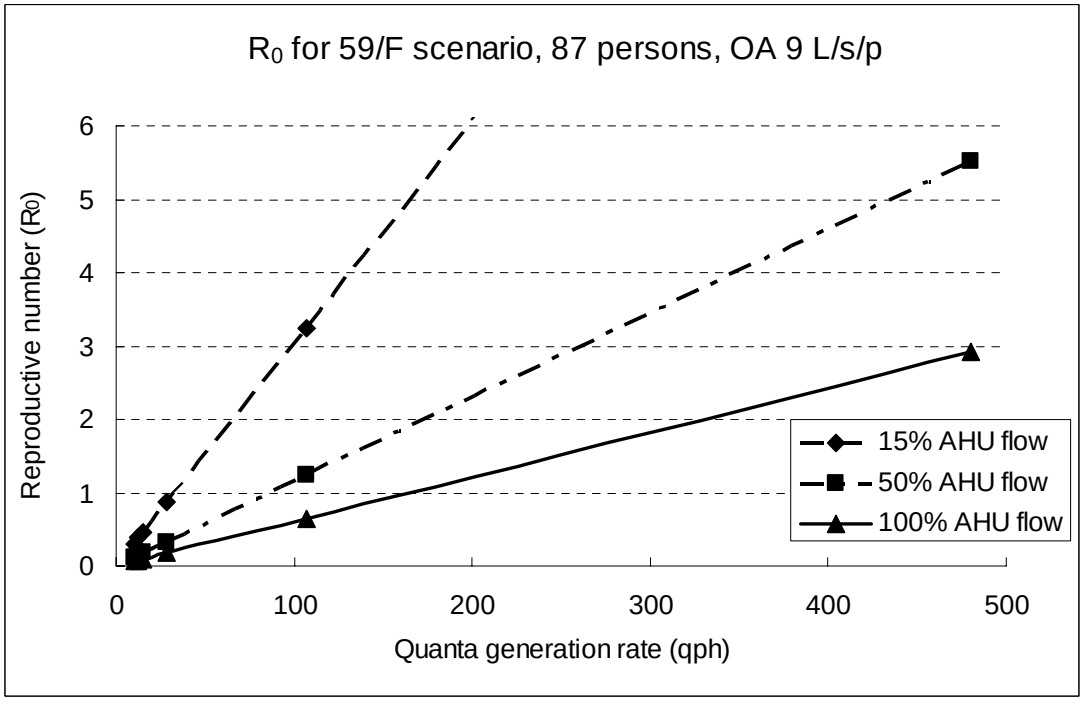

Figure 8.6 Reproductive number for 59/F scenario

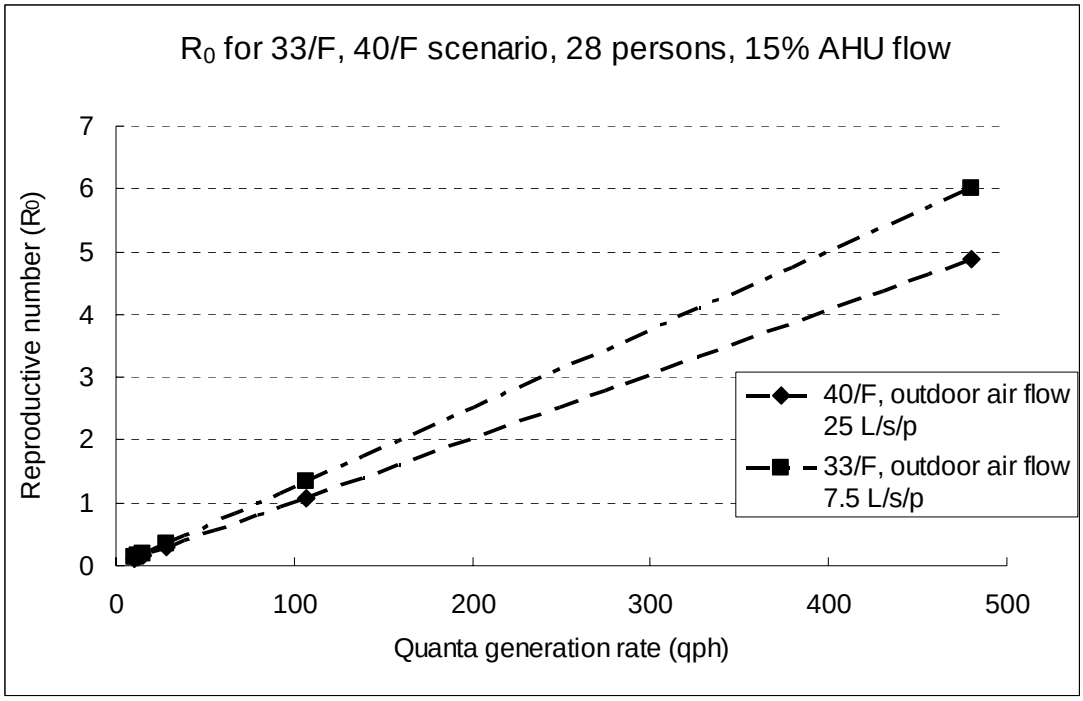

Figure 8.7 Reproductive number under same number of persons (28), at 15% AHU air flow, with different outdoor air supply flow rate

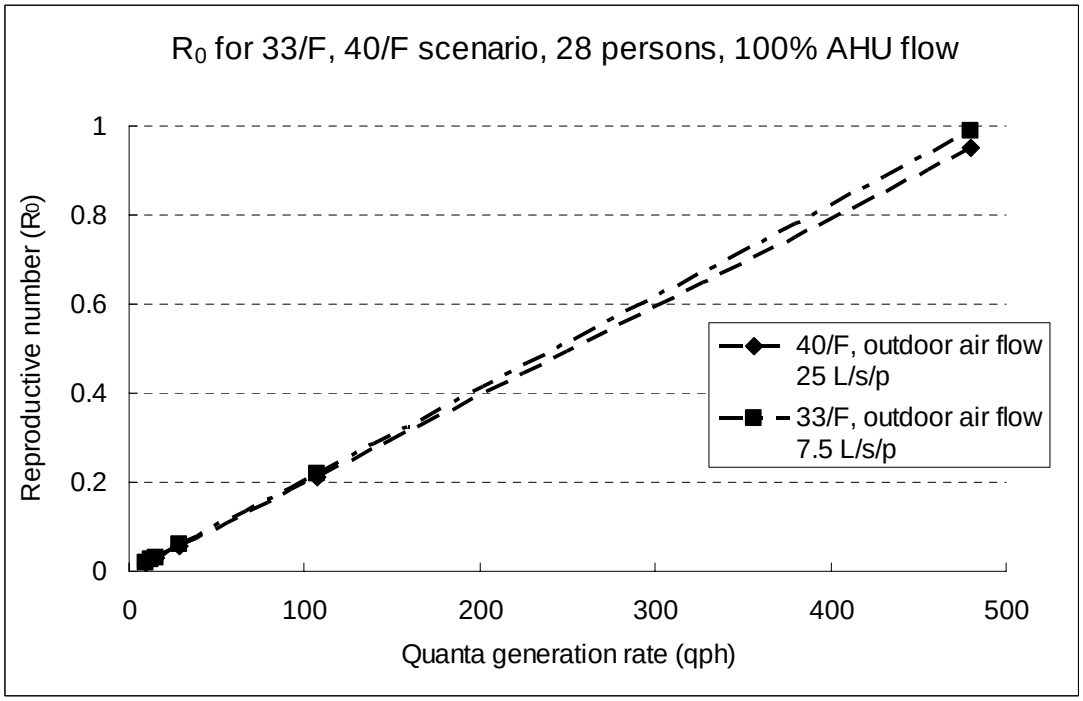

Figure 8.8 Reproductive number under same number of persons (28), at 100% AHU air flow, with different outdoor air supply flow rate

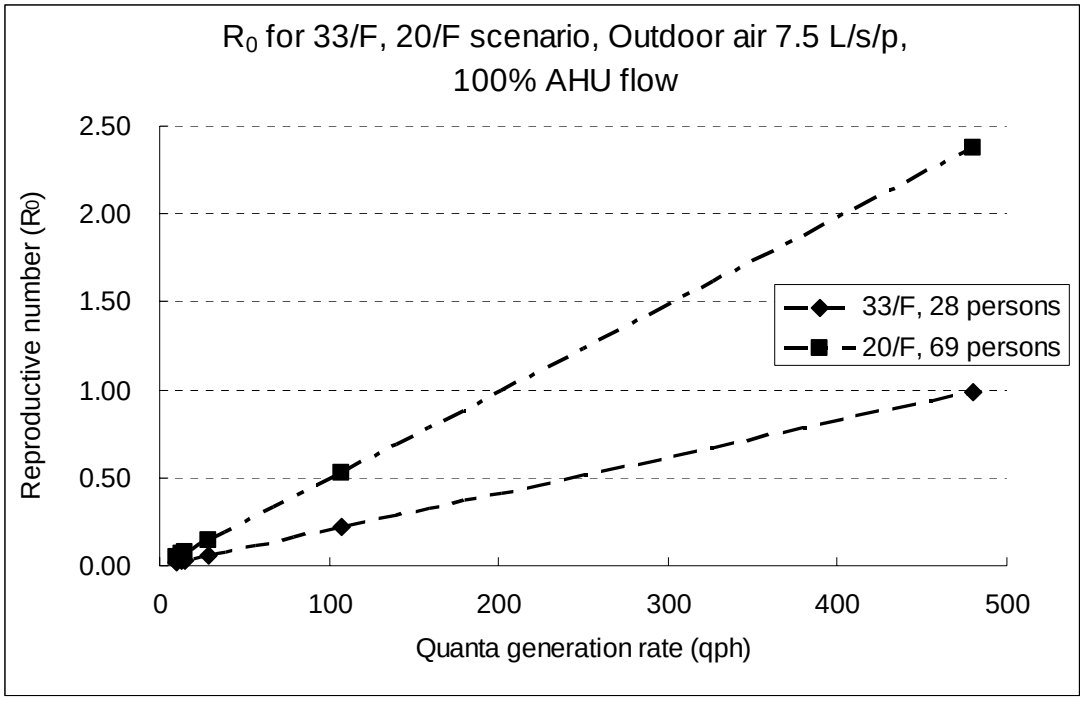

Figure 8.9 Reproductive number under same outdoor air supply flow rate (7.5 L/s per person), at 100% AHU air flow, with different number of persons at a floor

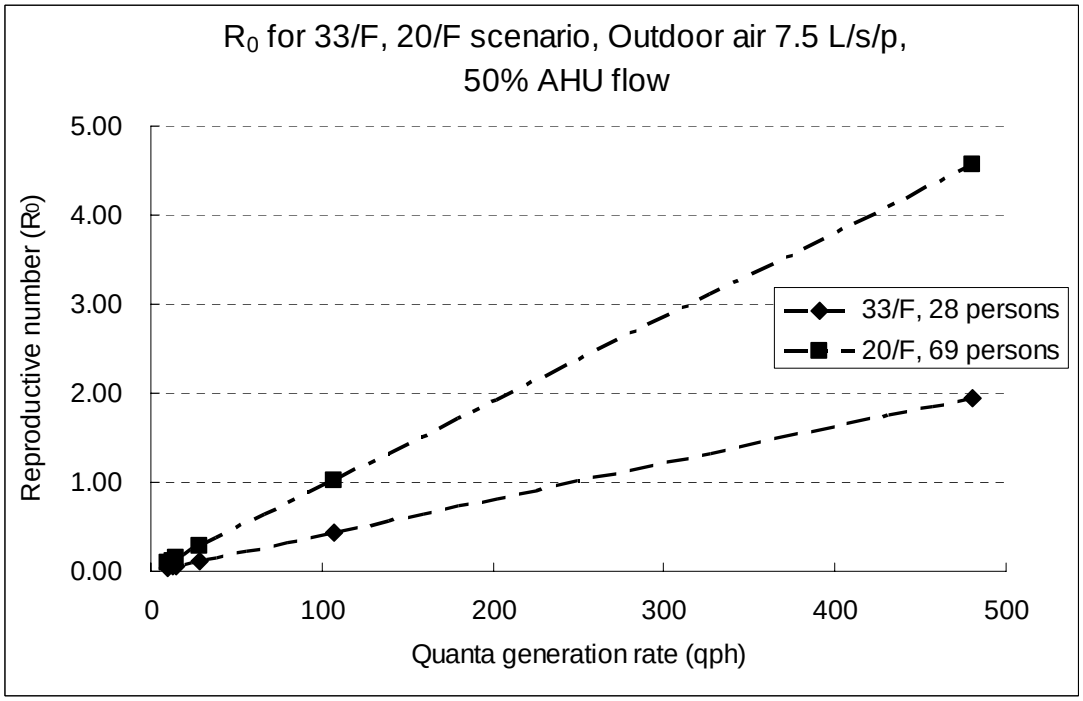

Figure 8.10 Reproductive number under same outdoor air supply flow rate (7.5 L/s per person), at 100% AHU air flow, with different number of persons at a floor

For the highly infectious measles case (q = 480 quanta per hour), with a low occupancy up to 24 persons at the floor, and the AHU operates at 100% full load, the reproductive number is still below 1. Reduced occupancy can potentially reduce the chance of epidemic outbreak to occur, as observed from figure 6.8 to 6.9. Observed from figures 8.7 and 8.8, the decrease of recirculation air flow rate to 15% capacity of air handling unit results in an increase in reproductive number $R_0 > 1$ when the index person is infected with SARS (q = 28.77) or measles (q = 107 or 480) which means that there is potential for the epidemic outbreak to occur. In this case, the increase of outdoor air flow rate from 757 m^3/hr (7.5 L/s per person) to 2521 m^3/hr (25 L/s per person) is comparatively less significant when the recirculated germ-free air production rate is 45000 m^3/hr.

8.2.5 Effect of outdoor air ventilation on predicted risk of epidemic airborne infection

The reproductive number (R_0) derived in section 8.1.3 serves as an index of the risk of epidemic airborne infection to occur, when one infected person enters a room. While in the case study building, the 85% dust-spot-efficiency filter in Variable-Air-Volume (VAV) Air-handling unit serves to filtrate the re-circulated air

from the occupy space, in some other buildings it can be the case that fan coil system is used and the typical aluminum-mesh filters used in the occupancy zone would have neligible effect on the small size infectious particle of 2.7 μm (note that for aluminum-mesh filters are rated at MERV 4 the highest, typically used in fan coil units, the particle size efficiency at the range of 1.0 to 3.0 μm is neligible, while even for particles of 3.0 – 10.0 μm the particle size efficiency is <20%, according to ASHRAE Standard 52.2 [2007]). If only outdoor air ventilation serves to provide germ-free air for dilution of infectious quanta, equation 8.13 becomes

$$R_0 = \frac{pq}{Q_o} \times N \times d \qquad \{\text{equation 8.15}\}$$

Based on the information shown in table 8.2 and 8.3, and for 8 hours exposure at a pulmonary inhalation rate (p) of 0.42 m^3/hour, the reproductive number (R_0) at different outdoor air supply flow rate scenario can be calculated, and presented in table 8.4. For the prevention of the spread of rhinovirus common cold, an average outdoor airflow rate of 9.33 Litre per second per person or above would lead to a reproductive number $R_0 < 1$ and it can be expected that the infection will be cleared from the population. For tuberculosis an average outdoor airflow rate of 11.85 L/s per person supplied to the case study building would results in a reproductive

number <1. For influenza the corresponding outdoor airflow rate is 14 L/s per person. For SARS the corresponding outdoor airflow rate is 26.85 L/s per person. Figure 8.11 and 8.12 shows the corresponding reproductive number under various outdoor air flow rate (in L/s/person) for different quanta generation rate (q per hour).

Table 8.4 Reproductive number for various airborne infectious diseases in the case study office building

Floor	Population (N)	Outdoor airflow rate (Q_o)		Basic reproductive number (R_0)					
		(m^3/hr)	L/s/person	Measles (q=107)	Measles (q=480)	TB	SARS	Influenza	Rhinovirus
41/F	11	2150	54.3	1.84	8.25	0.22	0.49	0.26	0.17
57/F	18	2268	35.0	2.85	12.80	0.34	0.77	0.40	0.27
68/F	24	5033	58.2	1.71	7.69	0.20	0.46	0.24	0.16
33/F	28	757	7.5	13.30	59.65	1.58	3.58	1.86	1.24
40/F	28	2521	25.0	3.99	17.91	0.47	1.07	0.56	0.37
65/F	56	3624	18.0	5.56	24.92	0.66	1.49	0.78	0.52
56/F	65	341	1.5	68.53	307.43	8.13	18.43	9.61	6.40
25/F	66	1307	5.5	18.15	81.44	2.15	4.88	2.55	1.70
20/F	69	1853	7.5	13.39	60.06	1.59	3.60	1.88	1.25
26/F	76	145	0.5	188.44	845.33	22.37	50.67	26.42	17.61
59/F	87	2895	9.2	10.80	48.47	1.28	2.91	1.51	1.01

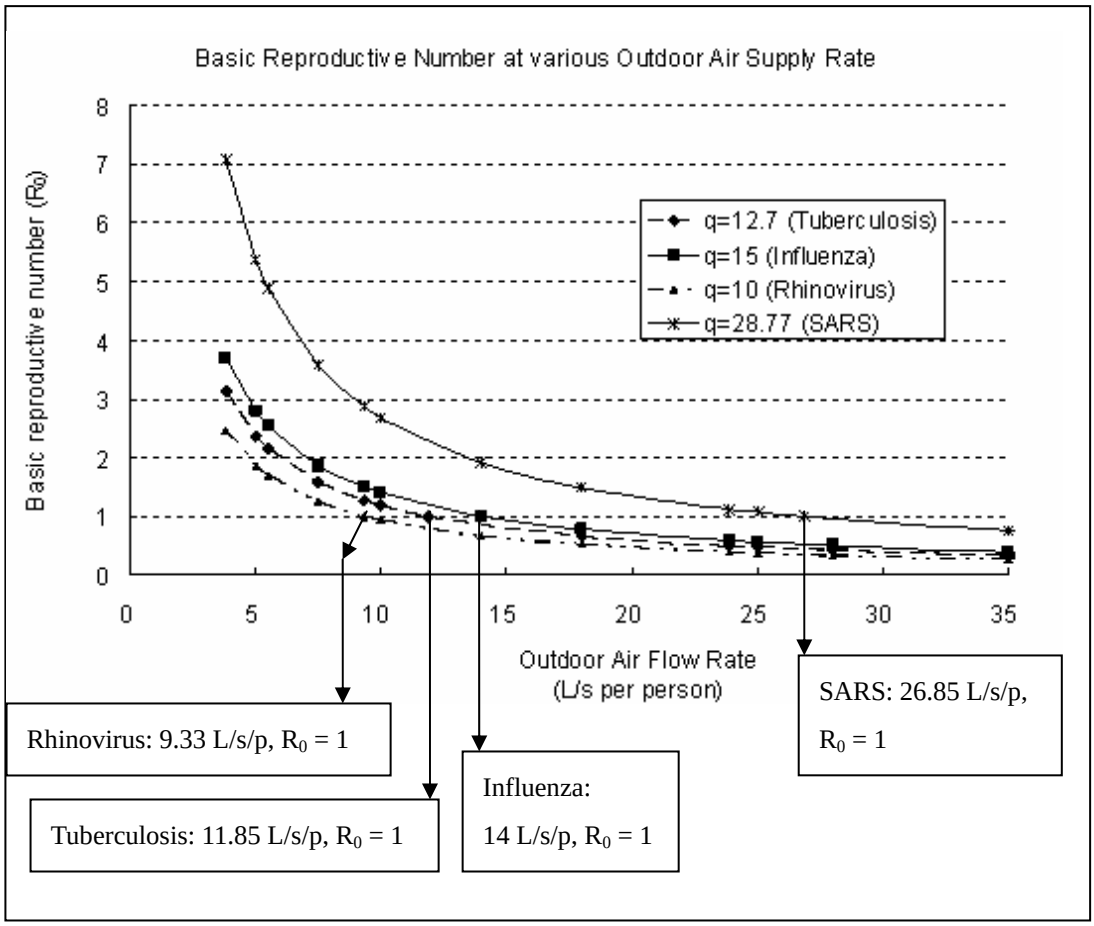

Figure 8.11 R_0 vs. outdoor air supply flow rate.

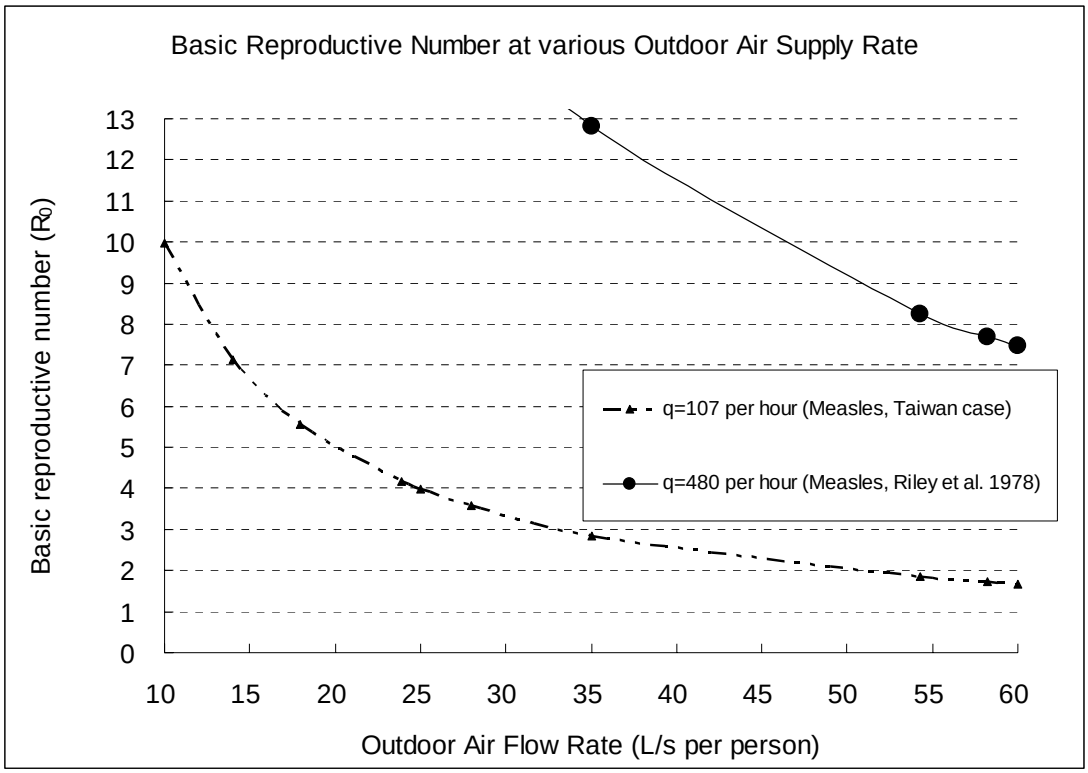

Figure 8.12 R_0 vs. outdoor air supply flow rate (measles)

For measles, the quanta generation rate reported in the case reported by Riley et al. [1978] is so large (480 quanta per hour) and it is predicted that none of the floor would be immune if the case is happened in the case study office building, even for the 68th floor with a large surplus of outdoor ventilation rate of some 58 L/s/person.

The result from reproductive number calculation can be compared with the outdoor air ventilation rate recommended by physician for the purpose to prevent disease spread. In the late nineteenth century, a physician named J.S. Billings observed that

the prevalence of phthisis (tuberculosis) and the spread of contagion or infection of specific fevers were much greater in indoor environment with insufficient ventilation. An outdoor air ventilation rate of 3600 cubic feet per hour (28.3 L/s) per person was suggested for the purpose of preventing spread of disease like Tuberculosis [Klauss et al. 1970 citing Billings 1893]. If this observation is adopted to compare with the prediction result from the reproductive number calculation, for tuberculosis case with a generation rate of 12.7 quanta per hour, the reproductive number is below 1 (the threshold criterion) at 28.3 L/s per person outdoor air flow rate, unless the effective infectious exposure is longer than 19 hours. For tuberculosis the period of communicability starts when the infected person develops active disease that presentation of symptoms including coughing with sputum, blood or phlegm from the lung can be observed [Heymann 2004, Turkington and Ashby 1998]. If the infected person with active disease can soon aware of these atypical symptoms, seek medical treatment and leave away from workplace or public buildings than the number of infective hours can be reduced; while for hospitals and healthcare facilities the total exposure period among healthcare workers can still be much longer than 19 hours. From today's infection control practice the effective use of protective respirators can further reduce the risk, as modeled by Nicas [1994, 1996] that a penetration fraction value would be multiplied with the pulmonary inhalation

rate *p*, such that the equivalent *p* can be reduced by using respirators. This calculation demonstrates that protection by increasing outdoor air ventilation rate to achieve a safe indoor air quality is theoretically possible while subject to the contact period between the infected person with active disease and the susceptibles. In addition, the analysis referencing the concept from Wells-Riley's model only consider a well-mixed average of quanta concentration, while does not account for the distance effect between infectives and susceptible persons. It is expected that for a close exposure to infective for prolonged period, the actual quanta concentration can be much higher than the well-mixed average such that the infection risk would increase even under a high outdoor air ventilation rate.

8.3 Chapter Summary

This chapter describes a method based on the concept of basic reproductive number integrated with Wells' concept of quantum of airborne infection to predict the epidemic potential when one infector is present in a building. The quanta generation rate is regarded as the loading of infectious organism to the indoor environment. The reproductive number equation is derived and checked with the epidemiological data for airborne disease outbreak cases reported in the literature. The predicted reproductive number is fairly close to the number of infected susceptibles as reported

from the real outbreak cases. The reproductive number equation is then adopted to predict the number of possible infected susceptibles if an index person enters an indoor environment with centralized air-conditioning system.

By using quantum generation rate, i.e. the “airborne infection unit” obtained from Wells-Riley equation in the analysis in this study, the predicted reproductive number is an average value calculated from a well-mixed average quanta concentration. While this may under-estimate the risk for the case of a close contact between susceptibles and the index infective person (at which the susceptible would be exposed to a higher than average infectious quanta concentration), the advantage of using the quantum generation rate from Wells-Riley equation is that the quanta generation rate is obtained from observations on real airborne disease outbreak cases.

According to Riley et al. [1978], two engineering measures are related to the airborne infection risk among the susceptible persons, one is dilution by germ-free air and the other is removal of infectious matter from the air by filtration (or air cleaning). Based on the information of quanta generation rate in previous outbreak cases reported in the literature, by using the reproductive number equation, it is anticipated that for influenza and rhinovirus common cold the epidemic potential is

low in the case study building with the use of air filters rated at MERV 13. For the measles case, the decrease on occupancy can result in the reproductive number less than one, which reduces the risk of developing disease epidemic.

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CHAPTER 9: CONCLUSION

In this thesis several aspects for the management of safe and healthy indoor air quality has been investigated, aiming at building immunization against sick building syndrome and microbiological contamination. Prediction on epidemic risk of airborne respiratory disease outbreak in indoor environment, with the use of Wells-Riley equation and the concept of basic reproductive number, has also been presented. Section 9.1 provides a summary of the study.

9.1 Summary

9.1.1 Managing sick symptoms prevalence among occupants

For sick-symptoms manifestation among occupants inside a building, several causes may be attributed, including presence of infectious pathogens causing respiratory symptoms like common cold or influenza, or the non-infection causes described as the phenomenon of sick building syndrome. For an “immune building”, the assessment and prevention of sick symptoms manifestation among the occupants, no matter caused by pathogen infection or by non-specific causes, is important. Chapter 3 covers the study on non-pathogen-related side named as Sick Building Syndrome, a non-specific health problem reported among occupants who suffer from sick

symptoms at work. An instrument “Environmental Health and Comfort Analyzer” has been developed in this study, for the assessment of sick symptoms through an electronic questionnaire and the monitoring of Indoor Environmental Quality indices for thermal comfort, indoor air quality, visual comfort and aural comfort. While the etiology of Sick Building Syndrome is usually unknown, the antagonist “stress at work” is identified as a factor which can trigger more sick symptoms among office workers under higher stress. Alleviators, including a high outdoor supply air flow rate (36.8 L/s/person or above), lower occupancy density, and a neutral or slightly cool environment (indoor air temperature between 23.5°C to 24.5°C and a PMV between -0.5 to 0) are identified to have less symptoms reported from occupants staying in the indoor environment with these characteristics. While a campaign of keeping the indoor air temperature to a level of 25.5°C or above is promoted by the Hong Kong government, survey results show that under this thermal environment (indoor air temperature of 25.5°C or above) the occupants reported more sick symptoms.

9.1.2 Method of the Testing Air Cleaner Performance

After the SARS outbreak there was a market boom on household air cleaners. If effectively used this offers an engineering option for the immunization of indoor

built environment. These air cleaners were claimed to be capable on killing bacteria and virus, and employ a combination of several air disinfection technologies including ultraviolet germicidal irradiation, photocatalytic oxidation, high efficiency particulates air filter, negative ionization and chemical disinfectant with the use of traditional herbs. The performance of the air cleaners found in the commercial market, usually comprised with a combination of several technologies mentioned above, was tested in a residential household flat, using bacteria species that are commonly found in typical indoor environment to indicate the performance. Statistical method was applied to evaluate the percentage reduction on airborne bacteria count. One air cleaner, using traditional herbs extract for chemical disinfection, has a bacteria removal percentage of 15% to 24% in various locations in test room, and for another two cleaners adopting filters and air ionization technologies the bacterial removal percentage of 25% to 49% at various locations in the test room. The method of study in chapter 4 offers a common platform for the test of air cleaning ‘black boxes’ employing a combination of various air cleaning technologies. This study also proposes a method to estimate the air cleaning rate based on the test result. The air cleaners tested in this study can contribute an addition of 0.33 to 0.69 air change per hour. This estimated air cleaning rate can be compared with the result from air filter performance testing reported in chapter 5, or

compared with the ventilation rate evaluation in chapter 7, such that a decision on which engineering measure can offer the most significant reduction on airborne infection risk can be made by the use of Wells-Riley equation or the reproductive number calculation.

9.1.3 Stack Contamination as Means of Contaminant Spread in Buildings

Since the SARS outbreak in residential buildings in Hong Kong, there is a concern of the safeness of indoor environment and the risk of contaminant spread via building services systems and ventilation devices. In particular, the stacks connecting the residential flats within a high-rise building, for both the vertical drainage stack and the "stack" formed by the re-entrant light-well, were suspected as the possible routes for the spread of SARS virus. The study reported in chapter 6 offers a better understanding on the possibility of contaminant transmission via the drainage stack in a recently built, unoccupied high-rise residential buildings using tracer gas method. The infection risk at various operating modes of ventilation system is estimated by the Wells-Riley equation (with the reference of 28.77 quanta generation rate per hour according to a SARS outbreak case in Taiwan), under the condition that the water-trap seal to the drainage stack is emptied. For the re-entrant route, a similar test was also conducted and reported in chapter 7, which shows the possibility of

vertical contaminant transmission via the light-well. The concentration fraction of SF_6 tracer gas in the receiver room was not as high as the drainage route test.

9.1.4 Ventilation Performance in Residential Buildings with Re-entrant

Another concern triggered after the SARS outbreak is the ventilation performance in residential flats, in particular the bathroom and kitchen with windows facing the re-entrant light-well. Ventilation measurement using tracer gas technique was conducted in an unoccupied high-rise residential building with a re-entrant light-well width of 2.2 metre. For the vertical transmission of contaminant within the light-well, the concentration fraction at the receiver room is 0.005 compared with the source room located at one floor below the receiver room, which is much lower than the case of vertical transmission via the vertical drainage stack route. Ventilation assessment by tracer gas experiment was also conducted inside bedroom in a flat, at different operating mode (air-conditioned mode vs. natural ventilation mode). With reference to the air cleaning rate achieved by typical filters in window type household air-conditioner, as tested in chapter 5, the risk of disease transmission at different operating modes are predicted using the Wells-Riley equation, based on ventilation rate measured using tracer gas technique. For the estimation of ventilation rate of a flat at different outdoor wind speed and direction, Computational Fluid

Dynamics (CFD) analysis has been conducted. The predicted risk of disease transmission at various outdoor air ventilation rates is presented in chapter 7. Under natural ventilation through fully opened window, for airborne infectious disease with quanta generation of 12.7 per hour (such as tuberculosis) and 28.8 per hour (such as SARS), the one hour exposure infection risk is predicted to be below 0.15 according to the Wells-Riley equation, at all outdoor wind speed and direction within a period of five years.

9.1.5 Evaluation of Epidemic Potential in Buildings

In response to the quest of managing safe IAQ (minimizing risk of disease transmission induced by pathogenic or infective micro-organisms in the indoor air) after the SARS epidemic, Chapter 8 proposes the application of reproductive number (R_0) as an index to indicate the possibility and the scale if an epidemic occurs. Wells' concept of quantum of airborne infection is integrated to a mass balance analysis in an indoor environment, to enable the estimation of reproductive number based on outdoor air ventilation rate, efficiency of air filter and the deposition rate of the micro-organism, with reference to the SIR epidemic model. The epidemic potential in an office building under different ventilation and occupancy condition is evaluated with known outdoor air ventilation rate (ranged from 0.5 L/s per person to 54.3 L/s

per person) and known efficiency of air filter (85% dust spot efficiency) at air recirculation rate of 100% at the variable air volume air handling unit (50000 m^3/hr). It is predicted that for influenza and rhinovirus common cold, if one infected person entered the building and breathing out the infectious agent with the strength and generation rate same as the previous cases recorded in the literature, the theoretical epidemic risk is low (R_0<1) in the case study building.

9.2 Conclusion

The airborne infectious disease outbreaks appear at the beginning of twenty-first century have added a new dimension as the maintenance of safe indoor air quality, to protect building occupants against potential threats to the indoor environment from cross infection by pathogenic or infective micro-organisms. The concept of safe indoor air quality goes one step forward than the traditional concept of healthy building.

The research covers the study on the possible mechanisms for microbial transmission through the air. On the possibility of contaminant transfer via vertical drainage stack and the re-entrant “stack”, the tracer gas method shows that such a risk exists for both of these stacks. The contaminant transfer via the empty-trapped drainage

network under the operation of an exhaust fan shows the importance of maintaining the water trap seal in the drainage system as an important defense line in order to ensure the indoor environment can be immune from microbial contamination from the drainage system. The contaminant transfer via the re-entrant light-well reveals a need of providing windows facing a “true” open air in kitchens and bathrooms in residential units, instead of relying on the light-well “exhaust duct” for the intake of air and light.

On the problem of sick symptoms manifestation among building occupants, this thesis attempts to identify the non-infection-related causes (leading to sick building syndrome) and the infection-related cause through the questionnaire survey. This study contributes by identifying the possible antagonists and alleviators for the sick symptoms among building occupants. While the antagonist, stress level, experienced by the building occupants at work is not controllable by engineers and building managers, the other “alleviators” identified from this study can be created by a proper operation of the air-conditioning and ventilation systems in a building.

The research works reported in individual chapters collectively formulate a set of management principles aiming at increasing the resistance to communal disease in

indoor environment to immunize a building. These include the characterization of pathogenic source (by referencing the quanta generation rate of airborne infectious disease) and transmission mechanism in buildings (via. drainage system and/or re-entrant light-well); the monitoring of symptoms manifestation among occupants; the engineering control by ventilation, air filtration and air cleaning; and the prediction of reproductive number to evaluate the risk of cross-infection in indoor environment with a large number of occupants served by the same mechanical air-conditioning system.

By following the work presented from chapter 3 to 7, building services engineers can create an indoor environment, aiming at the “immune” level. The work from individual chapters can be integrated together by using the modified Wells-Riley equation from this study, such that the contribution of the engineering interventions (mentioned in various chapters) together on reducing the relative risk of airborne disease transmission by one single simple equation. While the assumption like the single zone perfect mixing condition is made, if the objective is to compare the relative risks between different engineering effort and intervention options, the modified equation offers a tool for such practical application.

9.3 Suggestions for Future Research

9.3.1 Prediction on airborne infection risk in indoor environment

In this study, the reproductive number equation is derived and checked with the epidemiological data for airborne disease outbreak cases reported in the literature, while the number of airborne disease outbreak cases reported in the literature is limited. For some cases in the literature the information on outdoor air ventilation rate is not available, and for those cases provided with outdoor air ventilation rate information, the case with the largest quantity of outdoor air supply is 7 L/s person, such the predicted risk of epidemic outbreak under increased outdoor air ventilation rate is an extrapolation based on the information available in the literature. For epidemiological study in indoor airborne disease outbreaks in future, it is highly recommended to conduct ventilation study and gather engineering specification of the air-conditioning and ventilation system (in particular the filter efficiency rating and the quantity of indoor air recirculated to the filter) in parallel to typical epidemiological investigation procedure, if anyone was found to be infected by airborne respiratory disease in an indoor environment in future, even if no other person share the room was suffered from infection. This helps a deeper understanding on the level of outdoor air ventilation that the possibility of airborne disease spread can be minimized.

9.3.2 Performance of air filters on pathogenic micro-organisms filtration

Field evaluation of particle size efficiency of air filters are tested using environmental dust in this study. Research on filtration efficiency over selected airborne microbes (*Staphylococcus aureus* and fungal spore) has been reported by Yanagi and Ikeda [2005]. There is a lack on experimental data on the filtration efficiency against typical airborne pathogenic bacteria and virus. For a more accurate evaluation of filtration efficiency on pathogens, in the future it is suggested to use real pathogenic micro-organisms as testing agent for commercial air filter efficiency testing in suitable bio-safety experimental facilities.

9.3.3 Air cleaning by chemical disinfection

The use of chemical disinfectants or air freshener for air cleaning was widely adopted between the 1940s to the 1960s, while there is less much literature on this subject since the 1970s. While disinfection modeling for various technologies including ultraviolet germicidal irradiation, gas phase filtration, electrostatic filtration, pulsed light and thermal disinfection are well documented [Kowalski 2006], there is a lack of studies reported for the modeling of disinfection effect of chemical air fresheners and disinfectants. More research effort is needed in order to

attain a better understanding on the effectiveness of using this technology when comparing with the others.

9.4 Relationship between sick symptoms or risk of airborne infection with IEQ or indoor air pollutant concentrations

The hypothesis proposed by Prof. P Jones [1996] on the effect of IEQ and sick symptom prevalence is adopted in this study. An epidemiological approach to investigate this particular area is recommended. In addition, in the SBS study reported in chapter 3, measurement on indoor air pollutants such as TVOC (measured by ppbRAE calibrated by certified laboratory), individual VOCs identified from gas chromatography/mass spectrometry (GC/MS) analysis, and PM_{10} (measured by a calibrated DustTrak) was conducted. Through a preliminary analysis, no significant relationship between sick symptoms prevalence and each of the above mentioned indoor air pollutant can be observed in this study. More research on this area is recommended.

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APPENDIX 1

A1 Questionnaire for Sick Building Syndrome and Indoor Environmental Quality Perception Survey

(see next page)

Survey on Occupants' Health and Indoor Environmental Quality Perception
樓宇用戶健康狀況及室內環境觀感調查

Indoor Environmental Quality Research Group,
Department of Building Services Engineering, The Hong Kong Polytechnic University

The research group is now exploring appropriate measures to enhance the indoor environmental quality in campus. Your information is of vital importance and we hope you can spend a few minutes to complete the questionnaire. The information is for research purpose and will be treated in **confidential**. Thank You!

為提高校園室內環境質素，研究小組現正收集樓宇用戶的健康狀況及意見。你的資料對提升校園環境質素非常重要，所有資料將用作研究用途並會**保密**. 希望您能用幾分鐘時間填寫問卷，多謝!

A. Demographic Data 基本資料		
1. Gender 性別	* Male 男 / Female 女 (*Please circle as appropriate 請圈適當者)	
2. Position 職銜	* Student 學生 / Academic Staff 教職員 / Other Staff 其他職員	
3. Age 年齡		
4. Date and Time 日期及時間		
5. How many hours per week do you stay here? 一星期內你會身處這裡有多久?		Hours 小時
6. Room no. (that you are now staying in) 現時身處房間編號		
7. Location ID 位置編號		

B. Health Status 健康狀況

1. In the past **month**, do you suffer from any symptom(s) **in the workplace**? Please √ yes or no in column I, and if yes please √ your extend of feeling in column II, and occurance after work in column III.

   在**過去一個月內**, 在**工作間內**你有沒有下列徵兆, 請在第 I 欄 √ 有或沒有. **如第 I 欄 √ 有**, 請在 II 欄內 √ 適當的感覺程度, 並在第 III 欄內 √ 離開工作間後有沒有同樣的徵兆.

Do you suffer the symptom **after leaving the workplace**?

離開工作間後有沒有這徵兆?

Symptoms 徵兆		I		II					III	
		Yes 有	No 沒有	Not at all 從不 ◀				▶ Very much 經常	Yes 有	No 沒有
				1	2	3	4	5		
Dry eyes	眼乾									
Stuffy / blocked nose	鼻塞									
Dry, sore throat	喉乾痛									
Headache	頭痛									
Lethargy	疲乏									
Watering eyes	流眼水									
Running nose	流涕									
Flu like symptoms	作感冒									
Breathing tightness	呼吸不暢									
Chest tightness	胸部壓迫感									
Skin itching	皮膚痕癢									
Rash	發疹									
Ear rings	耳鳴									
Nausea	作嘔									
Dizziness	頭暈									
Asthma	哮喘									
Muscle pain	肌肉痛									
Other uneasiness	其他不適									

B. Health Status 健康狀況

2.	What is the number of sick leave days in the **past month** of work? 你**在過去一個月內**平均告了多少日病假?	(days 日)
3.	In those sick leave days, how many days of the above you think are due to an adverse effect of **workplace environmental quality**? 在上述日子中，有多少天你**覺**得是因**室內環境質素**而引致病假?	(days 日)
4.	What is the number of sick leave days in the **past year** of work? 你**在過去一年內**平均告了多少日病假?	(days 日)
5.	In those sick leave days in a year of time, how many days you think are due to an adverse effect of **workplace environmental quality**? 在上述一年的日子中，有多少天你**覺**得是因**室內環境質素**而引致病假?	(days 日)

		None 沒有	Once 一次	Twice 兩次	More than twice 多於兩次
6.	In the past year, have you suffered from common cold or influenza, which you are most likely getting infected from sick colleagues in the same building? 在過去一年，有否試過**感染傷風或流感**，當中有很可能是從染病的同事 (在相同樓宇工作) 傳染而得病?				

7.	Do you smoke? 你有沒有吸煙習慣?	Yes 有 ☐	No 沒有 ☐	Former smoker 已戒煙 ☐			
8.	How is your eyesight? 你的視力如何?	Normal 正常 ☐	Short-sighted 近視 ☐	Long-sighted 遠視 ☐	Astigmatic 散光 ☐		
9.	Do you wear eyeglasses? 你有沒有配戴眼鏡?	Contact lens 隱形眼鏡 ☐	Yes 有 ☐	No 沒有 ☐			

C. Outdoor Pollution 室外污染程度

1. How do you feel from any **outdoor pollution**? (Please √ your feeling on the following items) 你感受到戶外污染的程度如何? (請在下列各項 √)		1 = Not at all, 完全沒有				5 = Very much so 非常嚴重
		1	2	3	4	5
Air pollution	空氣污染					
Traffic noise	交通噪音					
Airport noise	飛機噪音					
Other: (_____)	其他: (_____)					

D. Work Space 工作活動環境

1.	Your feeling to your own work space: 你**覺**得工作環境的 **空間感覺**:	Very spacious 非常寬敞	Spacious 寬敞	Normal 適中	Tight 緊迫	Very tight 非常緊迫

2. Type of your own work space?
你的工作空間是:

☐ Individual room 獨立房間	☐ Shared room (2 – 4 persons) 二至四人共用房間	☐ Open plan office 多人共用空間	☐ Site office 地盤

3.	Is there any **window** (facing outdoor) near your work space? 你的工作空間內是否靠近**窗戶** (向戶外)?	Yes 有 ☐	No 沒有 ☐

		No 從不	Occasionally 偶然	Often 間中	Very often 很多時	Always 經常
4.	Do you suffer from **muscle strain**? 你是否因工作而感到 **肌肉勞損**?					
5.	Do you need to **maintain/repeat** a certain action or **posture** constantly? 工作時是否需要 **維持某一動作/姿勢**?					

E. Stress Level 壓力程度

1. Your rating for the **stress** you suffer is? (Please √ your feeling on the following items) 你在下列處境所受的壓力如何? (請在下列各項 √)		1 = Not at all, 完全沒有				5 = Very much so 非常嚴重
		1	2	3	4	5
At work	工作中					
At home	家中					
Other: (_____)	其他: (_____)					

F. Ranking the Indoor Environment 室內環境質素排列

Do you think which of the following is the best, which one is the worst? Please rank the workplace environment quality. **(Matching by drawing lines connecting the left & right columns)**

請用連線方式配對，排列你對以下五項環境的相對感覺.

The best	感覺最好	●	●	聽覺環境	Aural Environment
The second best	次好	●	●	活動環境	Ergonomic
The third best	第三好	●	●	室內空氣質素	Indoor Air Quality
The second worst	次差	●	●	氣溫, 濕度, 空氣流動	Thermal Environment
The worst	感覺最差	●	●	視覺環境	Visual Environment

G. Acceptance to the Indoor Environment 室內環境質素接受程度

1. Do you accept the current environment? Please indicate your rating to the parameter (Put a "X" on the line), **and** √ ("accept" or "not accept").
   你是否接受現時的室內環境? 請就以下各項在評分線上劃"X", **及** √"可接受"或"不可接受".

	(不滿意 Not satisfy) 0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100% (Satisfy 滿意)	Accept 可接受	Not accept 不接受
OVERALL Environment 整體環境			
Thermal Comfort 熱舒適度			
Temperature 室溫			
Humidity 濕度			
Air speed 風速			
Indoor Air Quality 室內空氣質素			
Air movement 空氣流動			
Visual Environment 視覺環境			
Aural Environment 聽覺環境			

H. Rating to the Indoor Environment 室內環境質素評核

1. Please √ in the box below to represent your satisfaction on the following parameters.
   請將閣下現時對 **以下各項** 的感受 √ 在適當方格內

	Very Good 很好	Good 好	Normal 適中	Bad 差	Very Bad 很差
OVERALL indoor environment (整體環境)					
Indoor Air Quality (室內空氣質素)					
Visual Environment (視覺環境)					
Aural Environment (聽覺環境)					

J. Thermal Comfort Rating 熱舒適評核

1. Your feeling to the room now? (Please √) 請將閣下現時的感受 √

Cold 寒冷	Cool 涼快	Slightly Cool 稍涼	Neutral 適中	Slightly Warm 稍暖	Warm 溫暖	Hot 炎熱

K. Thermal Status 熱舒適情況

1. Please describe your mid-layer clothing as below. (Please √ in the box)
   請形容閣下所穿的衣服如下: (請√ 在適當方格內)

Female 女

Are you wearing shirt with slack/skirt, or one-piece dress?
你現正穿著襯衫連褲/裙, 還是連衣裙?

Shirt 襯衫	Short-sleeved 短袖	
	Long-sleeved 長袖	
	Sleeveless 無袖	
Skirt or slacks 裙 / 褲	Ankle-length 長袖	
	Knee-length 及膝	
	Short-length 短袖	
One-piece dress 連衣裙		

Please √ the **thickness*** as below

請 √ 衣服**厚度***		1	2	3
Shirt	上身襯衫			
Skirt / slacks	下身裙/褲			
One-piece	連衣裙			

Male 男

Please √ the sleeve length and thickness of your clothing.
請 √ 你衣服的**袖長**及**厚度**:

Item 項目	Sleeve length 袖長			Thickness *厚度		
	None 無袖	Short 短袖	Long 長袖	1	2	3
Shirt 衫						
Short/trousers 褲						

* Key: 1 = Thin fabric (often worn in summer)
2 = Medium fabric
3 = Thick fabric (often worn in winter)

* 註: 1 = 薄身衣料 (通常在夏天穿著)
2 = 中等厚度衣料
3 = 厚身衣料 (通常在冬天穿著)

2. Please indicate your other clothing items as below. (Please √ the appropriate thickness)
   請形容閣下所穿的其它衣物如下: (請 √ 適當的厚度)

Female 女

Item	項目	No 無	Yes* 有*		
			1	2	3
Upper Underlayer	上身內衣				
Bottom Underlayer	下身內衣				
Underlayer Slip	襯裙內衣				
Jumper	毛衣				
Vest	背心				
Jacket/coat	外套				
Sock	短襪				
Pantyhose	褲襪				
Shoe	鞋				

Male 男

Item	項目	No 無	Yes* 有*		
			1	2	3
Upper Underlayer	上身內衣				
Bottom Underlayer	下身內衣				
Jumper	毛衣				
Vest (outermost)	背心 (外衣)				
Jacket/coat	外套				
Sock	襪				
Shoe	鞋				

L. Activity Level 活動程度

1. Please indicate your activity level in the previous hour. (Put √)
   請形容你過去一小時的活動程度. (請 √)

☐ Sitting reading 坐著閱讀	☐ Sitting typing 坐著打字	☐ Standing still 站立	☐ Work on your feet 站立工作
☐ Walking (indoor) 走動 (室內)	☐ Walking (outdoor) 走動 (室外)	☐ Physically demanding activity 體力勞動活動	

M. Environmental Control 環境控制

1. If the parameter can be modified by you, you prefer: (Put √)
   如果你能改變現時的情況, 你會選擇: (請 √)

Temperature	室溫	☐ Warmer 暖一些	☐ No change 不變	☐ Cooler 冷一些
Humidity	濕度	☐ More humid 濕一些	☐ No change 不變	☐ Drier 乾一些
Air speed	風速	☐ Faster 快一些	☐ No change 不變	☐ Slower 慢一些
Air movement	空氣流動	☐ More 多一些	☐ No change 不變	☐ Less 少一些
Visual environ.	視覺環境	☐ Brighter 光一些	☐ No change 不變	☐ Dimmer 暗一些
VDU brightness	電腦螢幕	☐ Brighter 光一些	☐ No change 不變	☐ Dimmer 暗一些
Aural environ.	聽覺環境	☐ Quieter 靜一些	☐ No change 不變	☐ Add sound 多些聲音

N. Description to Odour 室內空氣質素 (氣味)

1. Is there any odour in your workspace? 你的工作位置有沒有氣味?	None 沒有	Slight 輕微	Moderate 中等	Strong 強烈	Very strong 非常強烈	Overpowering 無法忍受

2. If you experience any odour, please √ the type(s) of smell you can detect
   如有氣味, 請用 √ 形容你感受到的氣味, 可選多項

		Once/day 每日一次	Twice/day 每日兩次	Often 經常
Tobacco smoke odour	煙味			
Mould growth	霉菌			
Volatile organic gas	揮發有機氣體			
Pungent chemical	刺味氣體			
Toilet	洗手間			
Kitchen	廚房			
Carpet worn out	地毯發霉			
Document worn out	文件發霉			
Food odour	食物氣味			
Body odour	體嗅			
Copier, printing machine	影印機			
Other odour	其他氣味			

P. Description to the Indoor Air Quality 室內空氣質素表述

1. How do you describe the quality of air in your workplace? (Please √ your feeling on the following 5 items) 您會怎樣形容工作位置的空氣質素? (請在下列 5 項 √)		1 = Never, 完全沒有				5 = Very much so 非常嚴重
		1	2	3	4	5
Stuffy	不流通					
Stale	污濁					
Smelly	有味					
Draught	氣流頗大					
Dusty	多塵					

Q. Visual Environment 視覺環境

1. How do you describe about the brightness? 你覺得現時的光暗水平如何?	Too dim 過暗	Dim 暗	Neutral 適中	Bright 光	Very Bright 過光

2. How do you describe the lighting quality? Please indicate your feeling by √ the following 3 items.
您會怎樣形容工作位置的燈光環境? 請在下列 3 項√ 出你的感覺

		1 = 最好 excellent, 5 = 最差 worst						
		1	2	3	4	5		
Steady	光線穩定						光線閃爍	Flickering
No glare	沒有刺眼						非常刺眼	Too much glare
Uniform	分佈均勻						分佈不勻	Uneven

3. Do you use a **computer or video display unit**? 你有沒有使用 **(電腦) 螢光幕** ?	☐ No 沒有	☐ Yes, (hour/week) 有, (每週 小時)
4. Is there any reflected image on the monitor screen? 電腦熒光幕上是否有反光影像 ?	☐ No 沒有	☐ Yes 有

5. If yes, where do you think the visual image on the screen come from?
如有 , 你認為在熒光幕中所見到的反光影像是因何引起 ?

☐ Windows 窗	☐ False ceiling panel 假天花板	☐ Suspended luminaries 光管燈箱	☐ Partition surface 隔板表面

Other: 其他:

6. How would you rate the brightness of image? 熒光幕中的反映光亮度如何?	Very dark 暗淡	Dim 略暗	Neutral 普通	Bright 略光	Too Bright 太光亮

7. Can you read the following items easily? Please √.
以下項目是否容易閱讀? 請 √

	1 = Very easy, 容易閱讀				5 = Very difficult 難以閱讀
	1	2	3	4	5
The information on the screen 熒光幕的影像					
The document put by the side 熒光幕旁的文件					

8. How much **visual discomfort** (eyestrain / fatigue) do you experience in reading the screen?
長時間閱讀熒光幕時,會否有視力疲勞 (例:眼痛,流眼水)?

1 = Never, 完全沒有				5 = Very much so 非常嚴重
1	2	3	4	5

R. Aural Environment 聽覺環境

1. How do you describe about the noise level? 你覺得現時的噪音水平如何?	Too noisy 過噪	Noisy 噪	Neutral 適中	Quiet 靜	Too Quiet 過靜

2. Is the following noise source presence in your workplace? Please √ the extent of influence.
你的工作位置是否受以下噪音源頭影響? 請在下列各項 √ 出你的感覺程度

Possible Noise source 噪音源頭		Not at all 完全沒有				Unbearable 不能忍受
		1	2	3	4	5
Air-conditioning	空調系統					
Telephone	電話聲					
Human	人聲					
Office equipment	文儀器材					
Indoor renovation work	裝修					
Traffic noise	道路噪音					
Construction site	建築地盆					
Other noise	其他噪音					

-- Questionnaire END, Thank you! 問卷完, 多謝! ---

APPENDIX 2 PARTICLE DECAY PROFILE (CHAPTER 5)

A2.1 Particle decay profile for trial 1

(see next page)

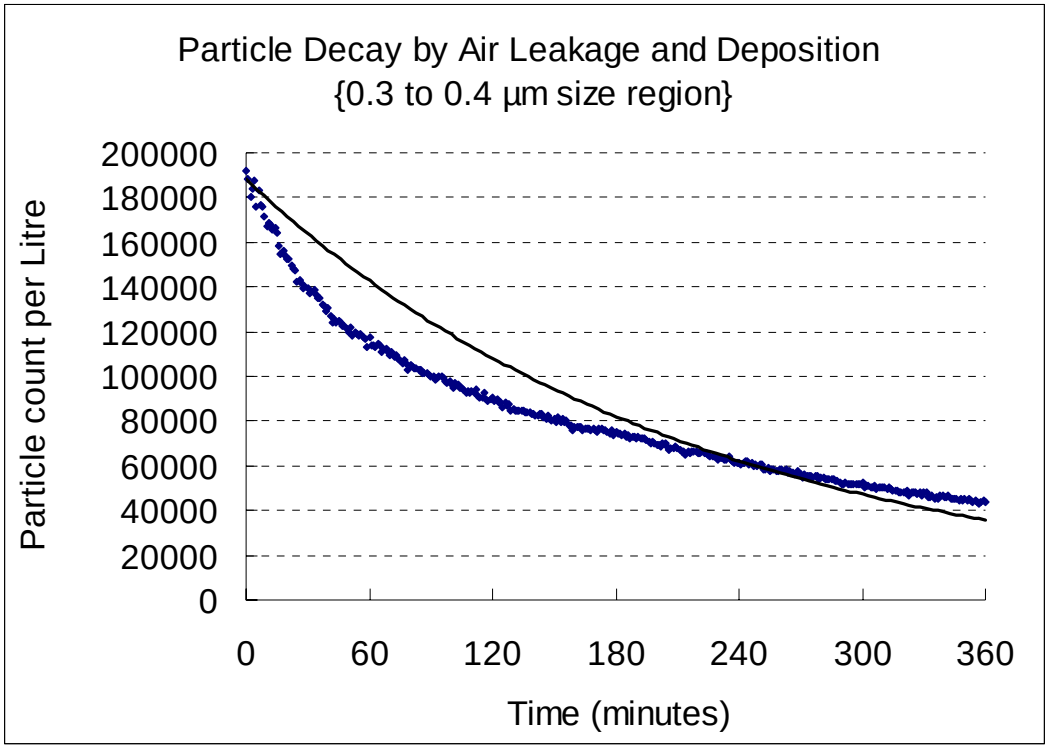

Figure A2.1 Particle decay profile in trial 1, 0.3 μ m to 0.4 μ m particle size range

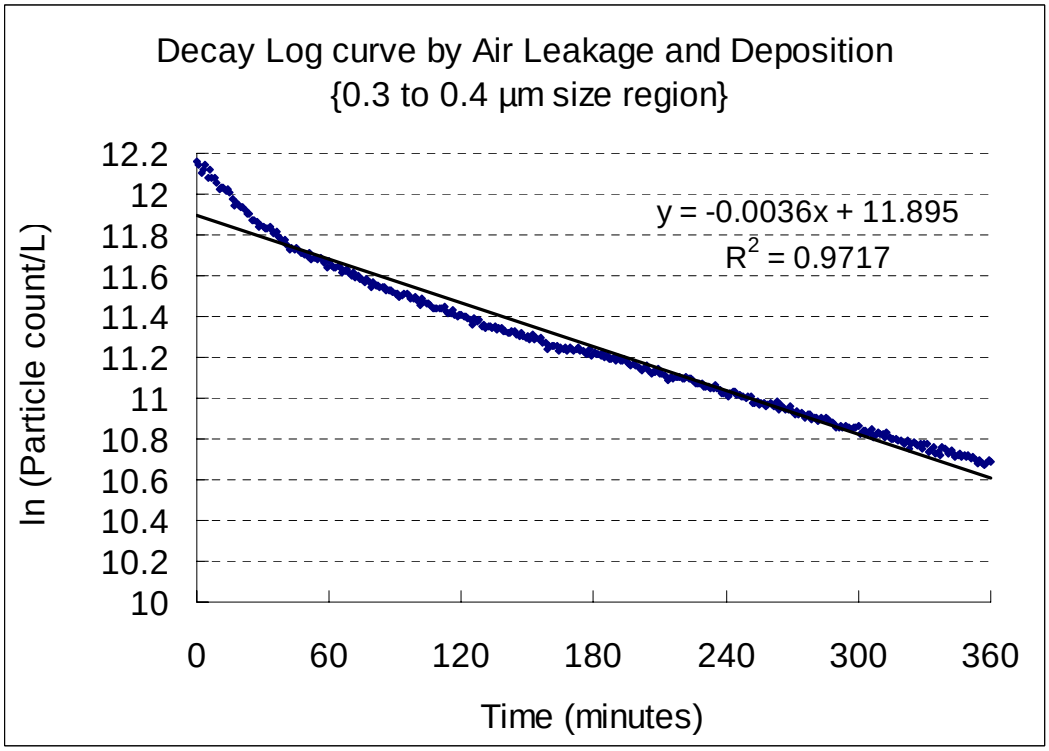

Figure A2.2 Natural log curve for trial 1, 0.3 μ m to 0.4 μ m particle size range

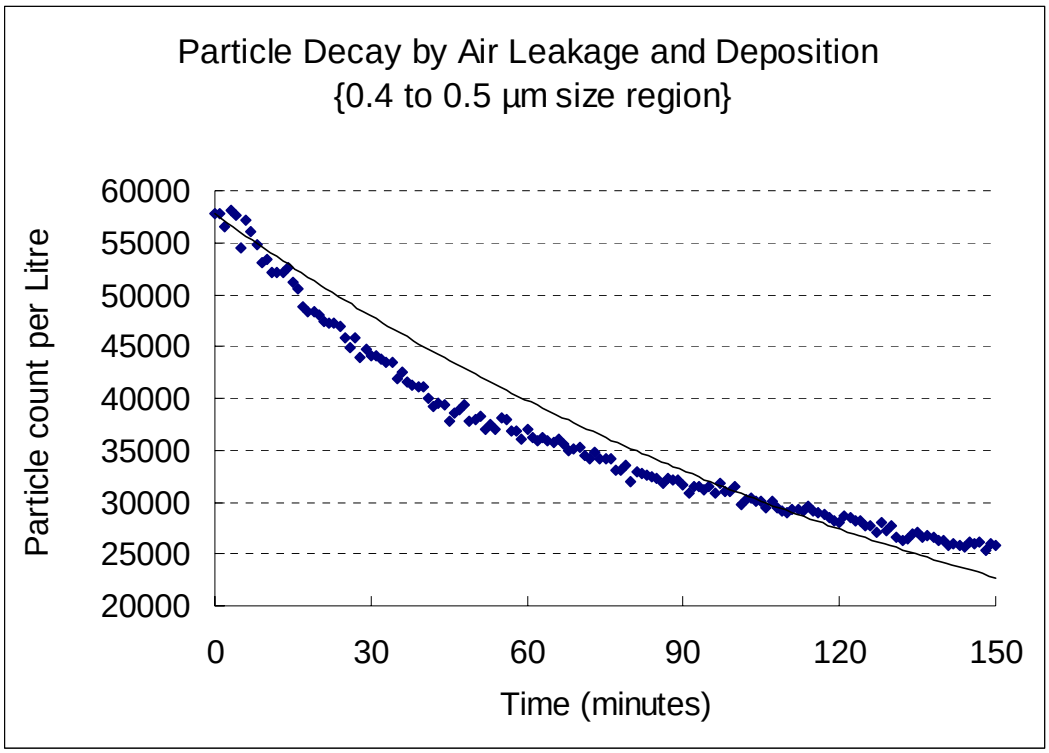

Figure A2.3 Particle decay profile in trial 1, 0.4 μ m to 0.5 μ m particle size range

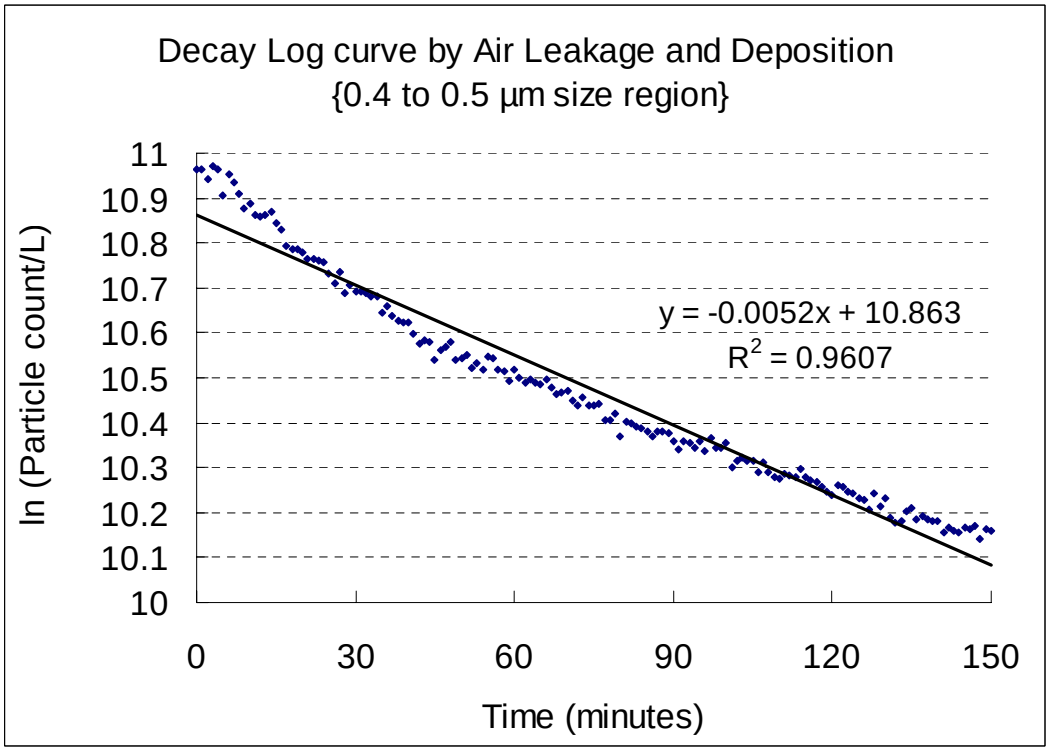

Figure A2.4 Natural log curve for trial 1, 0.4 μ m to 0.5 μ m particle size range

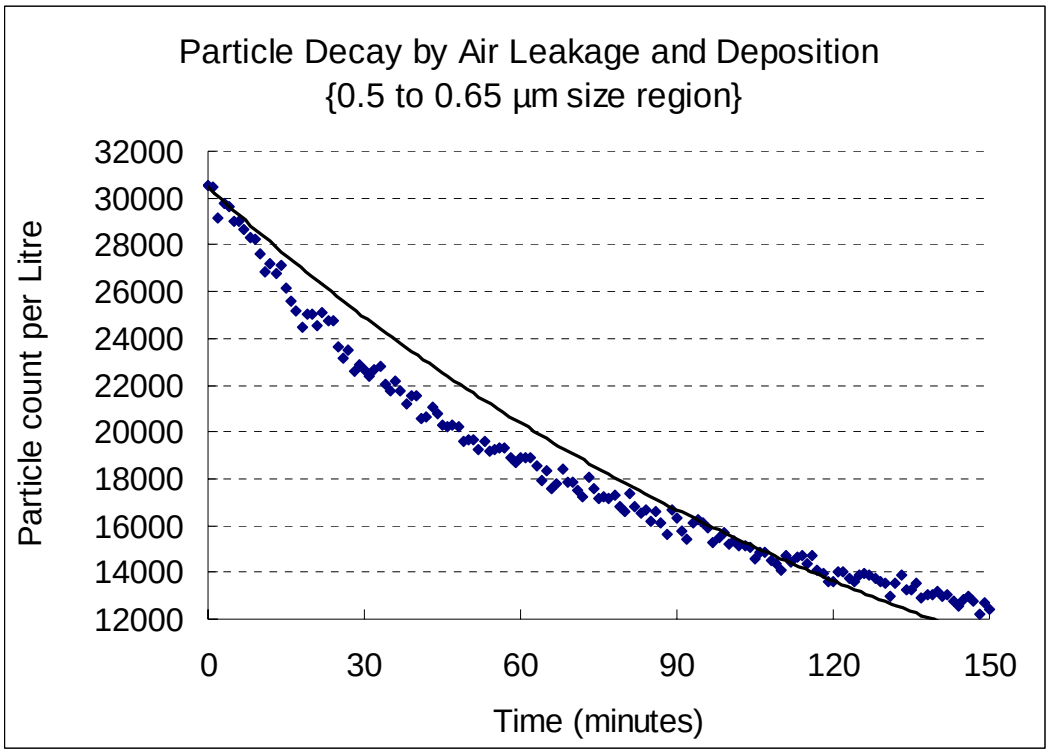

Figure A2.5 Particle decay profile in trial 1, 0.5 μ m to 0.65 μ m particle size range

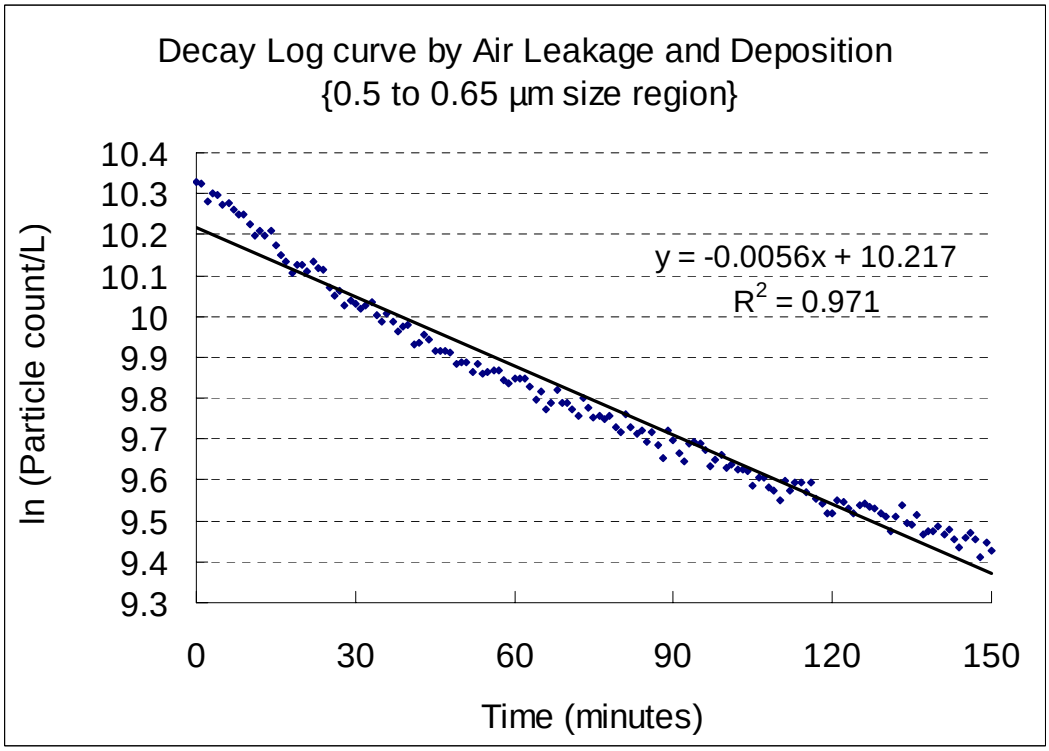

Figure A2.6 Natural log curve for trial 1, 0.5 μ m to 0.65 μ m particle size range

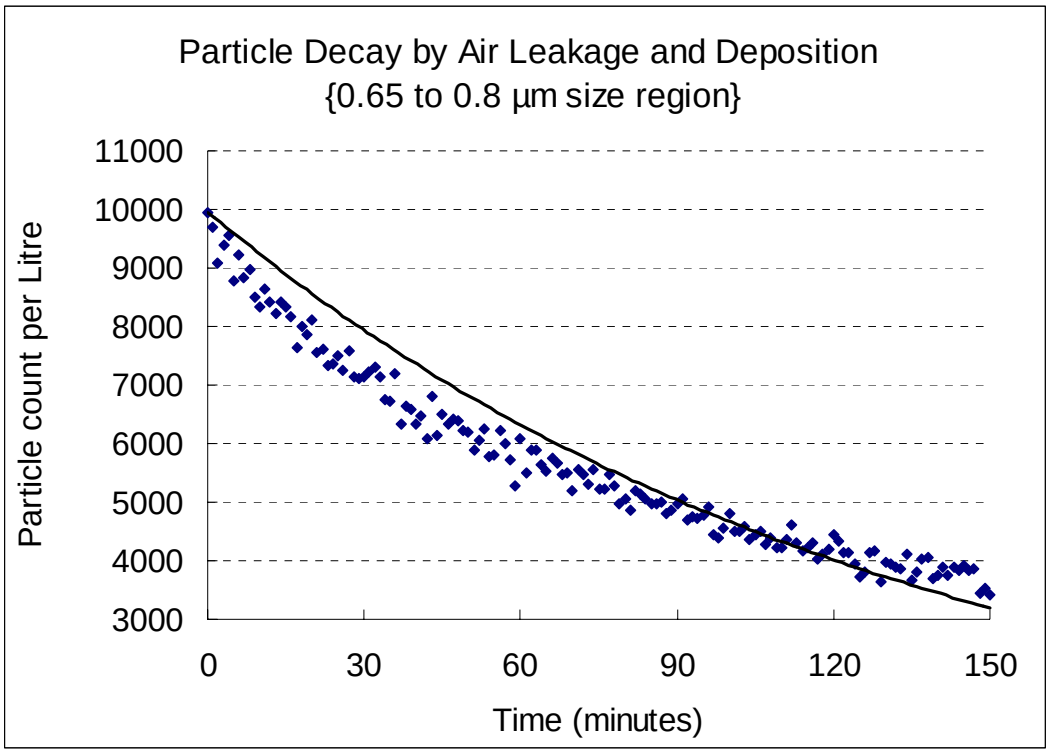

Figure A2.7 Particle decay profile in trial 1, 0.65 μ m to 0.8 μ m particle size range

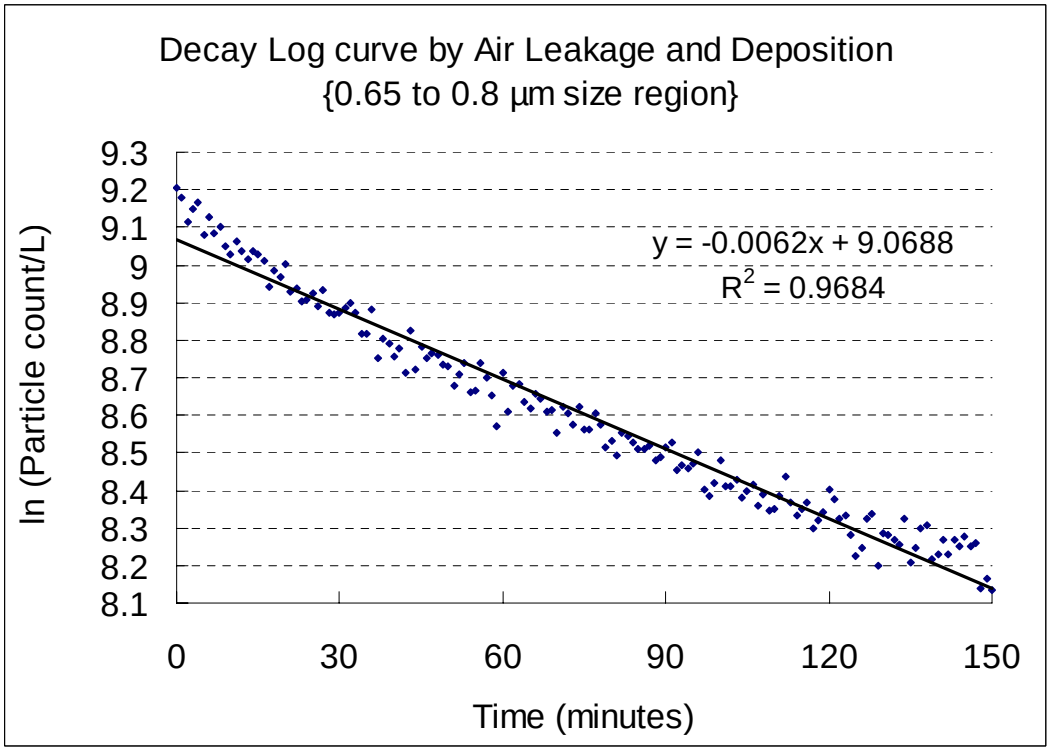

Figure A2.8 Natural log curve for trial 1, 0.65 μ m to 0.8 μ m particle size range

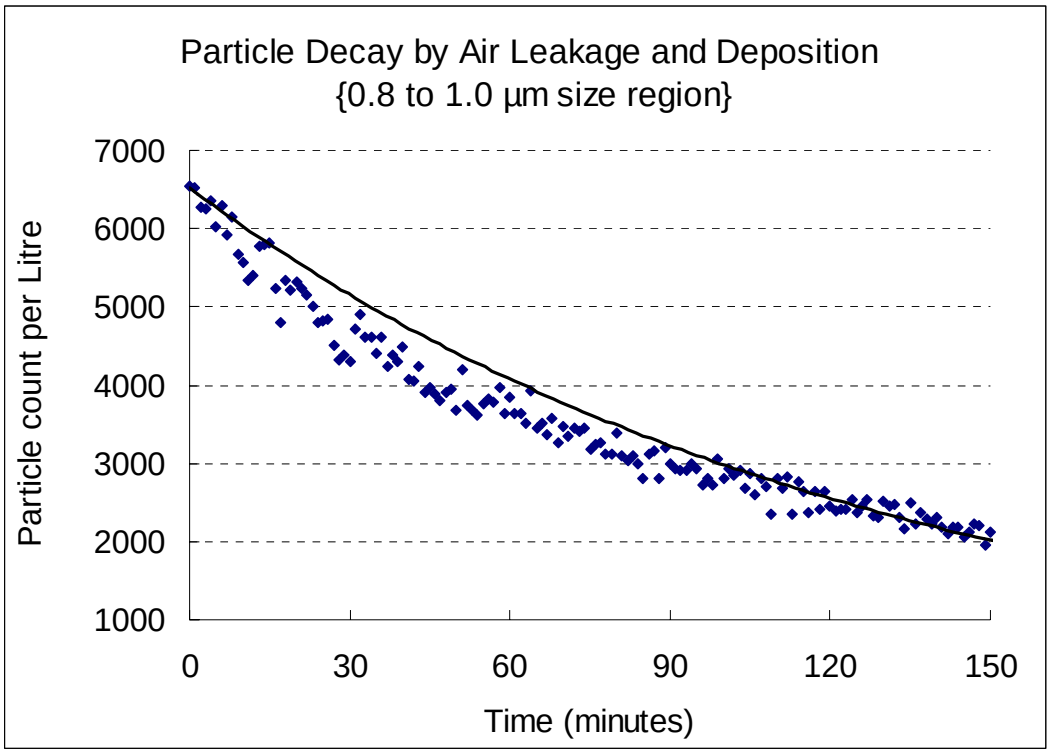

Figure A2.9 Particle decay profile in trial 1, 0.8 μ m to 1.0 μ m particle size range

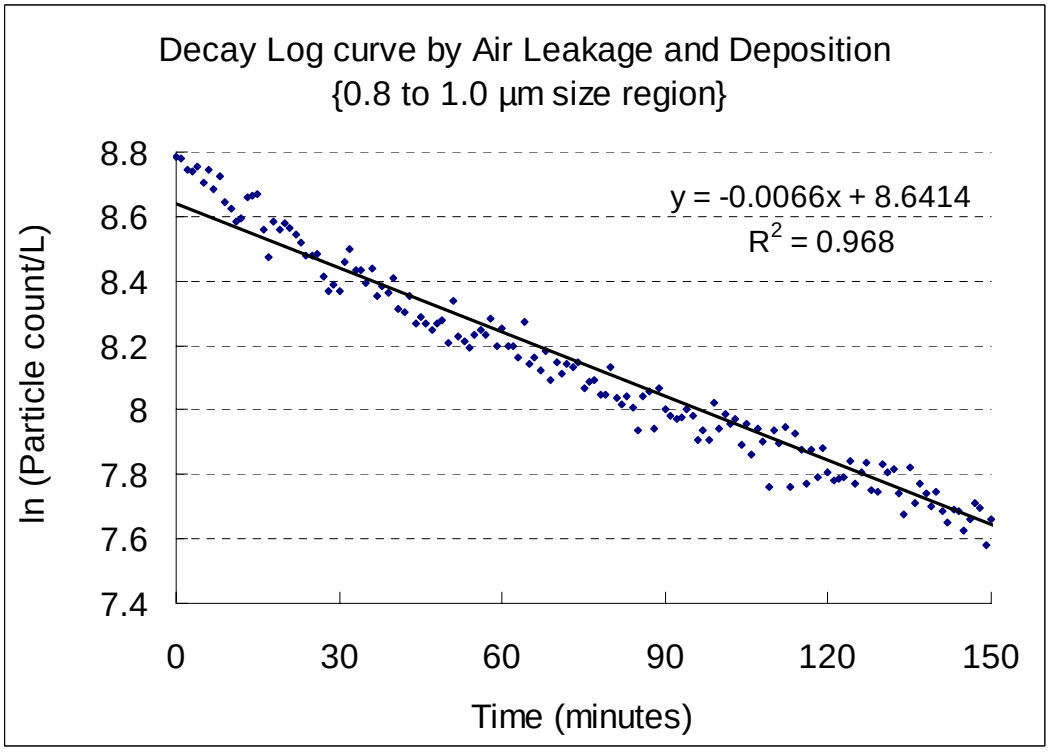

Figure A2.10 Natural log curve for trial 1, 0.8 μ m to 1.0 μ m particle size range

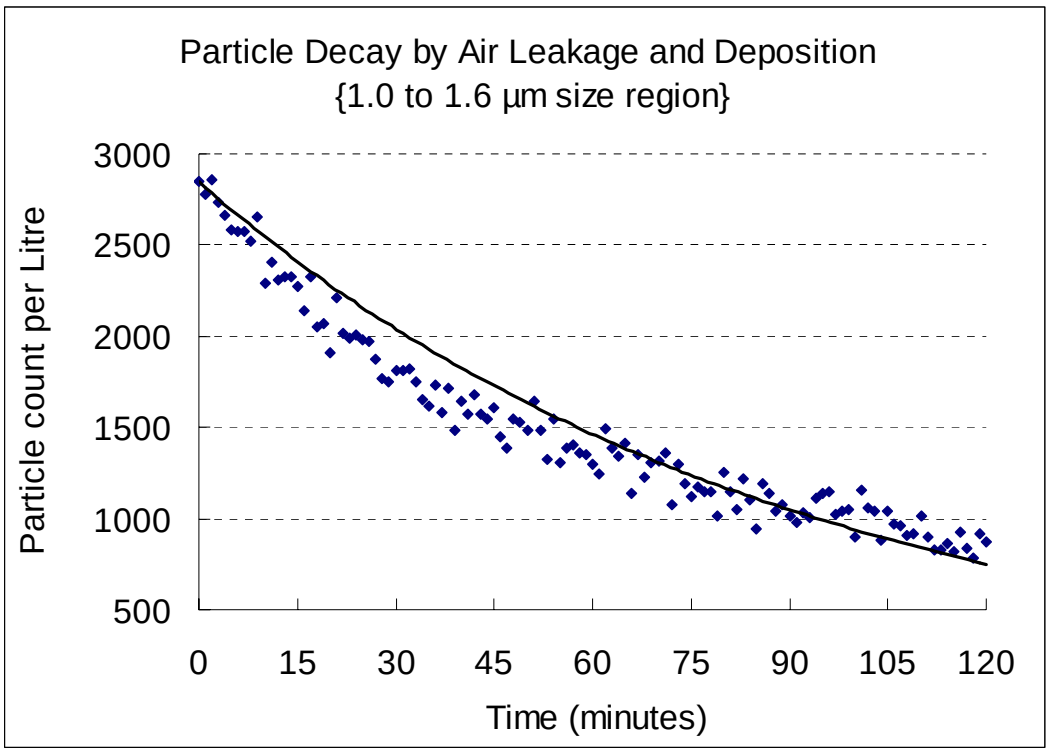

Figure A2.11 Particle decay profile in trial 1, 1.0 μ m to 1.6 μ m particle size range

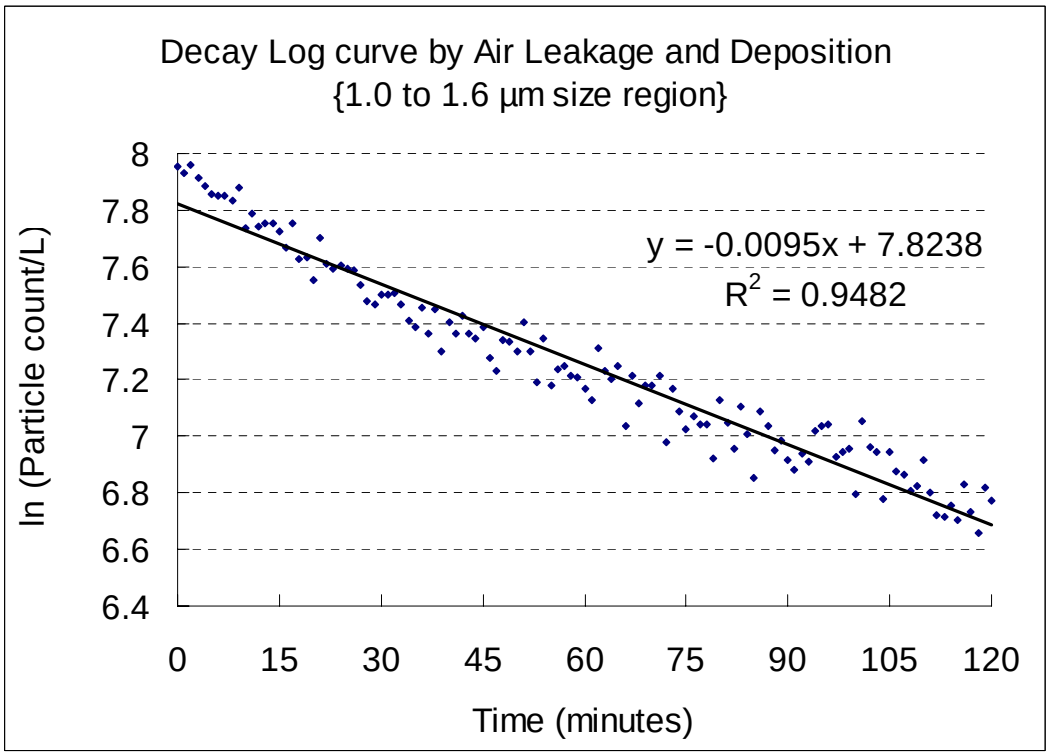

Figure A2.12 Natural log curve for trial 1, 1.0 μ m to 1.6 μ m particle size range

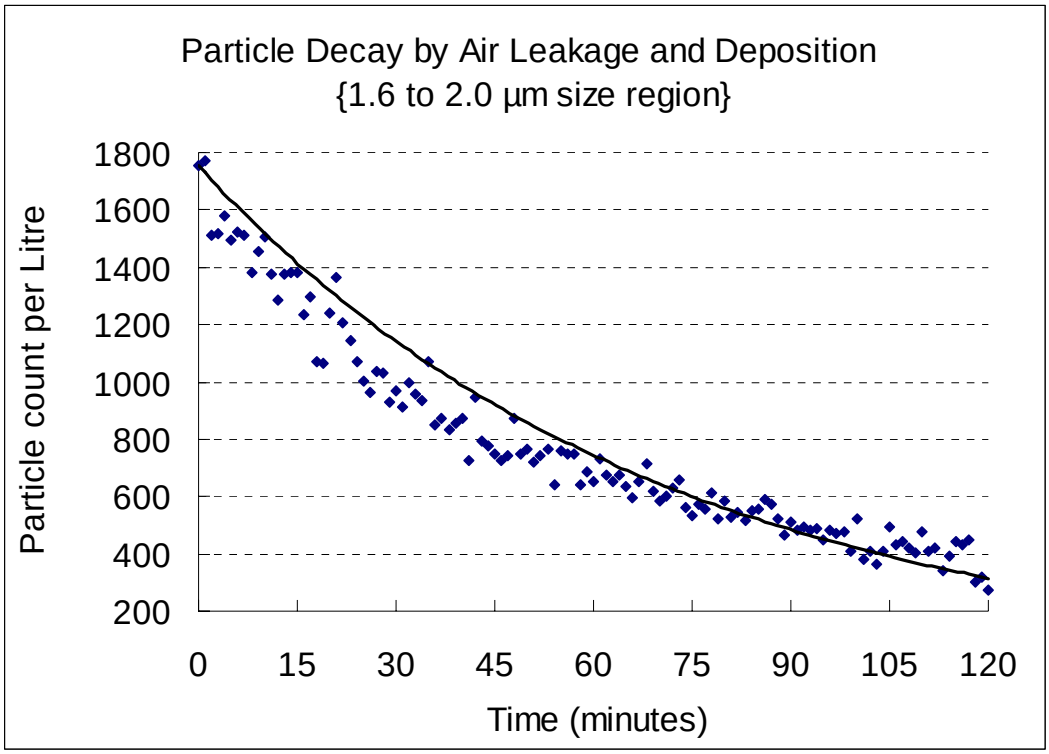

Figure A2.13 Particle decay profile in trial 1, 1.6 μ m to 2.0 μ m particle size range

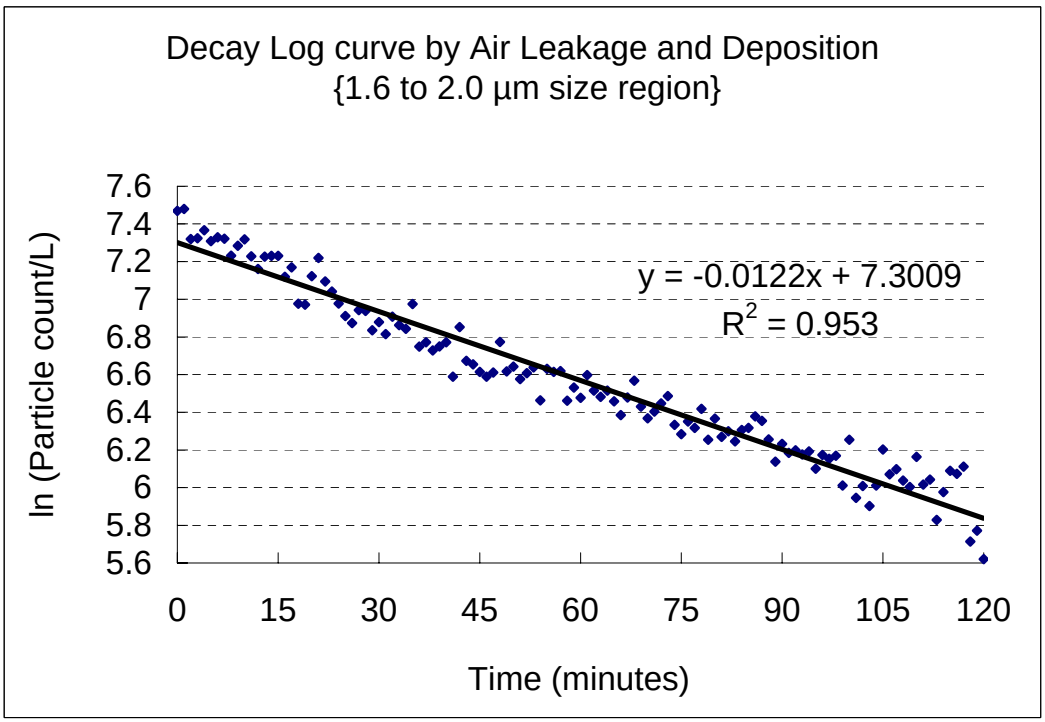

Figure A2.14 Natural log curve for trial 1, 1.6 μ m to 2.0 μ m particle size range

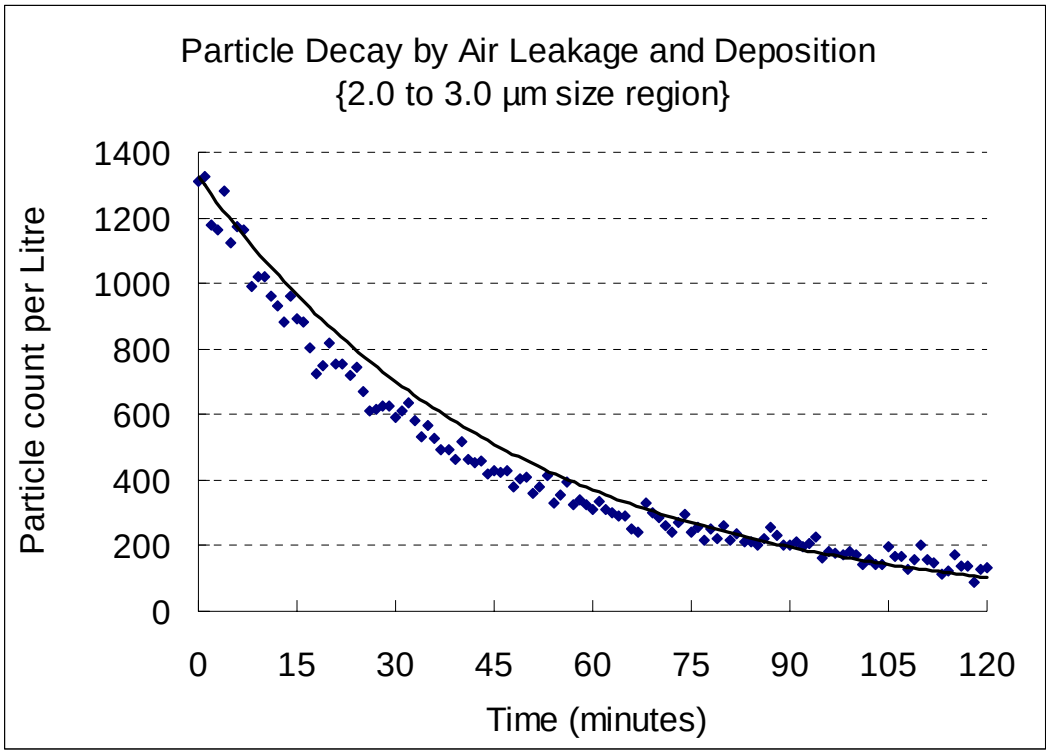

Figure A2.15 Particle decay profile in trial 1, 2.0 μ m to 3.0 μ m particle size range

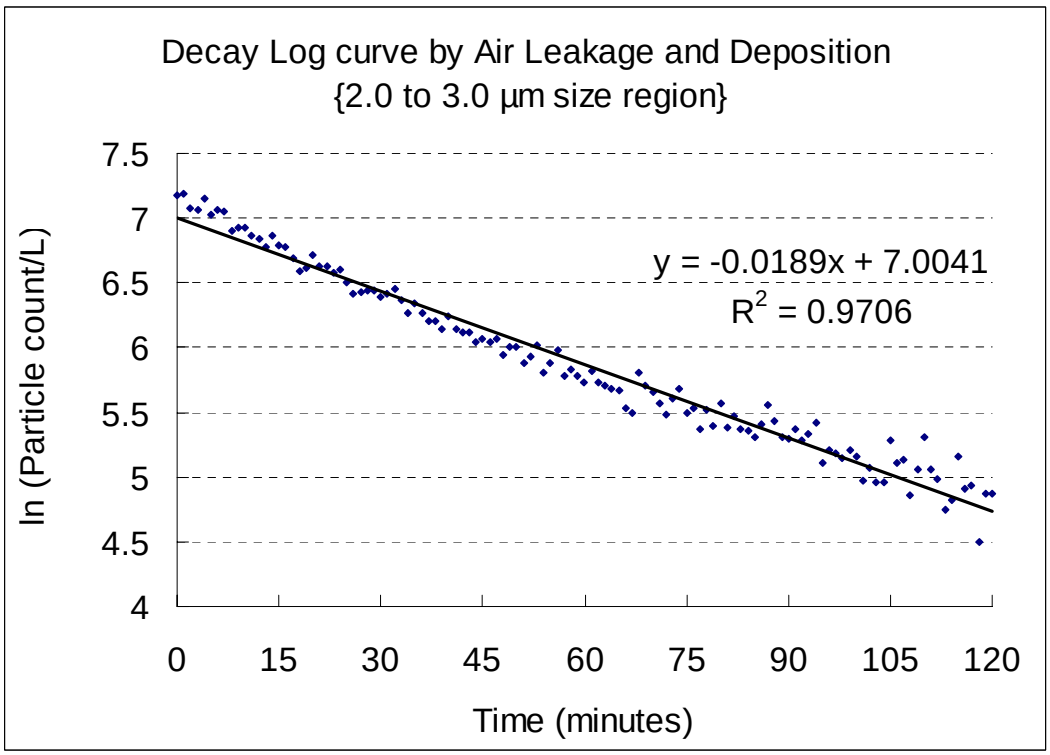

Figure A2.16 Natural log curve for trial 1, 2.0 μ m to 3.0 μ m particle size range

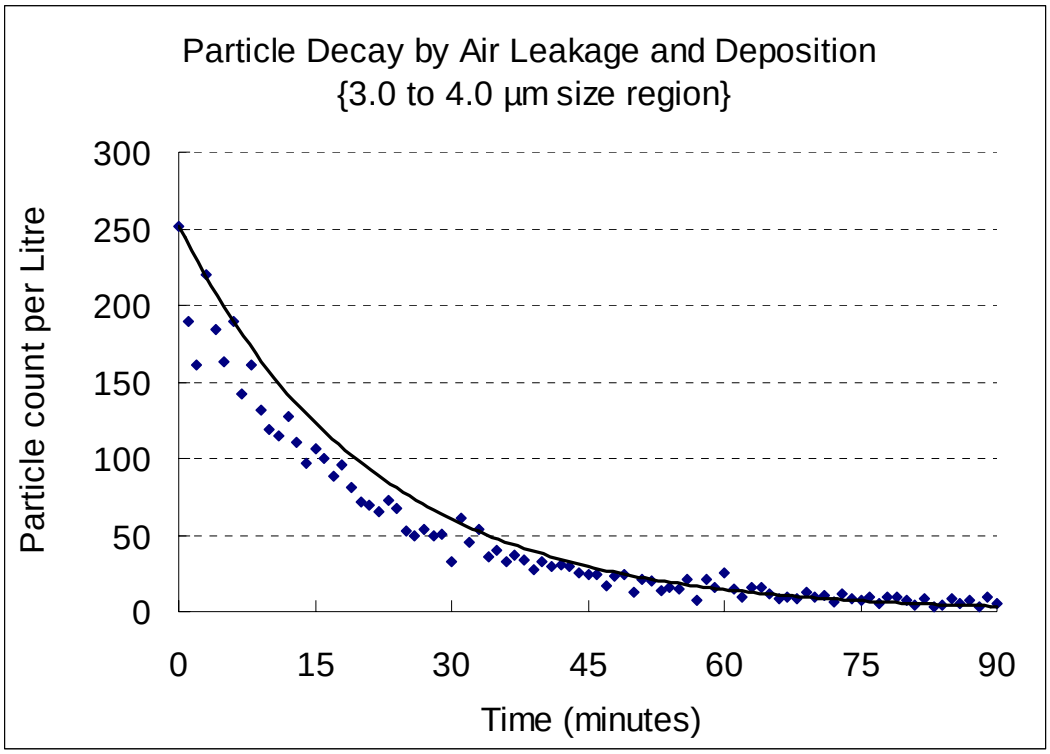

Figure A2.17 Particle decay profile in trial 1, 3.0 μ m to 4.0 μ m particle size range

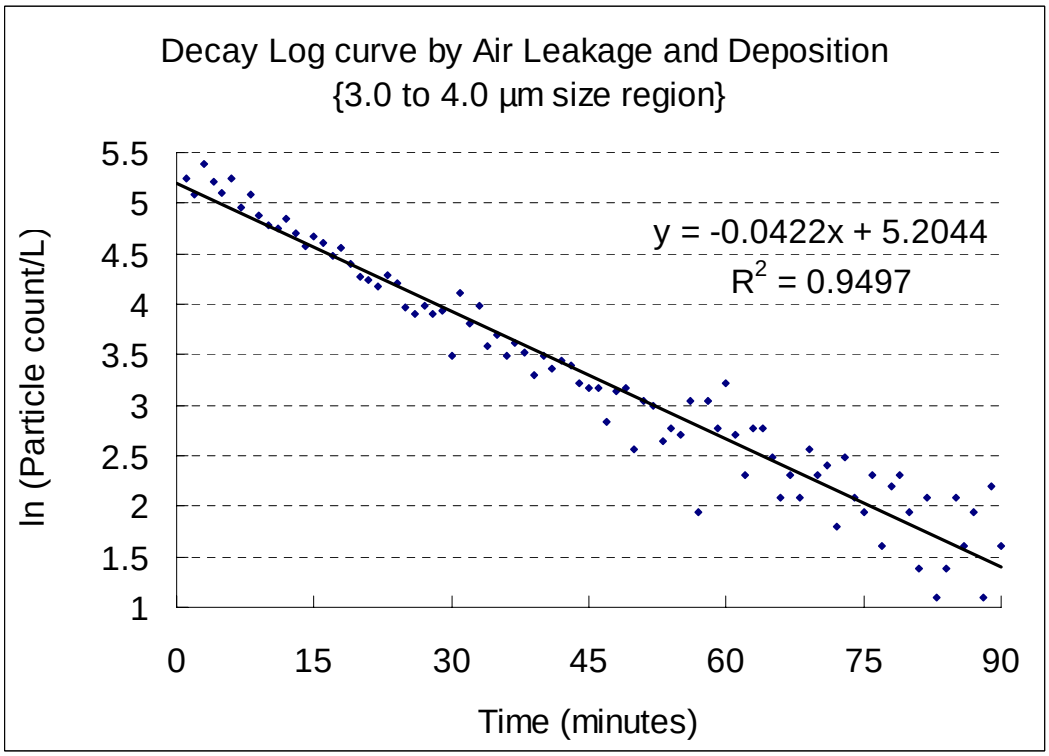

Figure A2.18 Natural log curve for trial 1, 3.0 μ m to 4.0 μ m particle size range

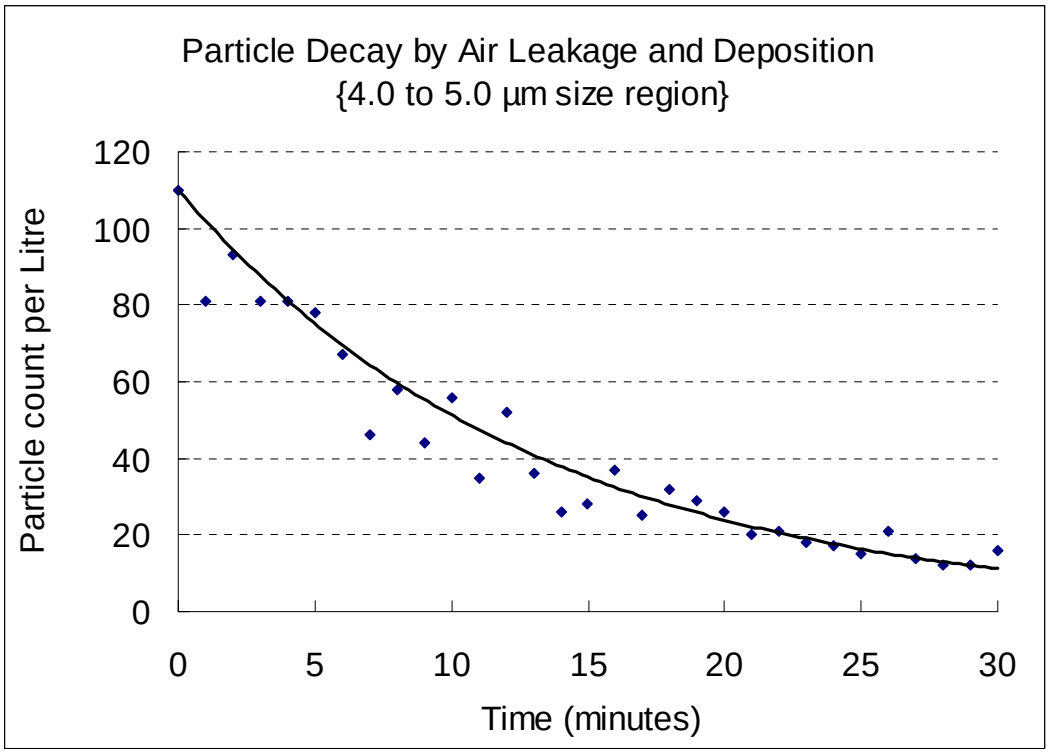

Figure A2.19 Particle decay profile in trial 1, 4.0 μ m to 5.0 μ m particle size range

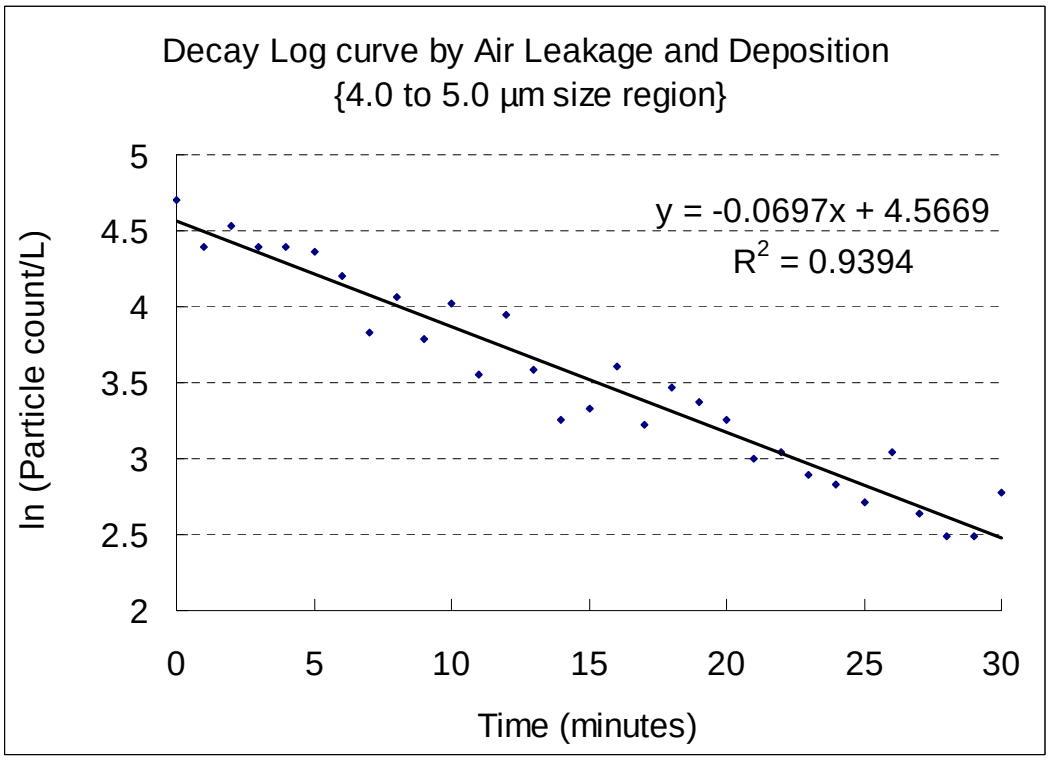

Figure A2.20 Natural log curve for trial 1, 4.0 μ m to 5.0 μ m particle size range

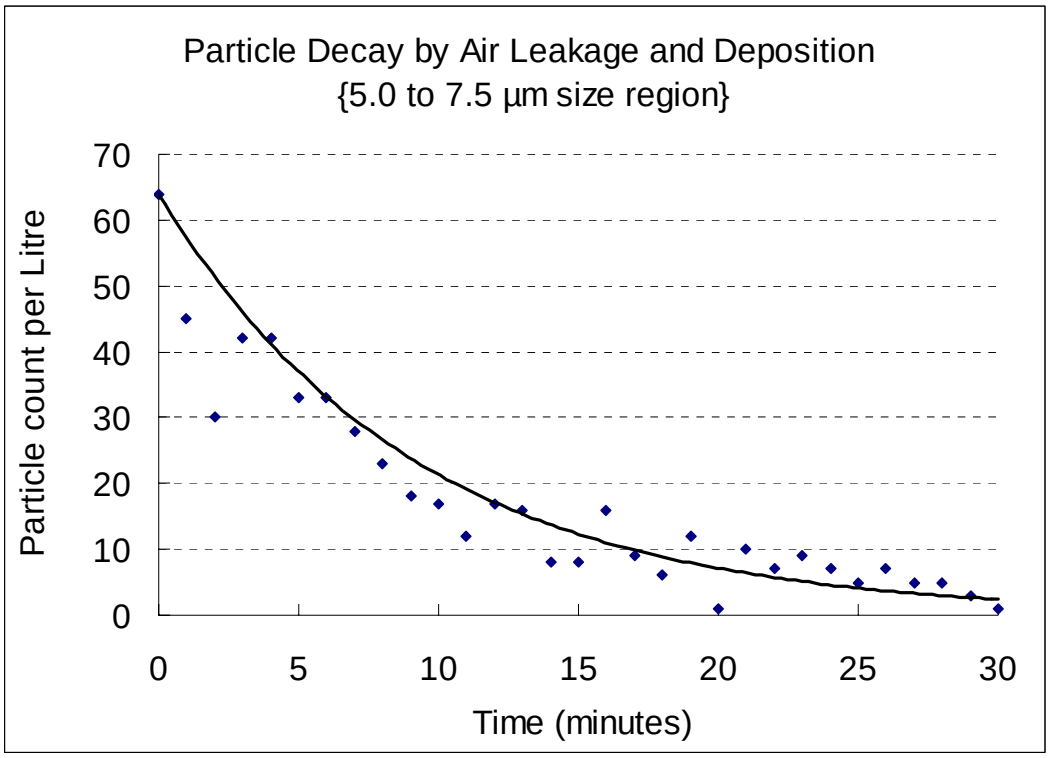

Figure A2.21 Particle decay profile in trial 1, 5.0 μ m to 7.5 μ m particle size range

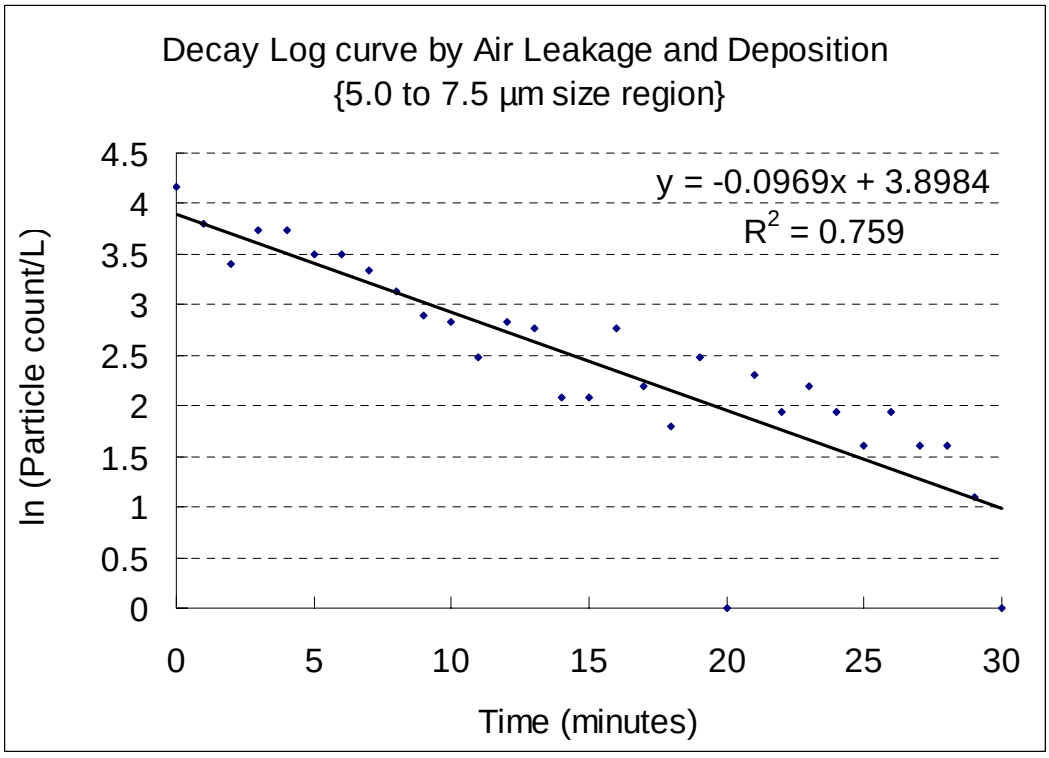

Figure A2.22 Natural log curve for trial 1, 5.0 μ m to 7.5 μ m particle size range

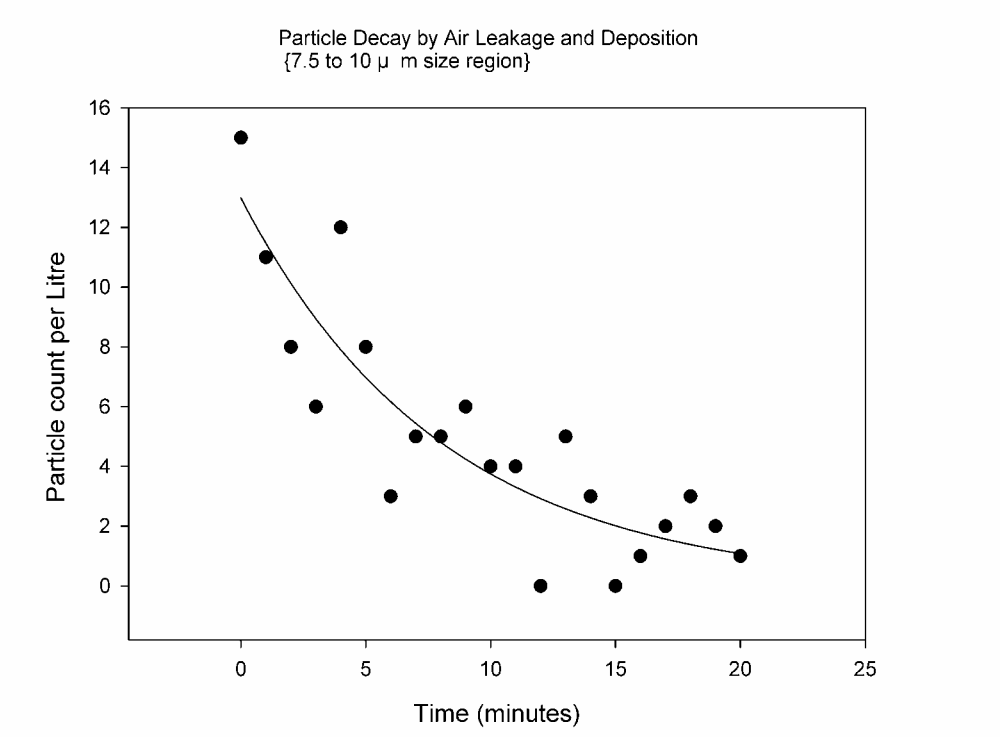

Figure A2.23 Particle decay profile in trial 1, 7.5 μ m to 10 μ m particle size range

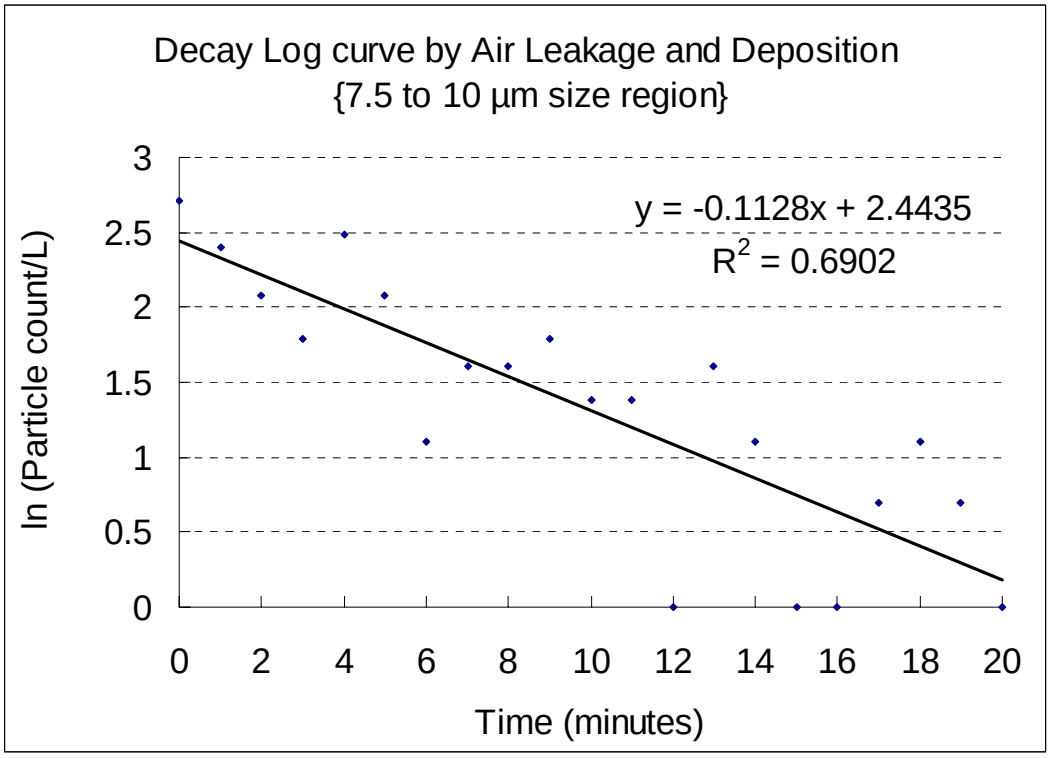

Figure A2.24 Natural log curve for trial 1, 7.5 μ m to 10 μ m particle size range

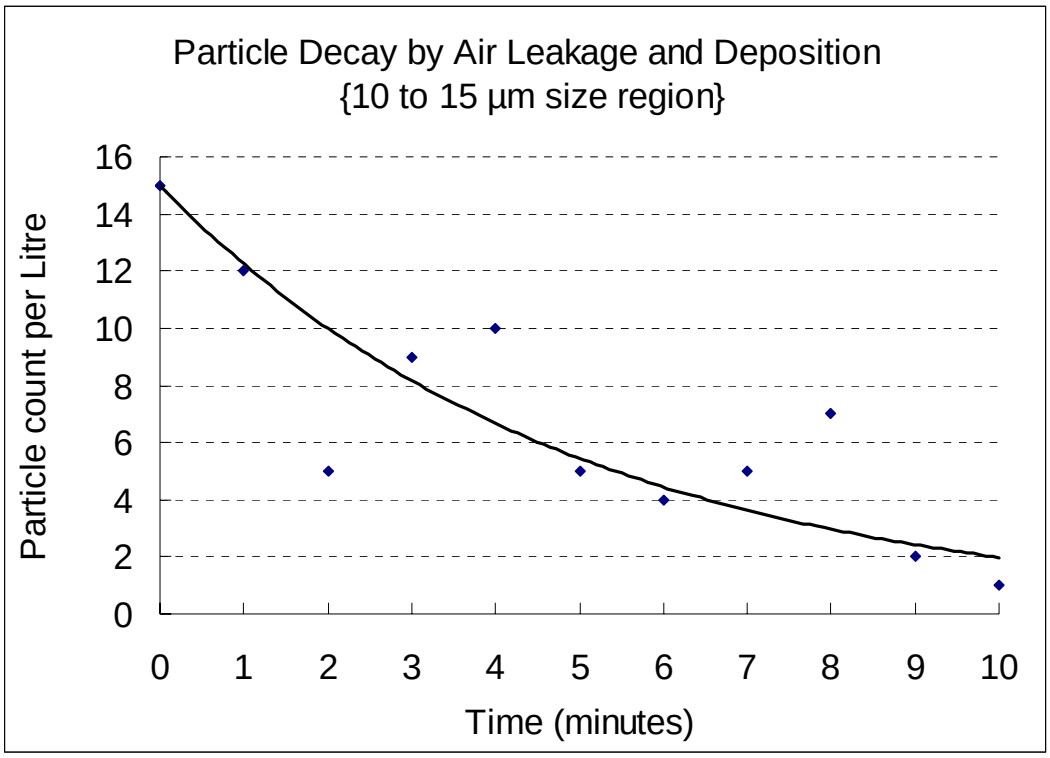

Figure A2.25 Particle decay profile in trial 1, 10 μ m to 15 μ m particle size range

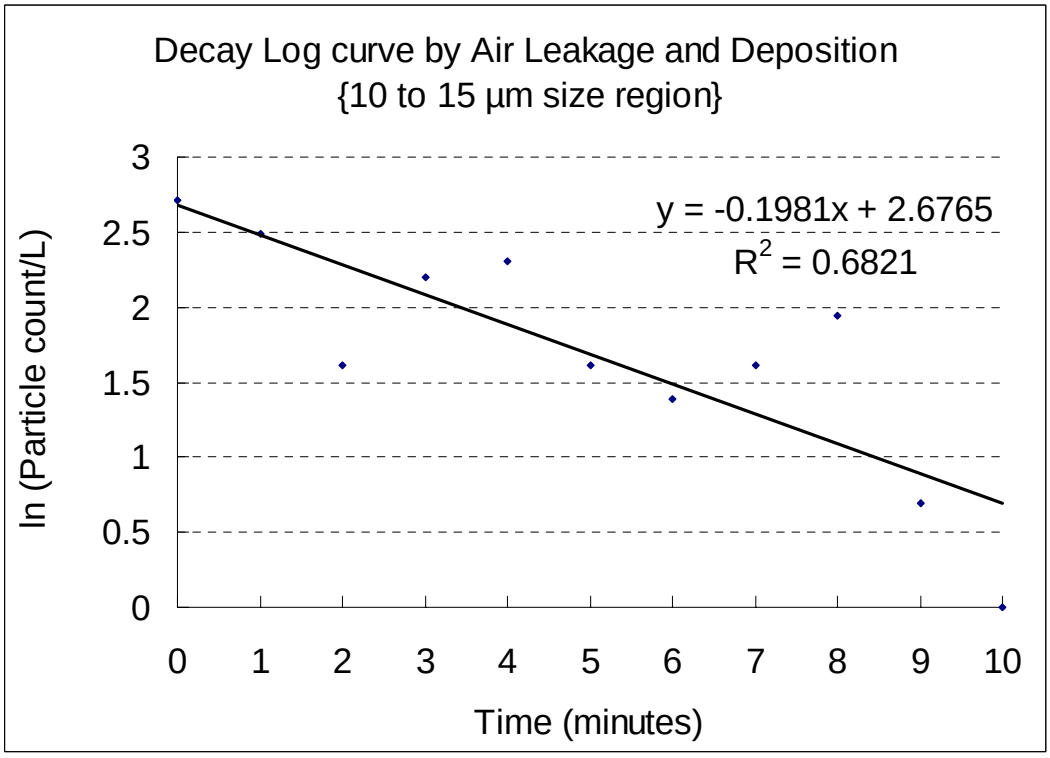

Figure A2.26 Natural log curve for trial 1, 10 μ m to 15 μ m particle size range

A2.2 Particle decay profile for trial 2

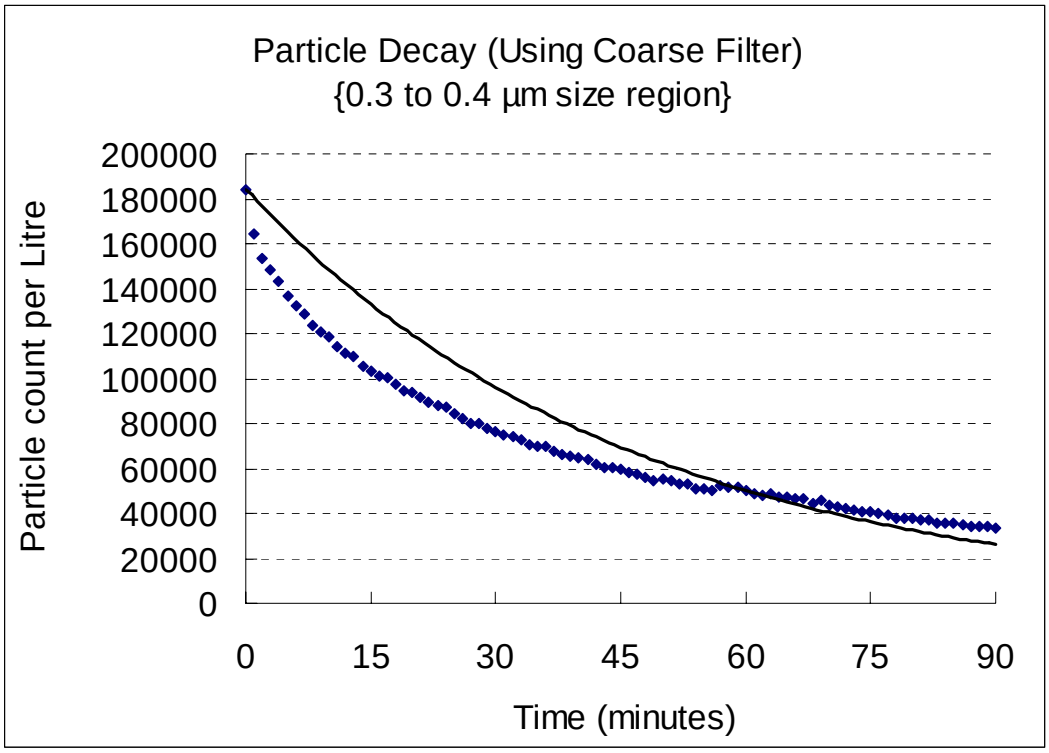

Figure A2.27 Particle decay profile in trial 2, 0.3 μ m to 0.4 μ m particle size range

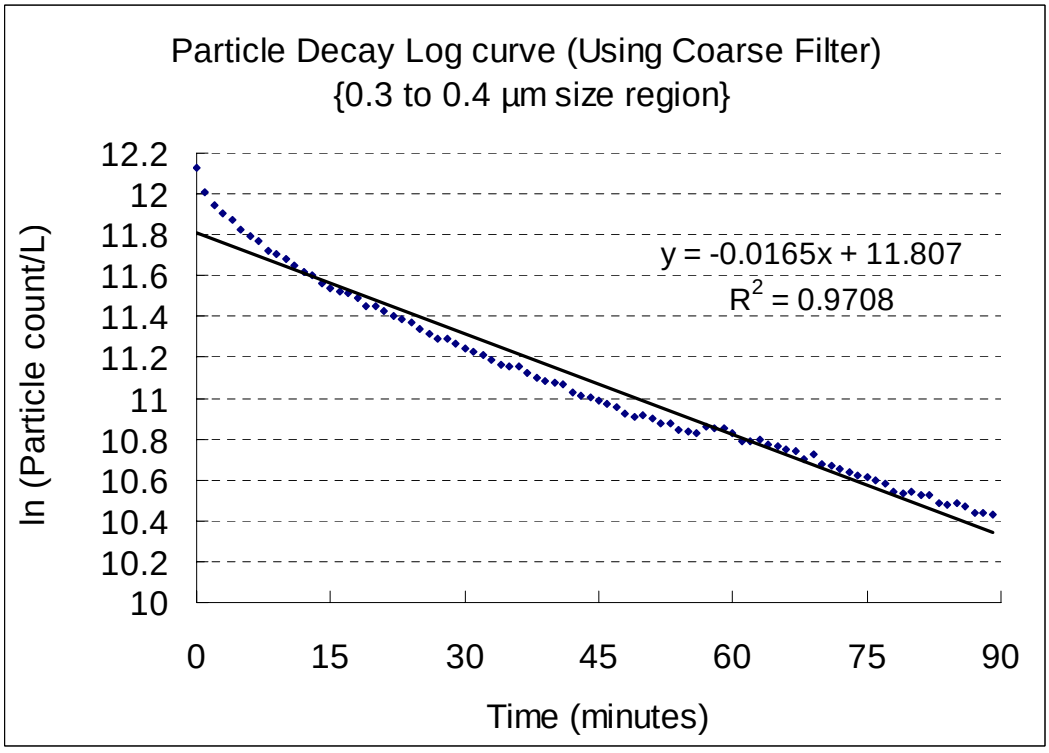

Figure A2.28 Natural log curve for trial 2, 0.3 μ m to 0.4 μ m particle size range

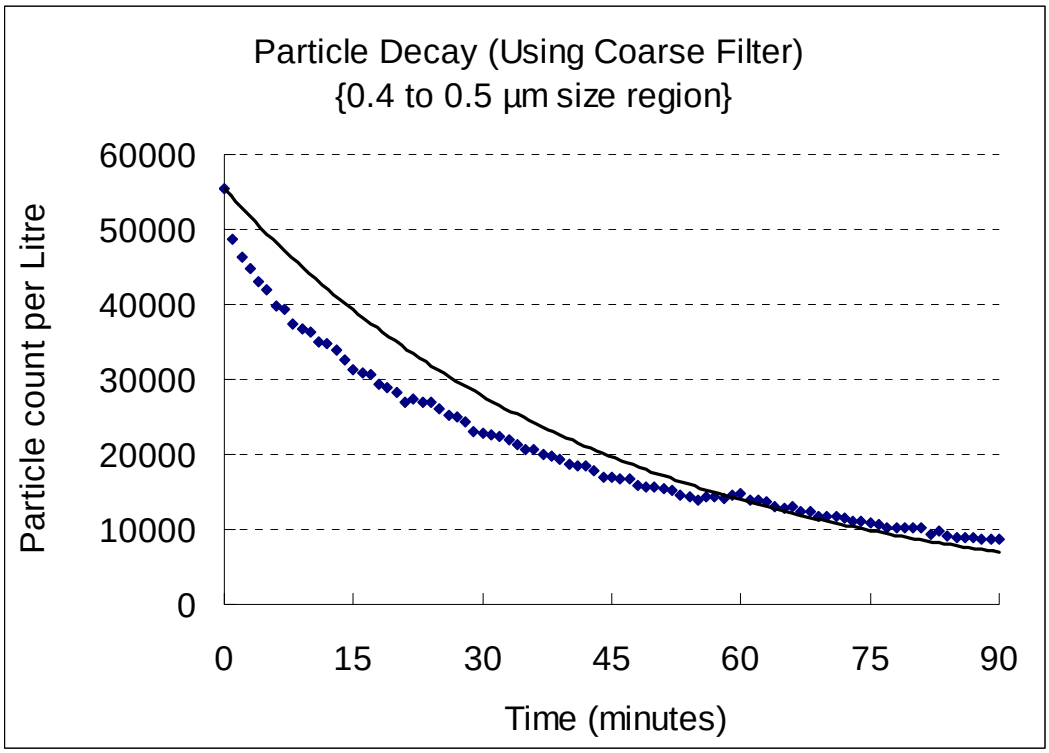

Figure A2.29 Particle decay profile in trial 2, 0.4 μ m to 0.5 μ m particle size range

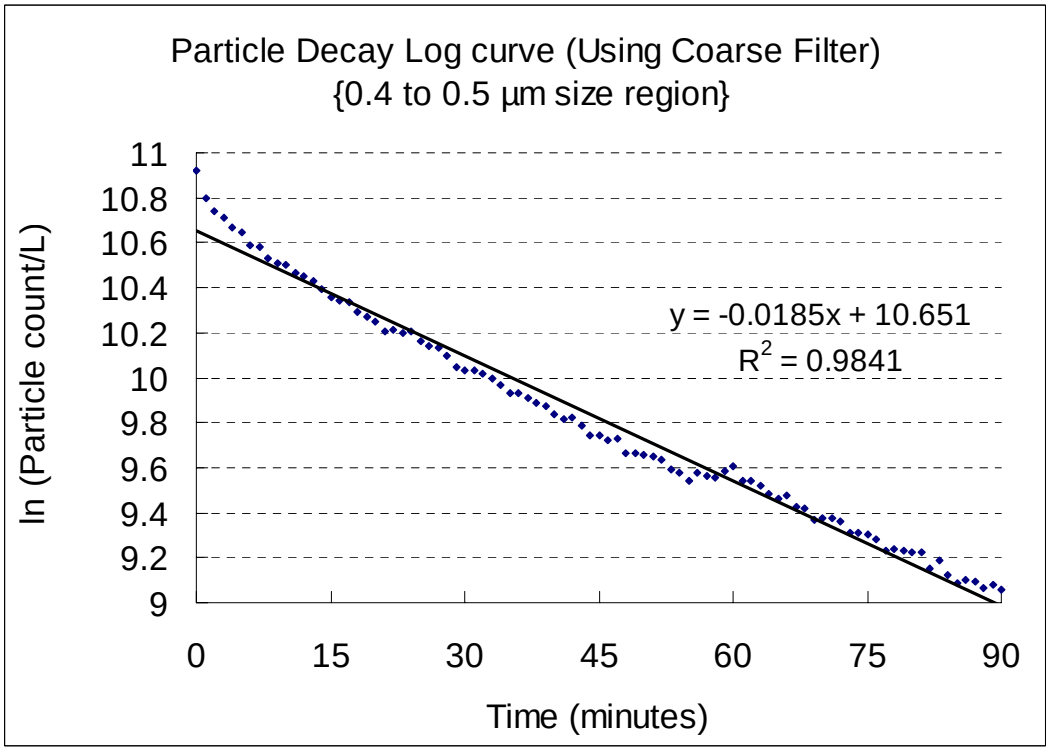

Figure A2.30 Natural log curve for trial 2, 0.4 μ m to 0.5 μ m particle size range

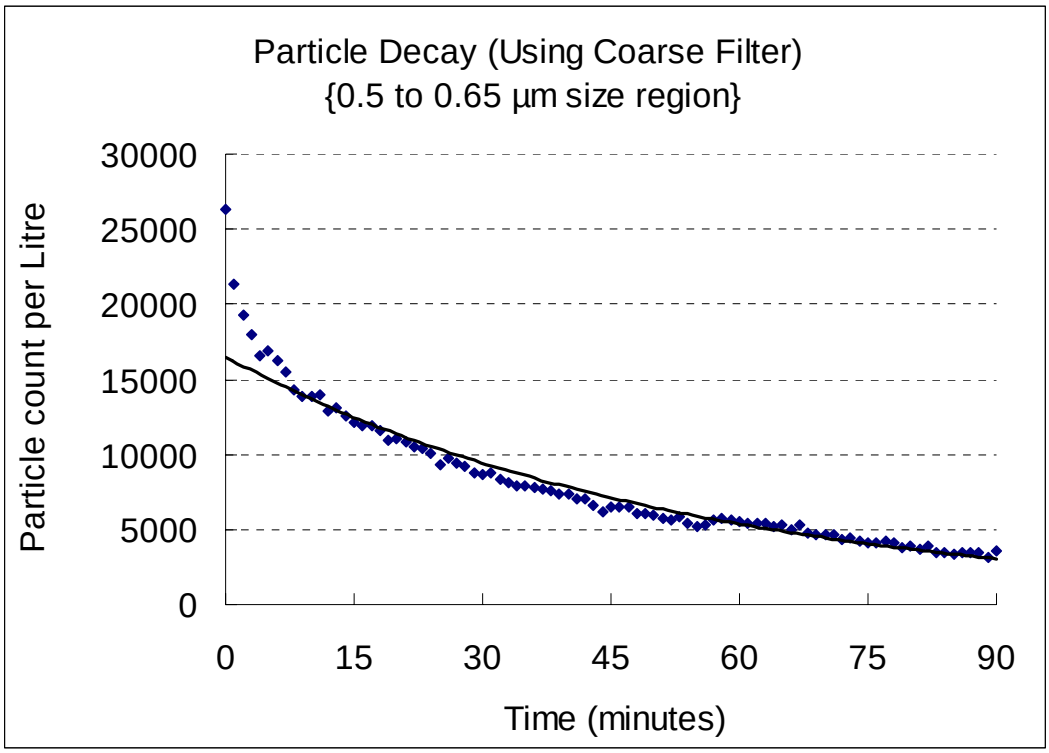

Figure A2.31 Particle decay profile in trial 2, 0.5 μ m to 0.65 μ m particle size range

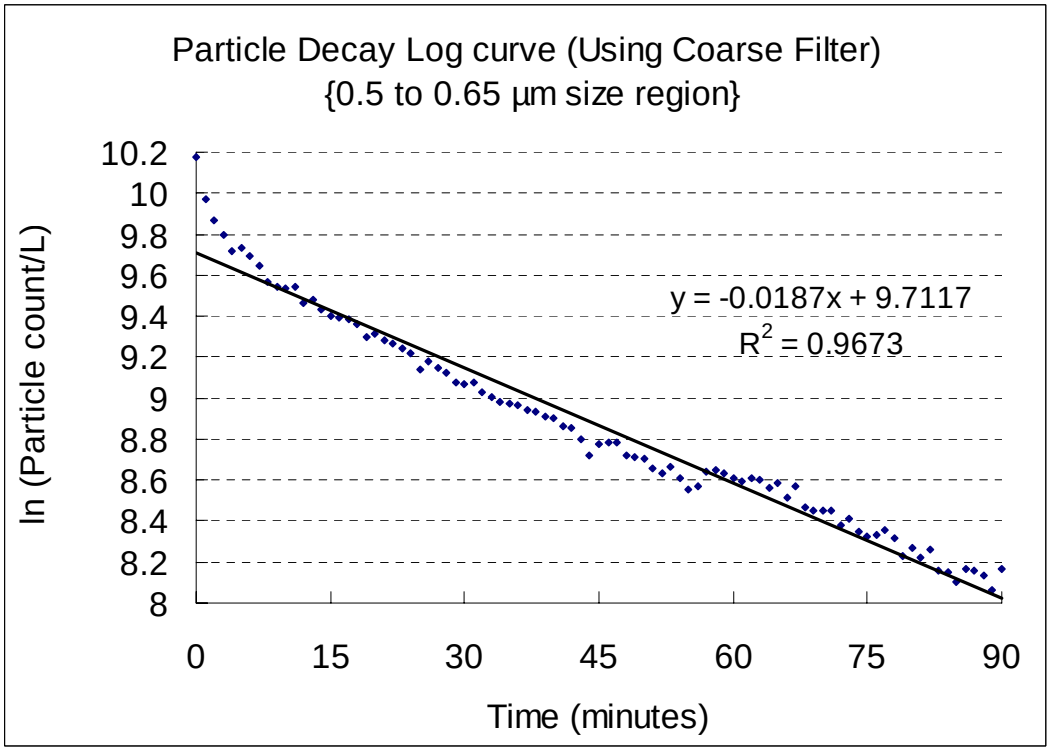

Figure A2.32 Natural log curve for trial 2, 0.5 μ m to 0.65 μ m particle size range

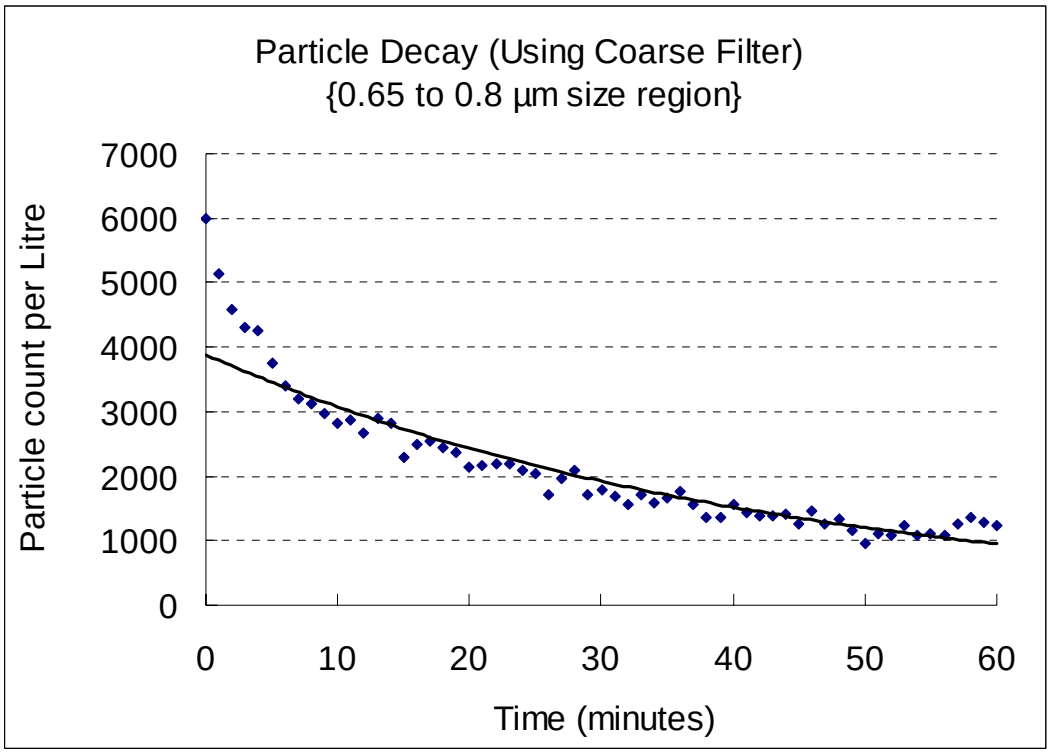

Figure A2.33 Particle decay profile in trial 2, 0.65 μ m to 0.8 μ m particle size range

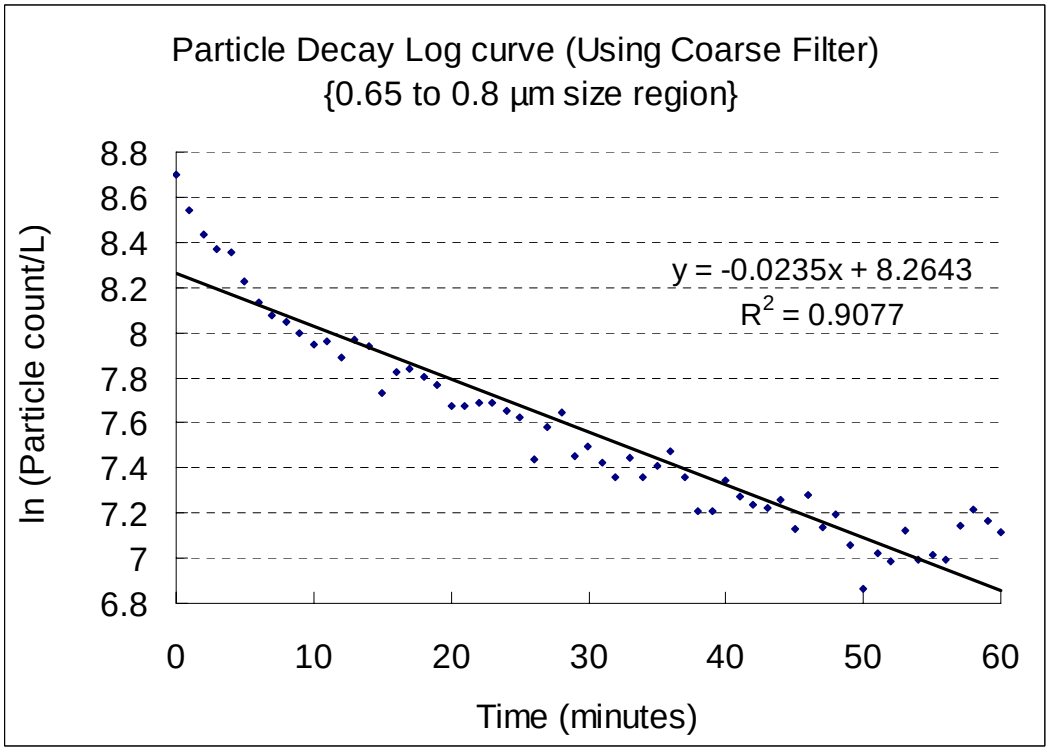

Figure A2.34 Natural log curve for trial 2, 0.65 μ m to 0.8 μ m particle size range

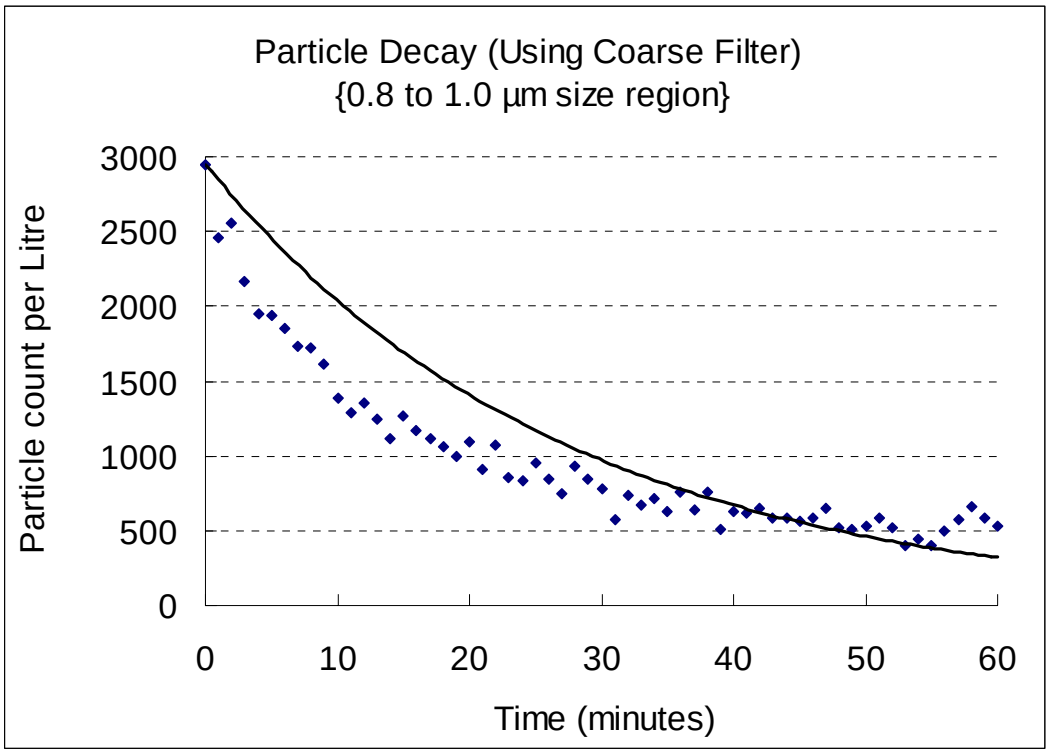

Figure A2.35 Particle decay profile in trial 2, 0.8 μm to 1.0 μm particle size range

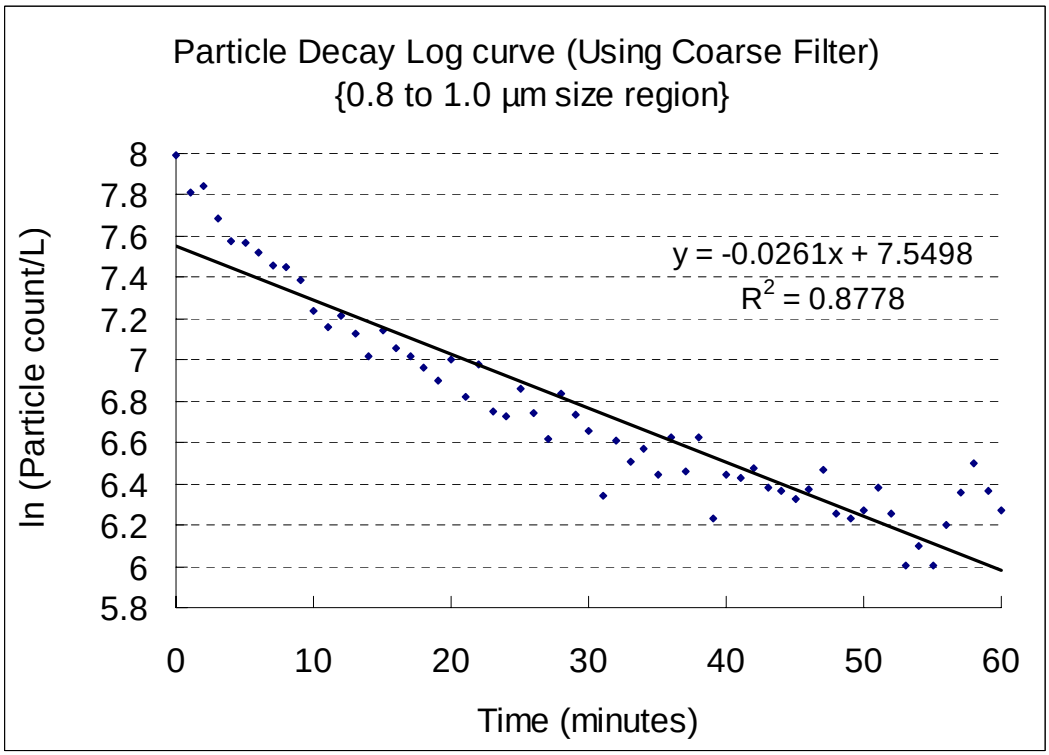

Figure A2.36 Natural log curve for trial 2, 0.8 μm to 1.0 μm particle size range

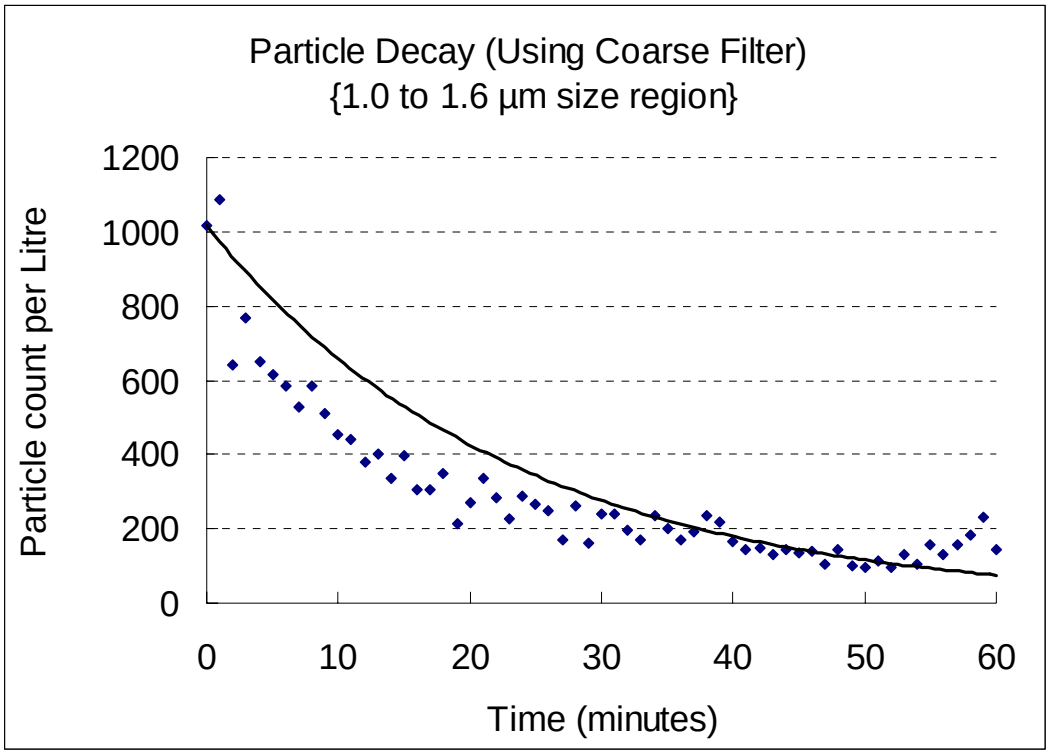

Figure A2.37 Particle decay profile in trial 2, 1.0 μ m to 1.6 μ m particle size range

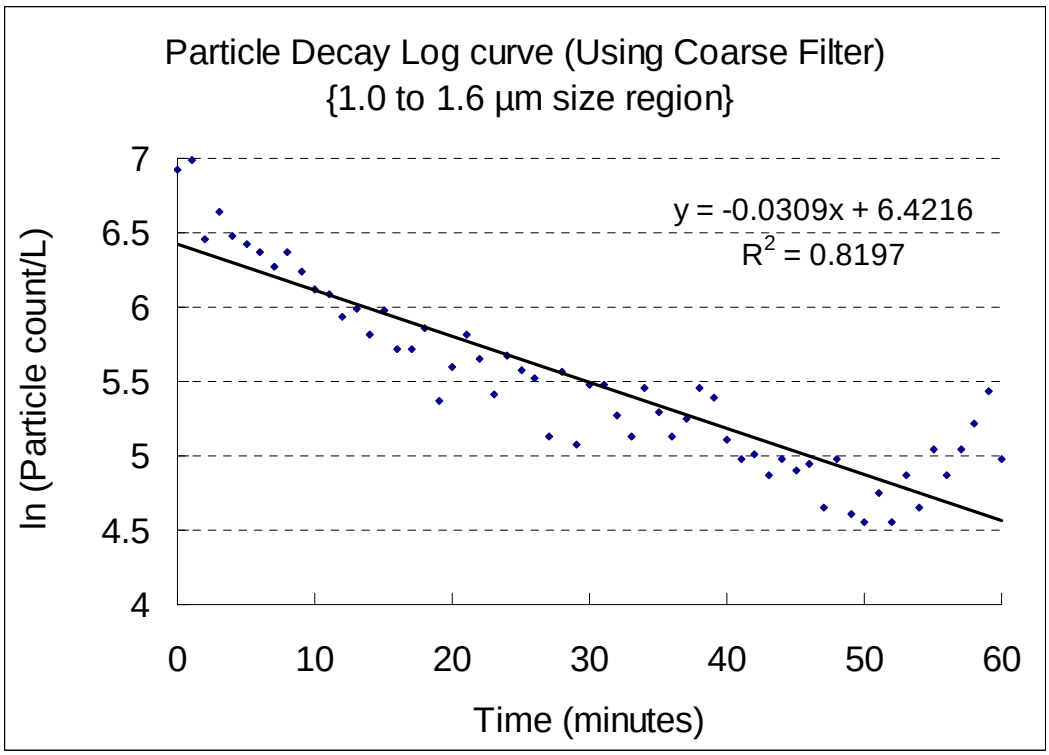

Figure A2.38 Natural log curve for trial 2, 1.0 μ m to 1.6 μ m particle size range

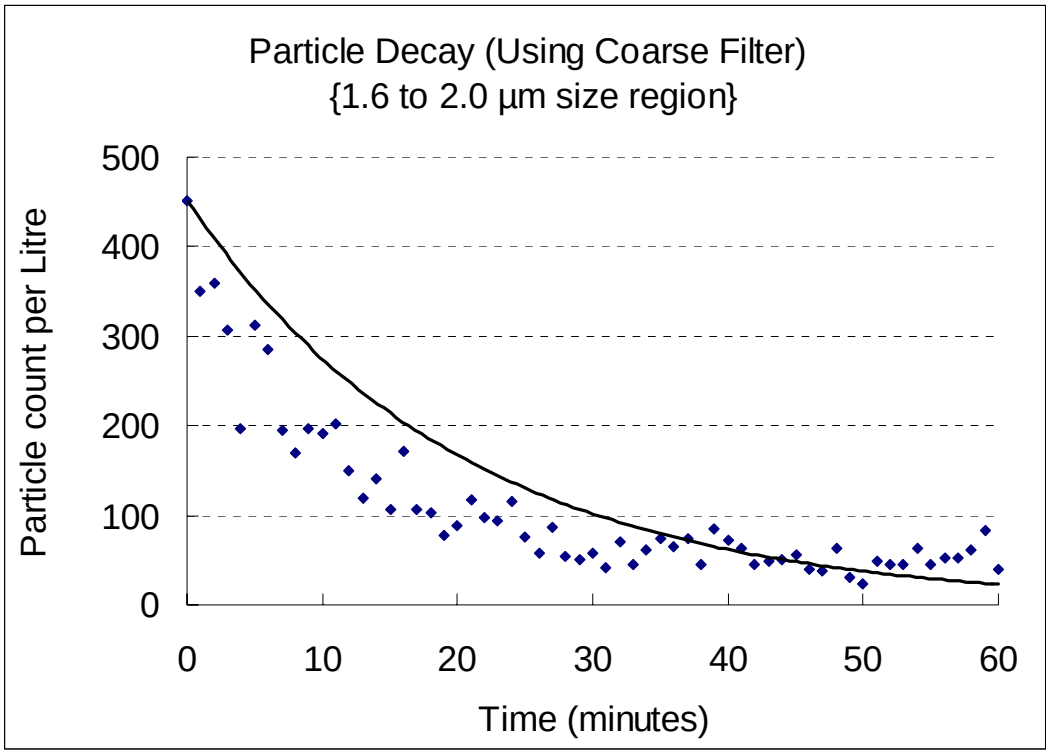

Figure A2.39 Particle decay profile in trial 2, 1.6 μ m to 2.0 μ m particle size range

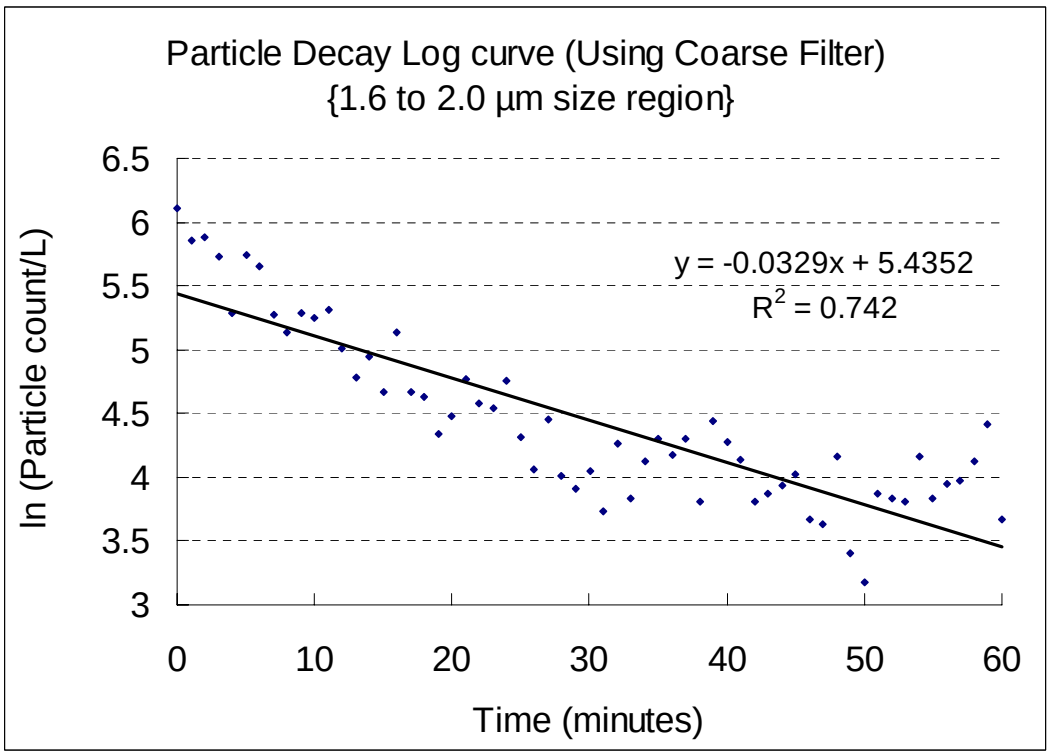

Figure A2.40 Natural log curve for trial 2, 1.6 μ m to 2.0 μ m particle size range

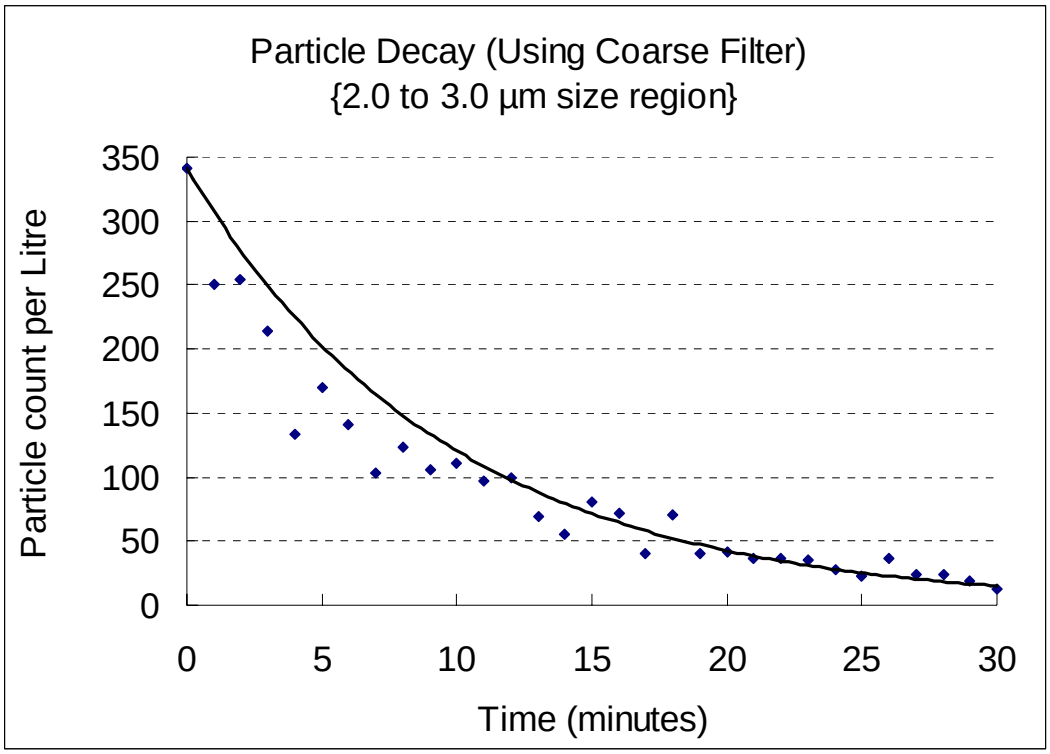

Figure A2.41 Particle decay profile in trial 2, 2.0 μ m to 3.0 μ m particle size range

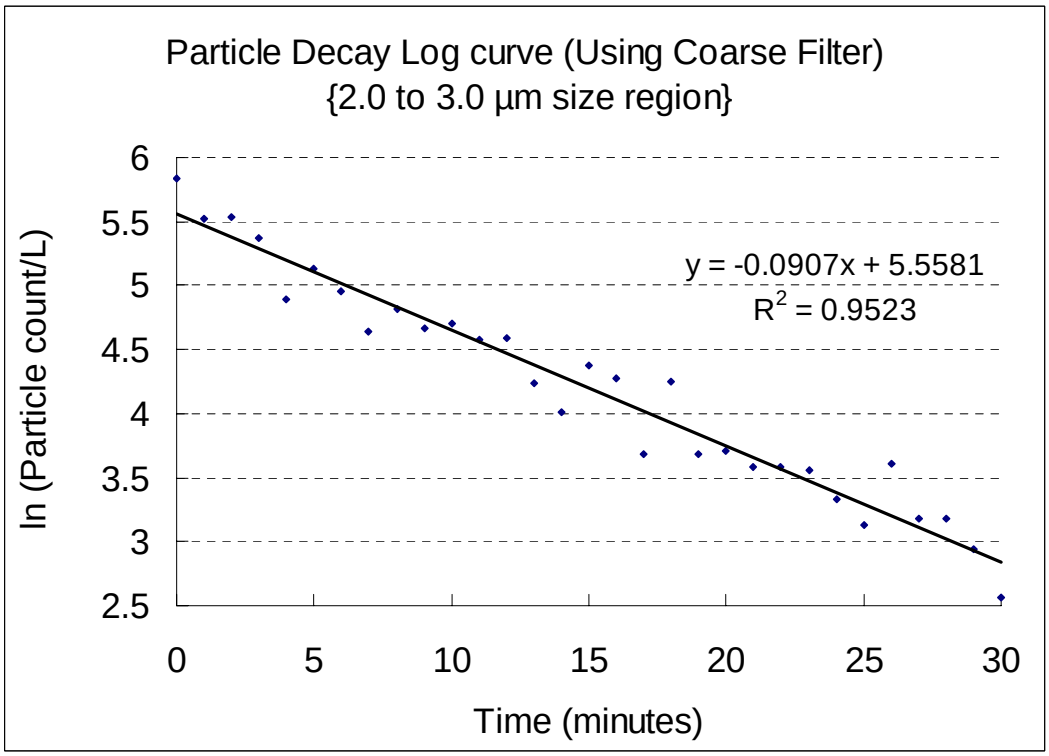

Figure A2.42 Natural log curve for trial 2, 2.0 μ m to 3.0 μ m particle size range

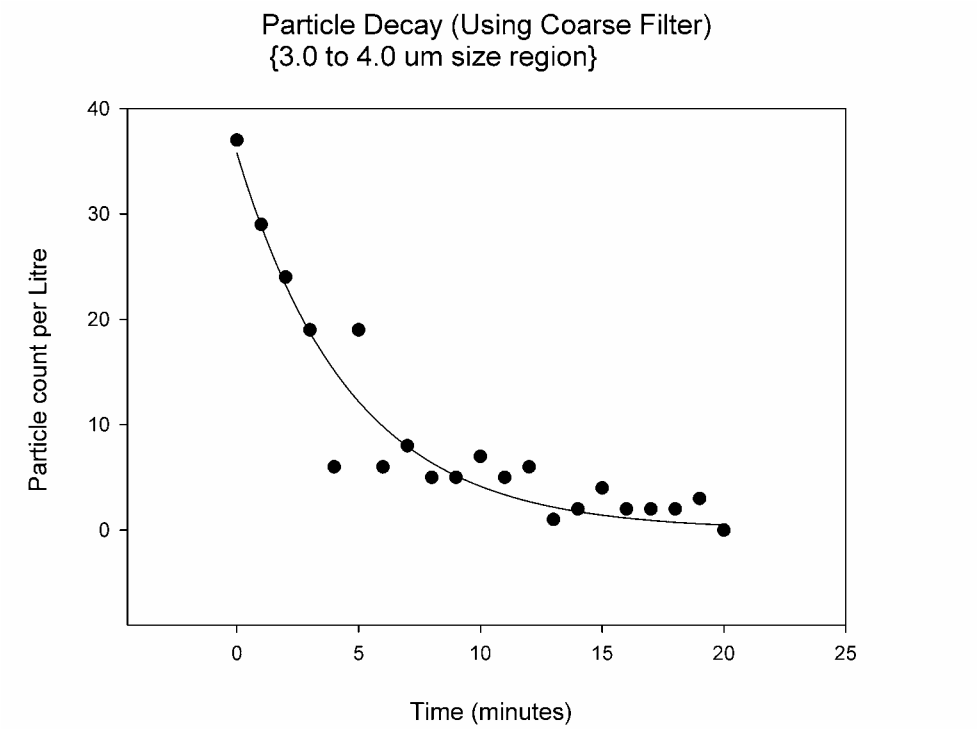

Figure A2.43 Particle decay profile in trial 2, 3.0 μ m to 4.0 μ m particle size range

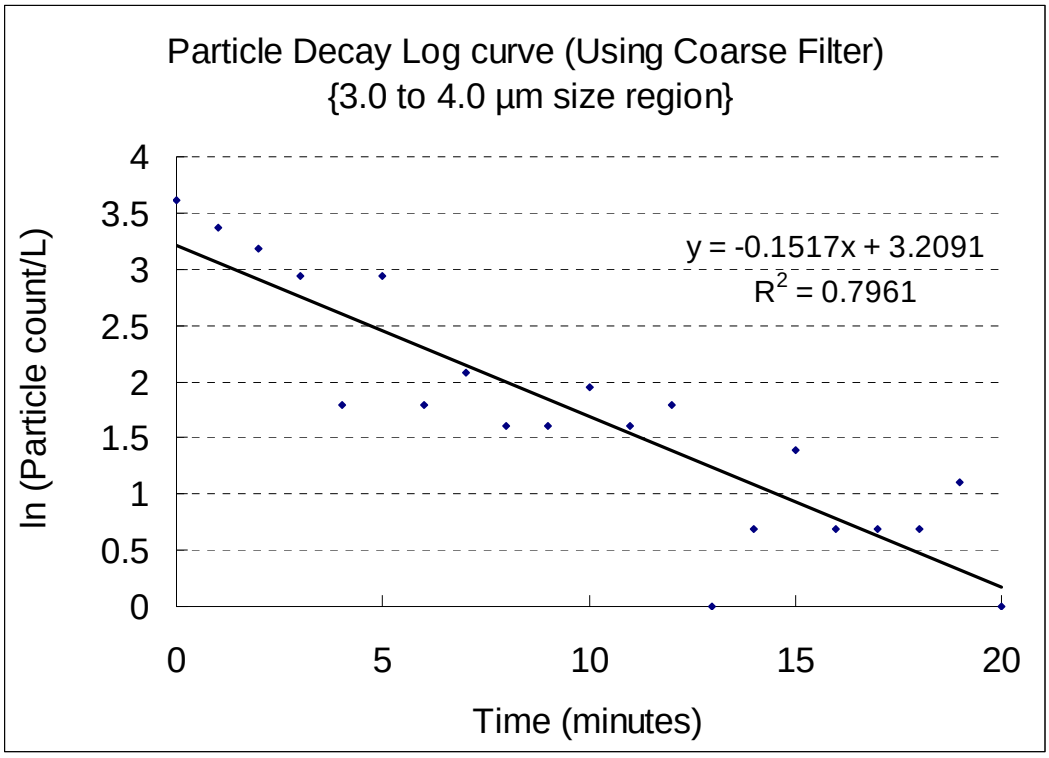

Figure A2.44 Natural log curve for trial 2, 3.0 μ m to 4.0 μ m particle size range

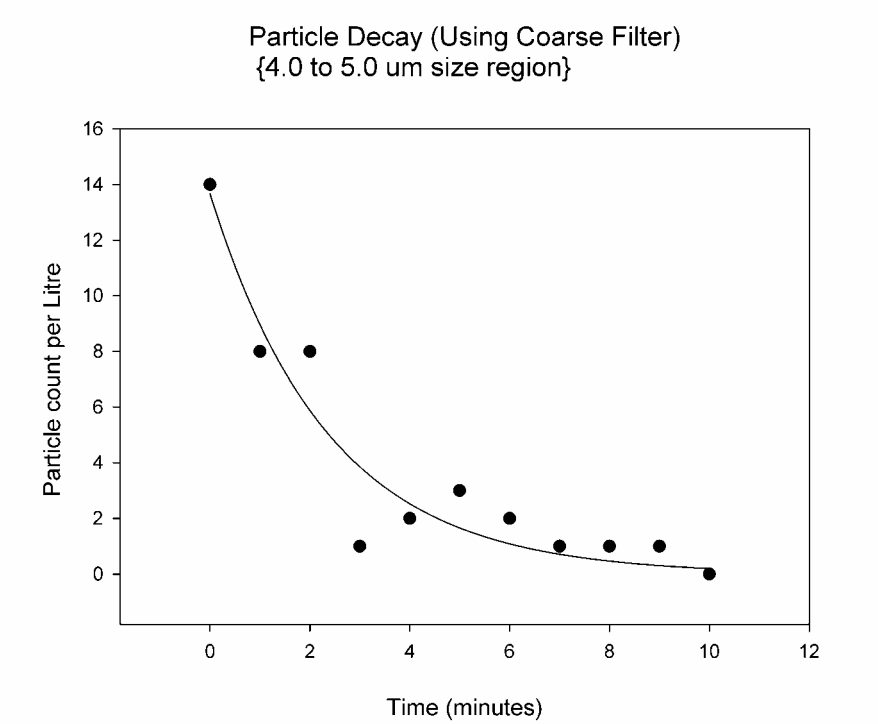

Figure A2.45 Particle decay profile in trial 2, 4.0 μ m to 5.0 μ m particle size range

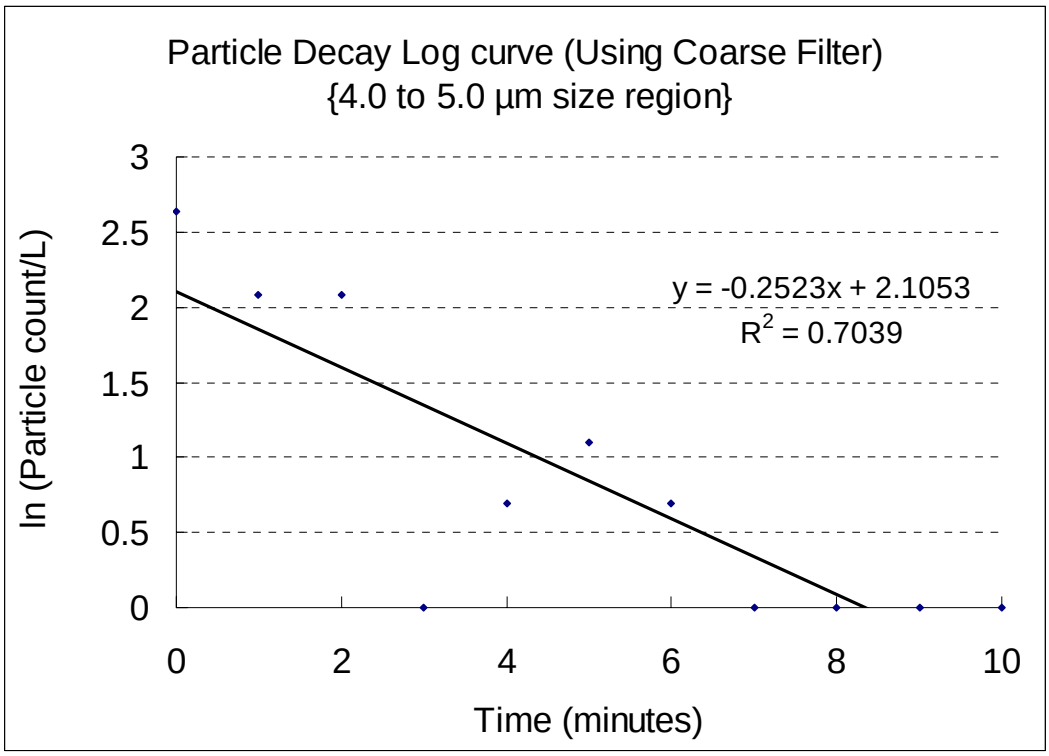

Figure A2.46 Natural log curve for trial 2, 4.0 μ m to 5.0 μ m particle size range

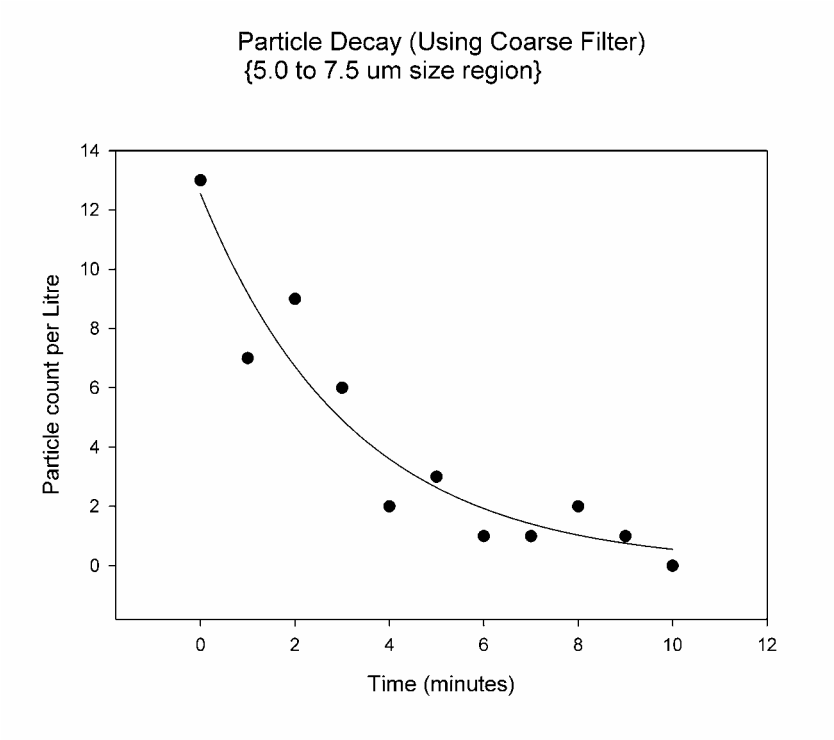

Figure A2.47 Particle decay profile in trial 2, 5.0 μ m to 7.5 μ m particle size range

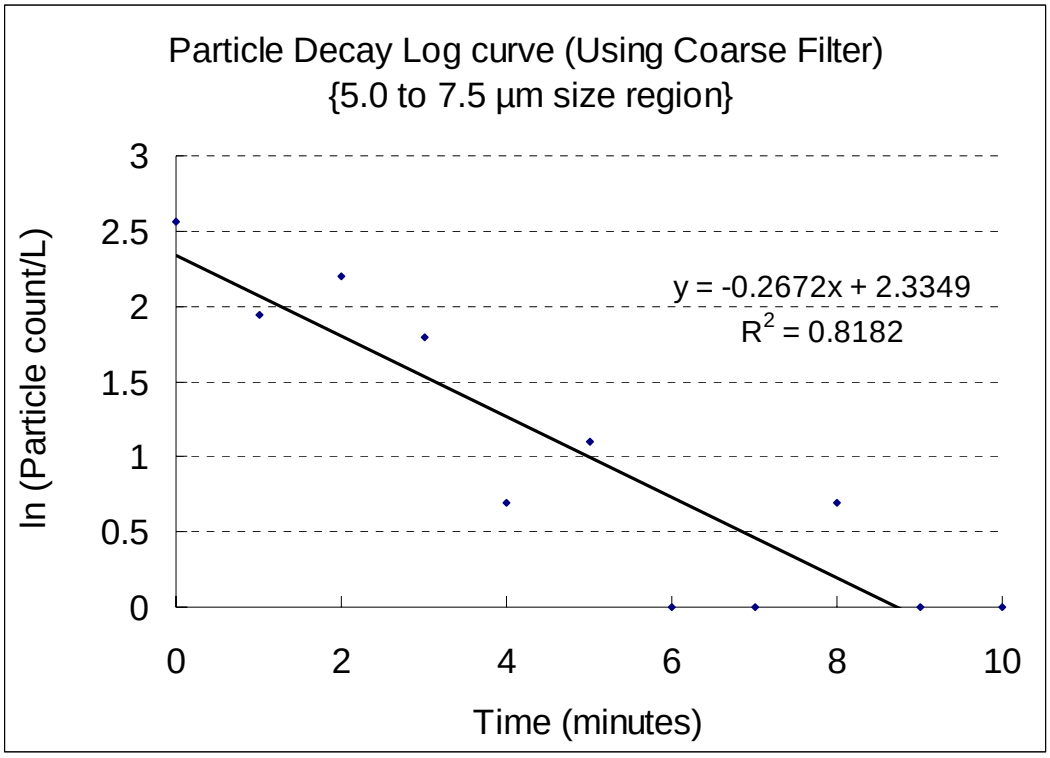

Figure A2.48 Natural log curve for trial 2, 5.0 μ m to 7.5 μ m particle size range

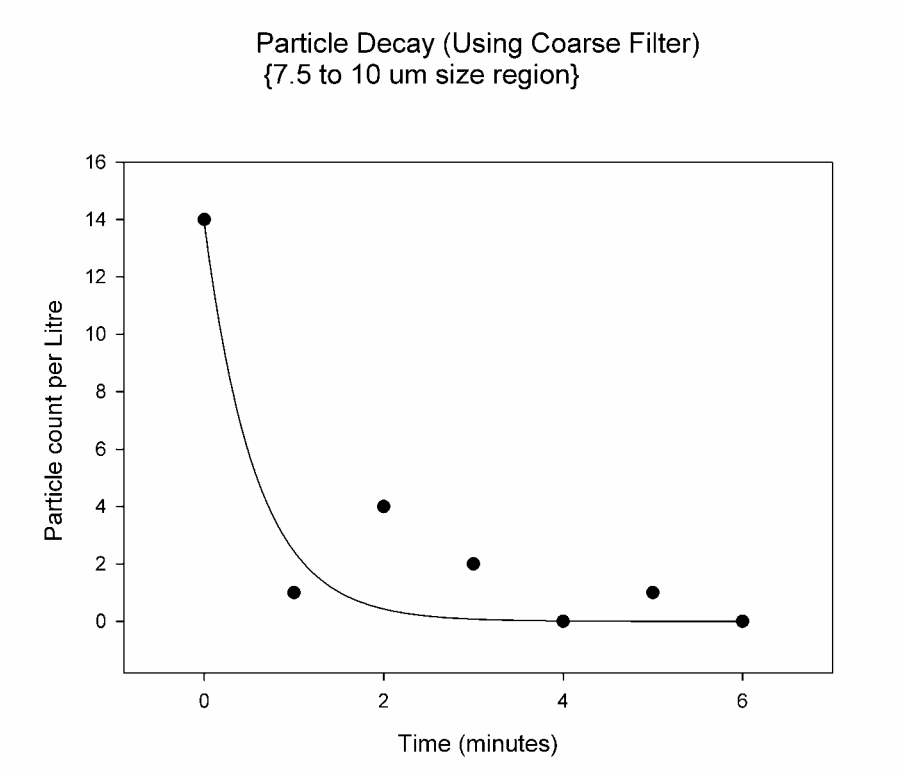

Figure A2.49 Particle decay profile in trial 2, 7.5 μ m to 10 μ m particle size range

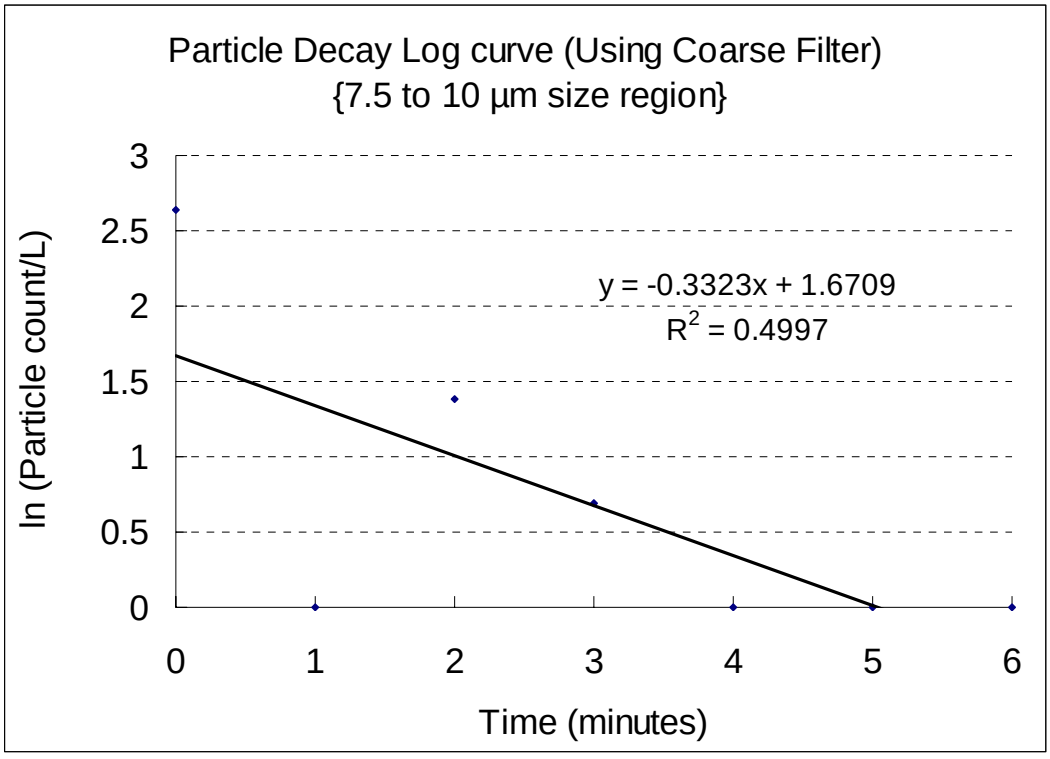

Figure A2.50 Natural log curve for trial 2, 7.5 μ m to 10 μ m particle size range

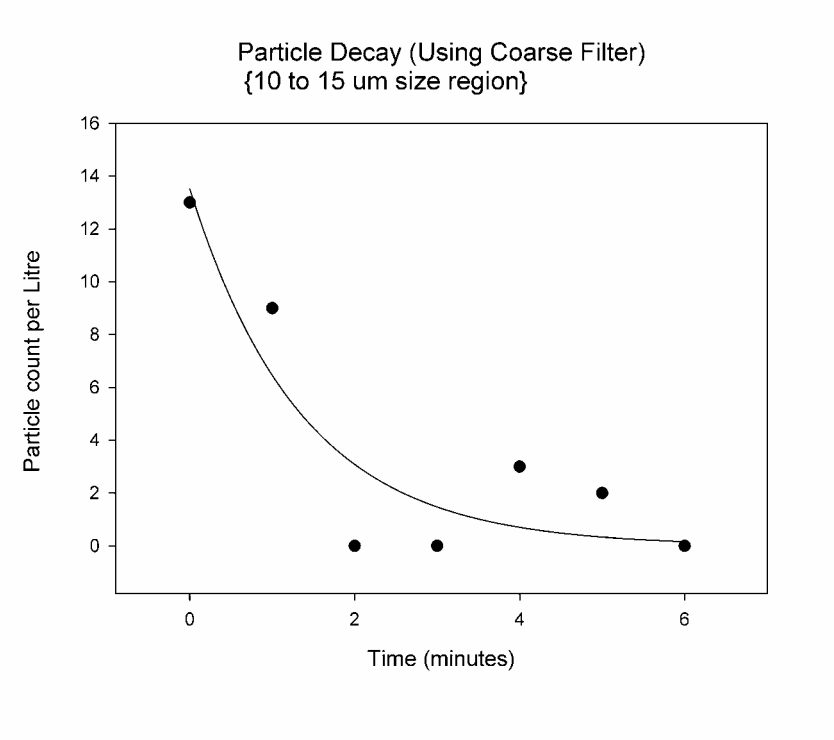

Figure A2.51 Particle decay profile in trial 2, 10 μ m to 15 μ m particle size range

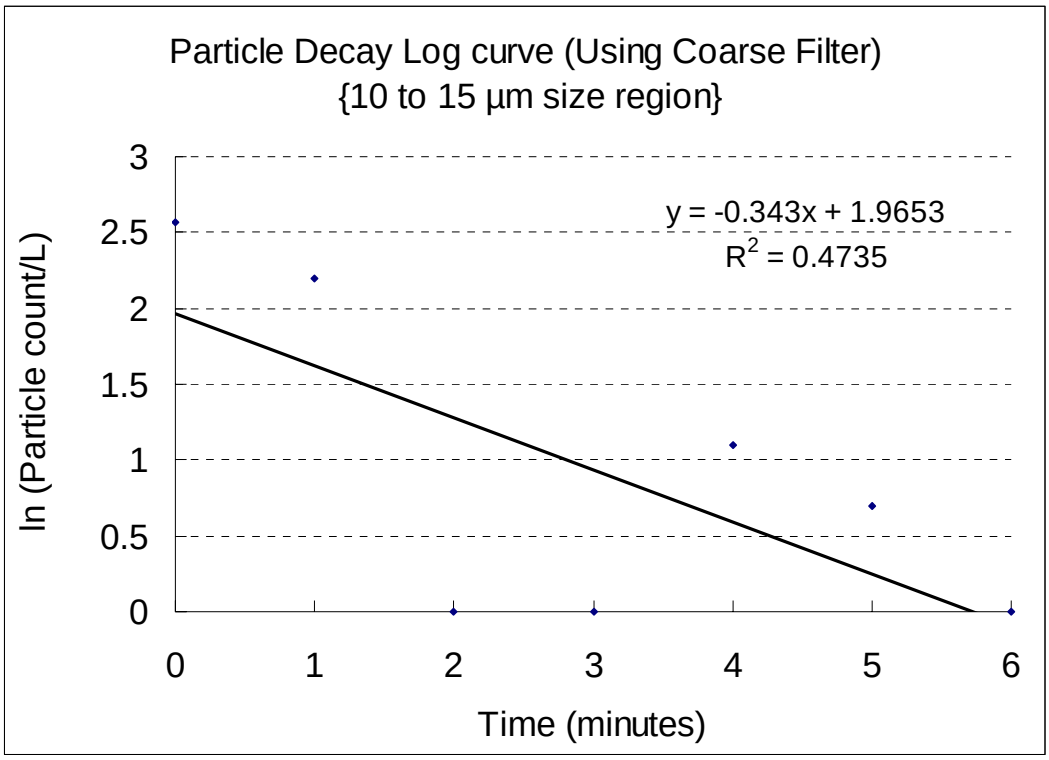

Figure A2.52 Natural log curve for trial 2, 10 μ m to 15 μ m particle size range

A2.3 Particle decay profile for trial 3

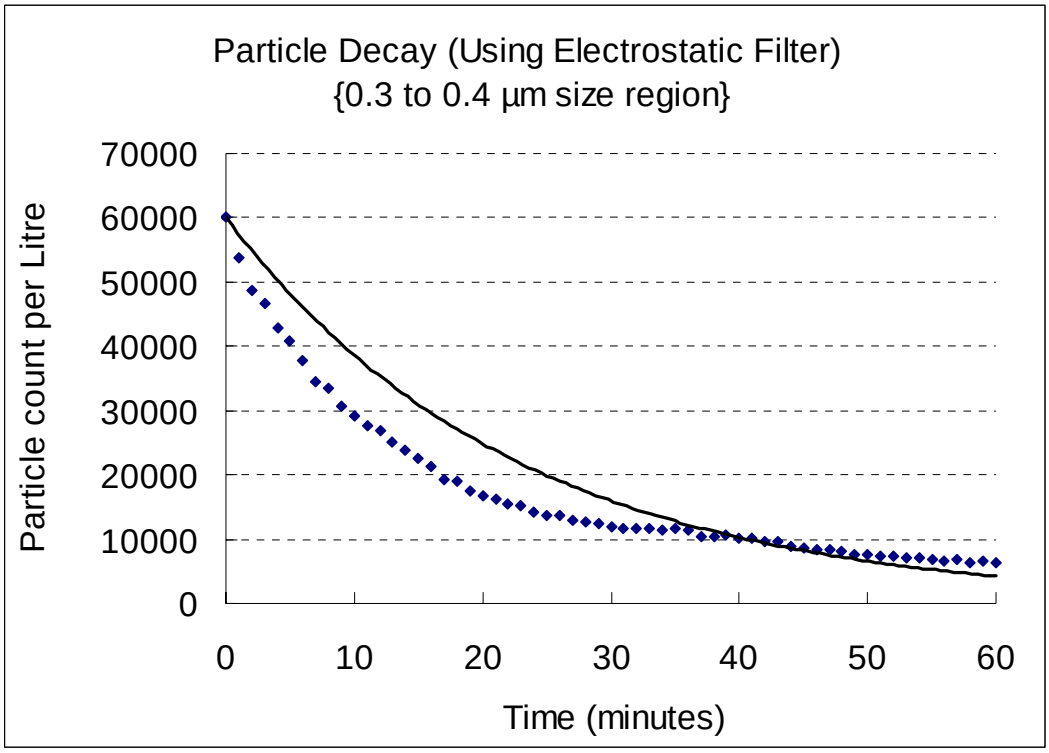

Figure A2.53 Particle decay profile in trial 3, 0.3 μ m to 0.4 μ m particle size range

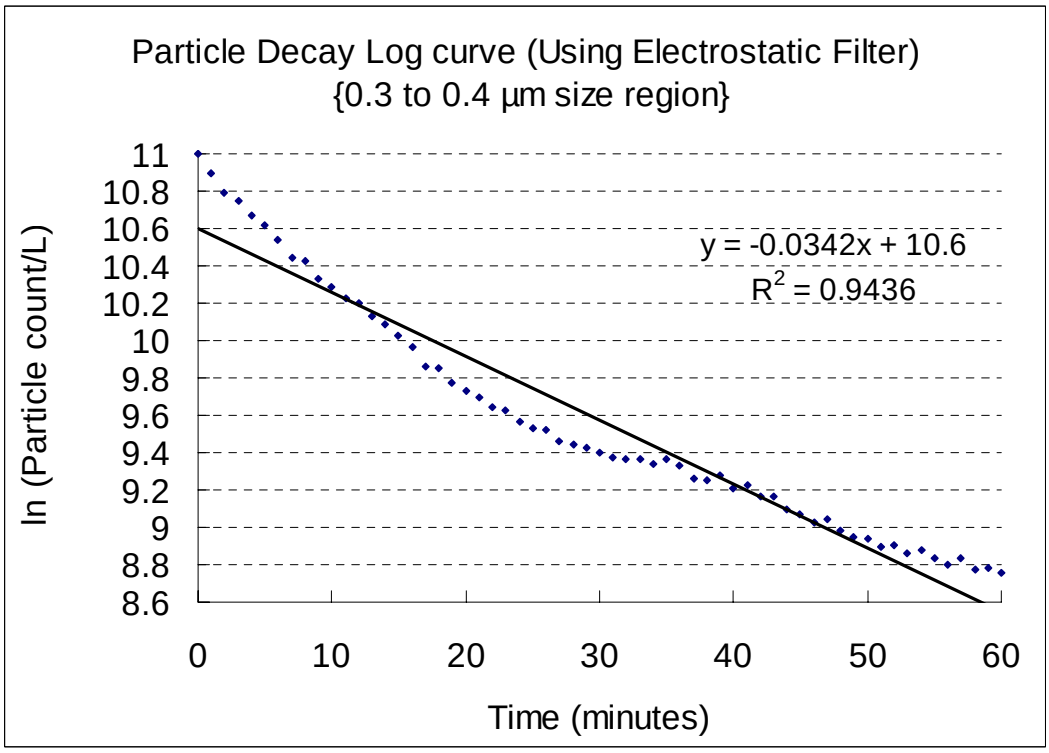

Figure A2.54 Natural log curve for trial 3, 0.3 μ m to 0.4 μ m particle size range

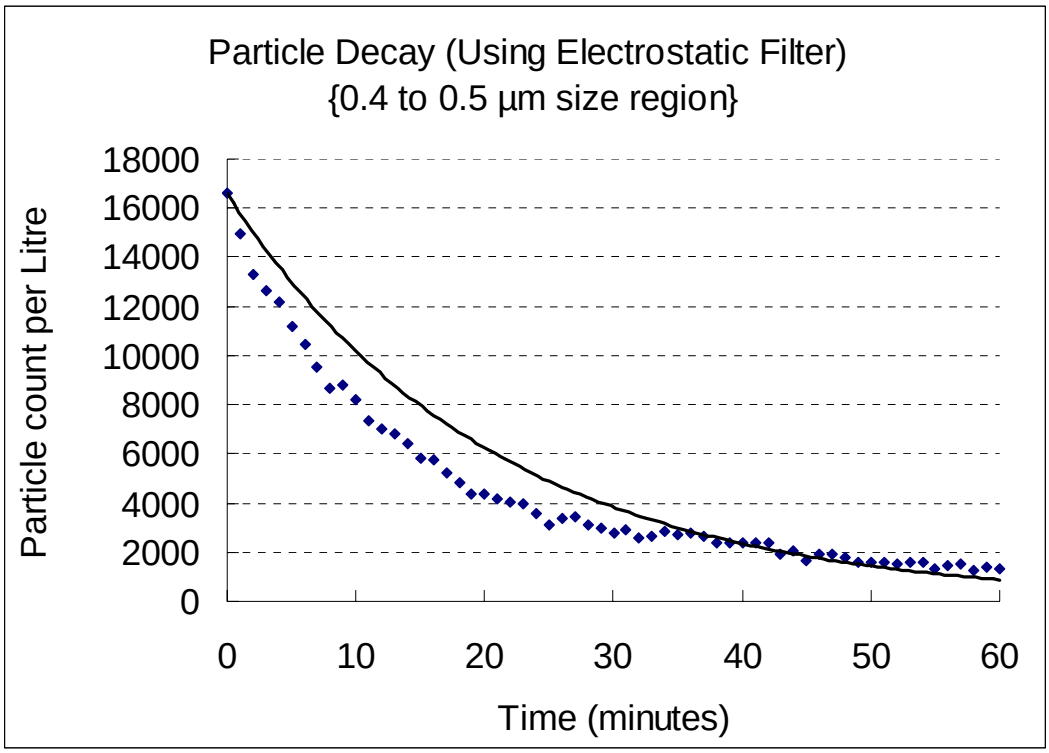

Figure A2.55 Particle decay profile in trial 3, 0.4 μ m to 0.5 μ m particle size range

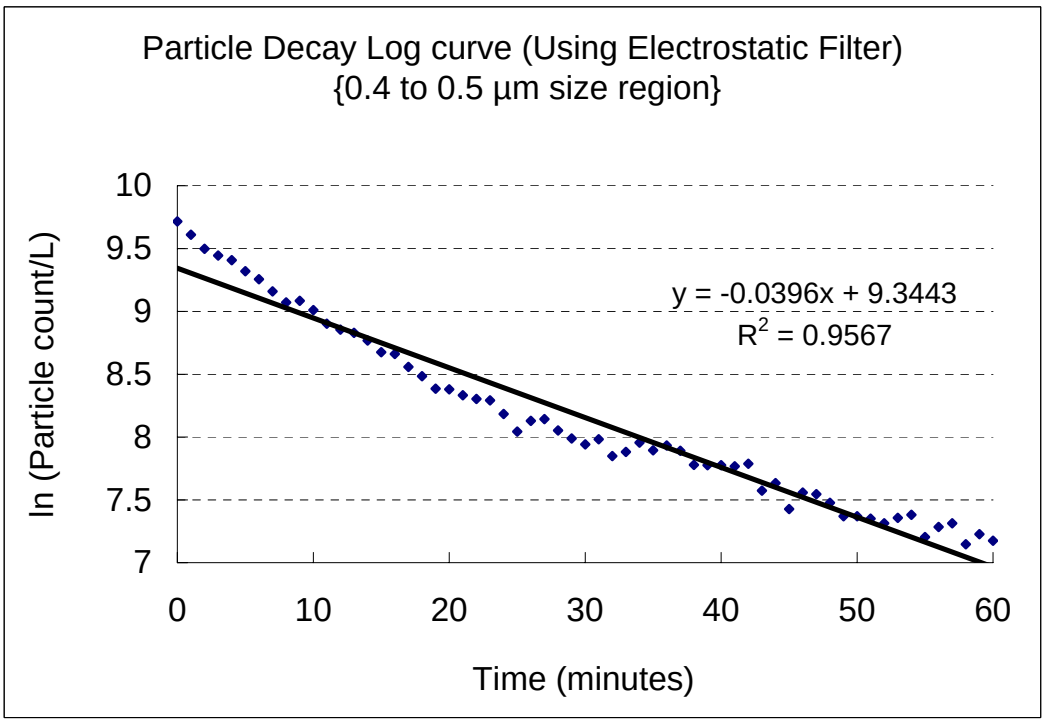

Figure A2.56 Natural log curve for trial 3, 0.4 μ m to 0.5 μ m particle size range

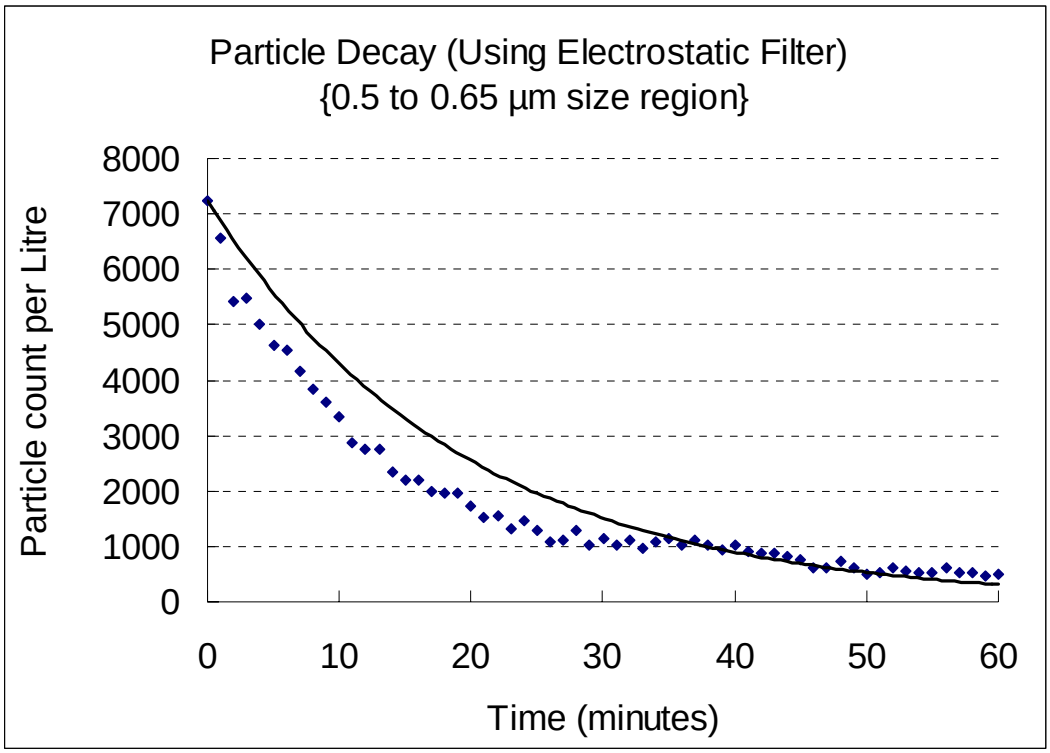

Figure A2.57 Particle decay profile in trial 3, 0.5 μ m to 0.65 μ m particle size range

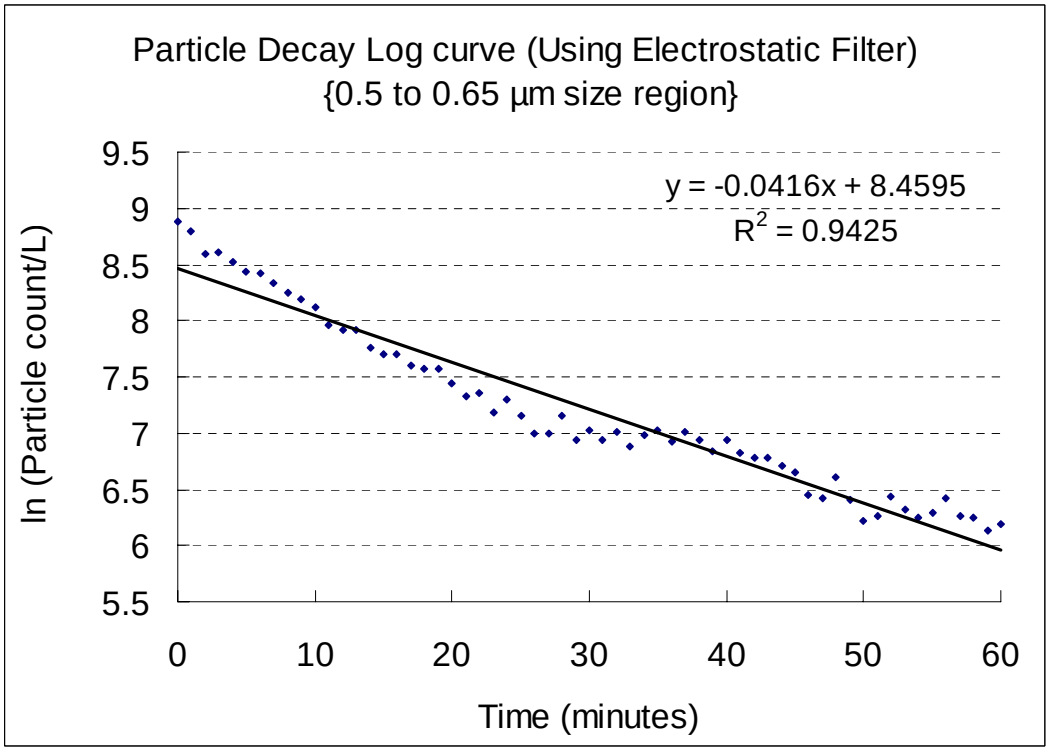

Figure A2.58 Natural log curve for trial 3, 0.5 μ m to 0.65 μ m particle size range

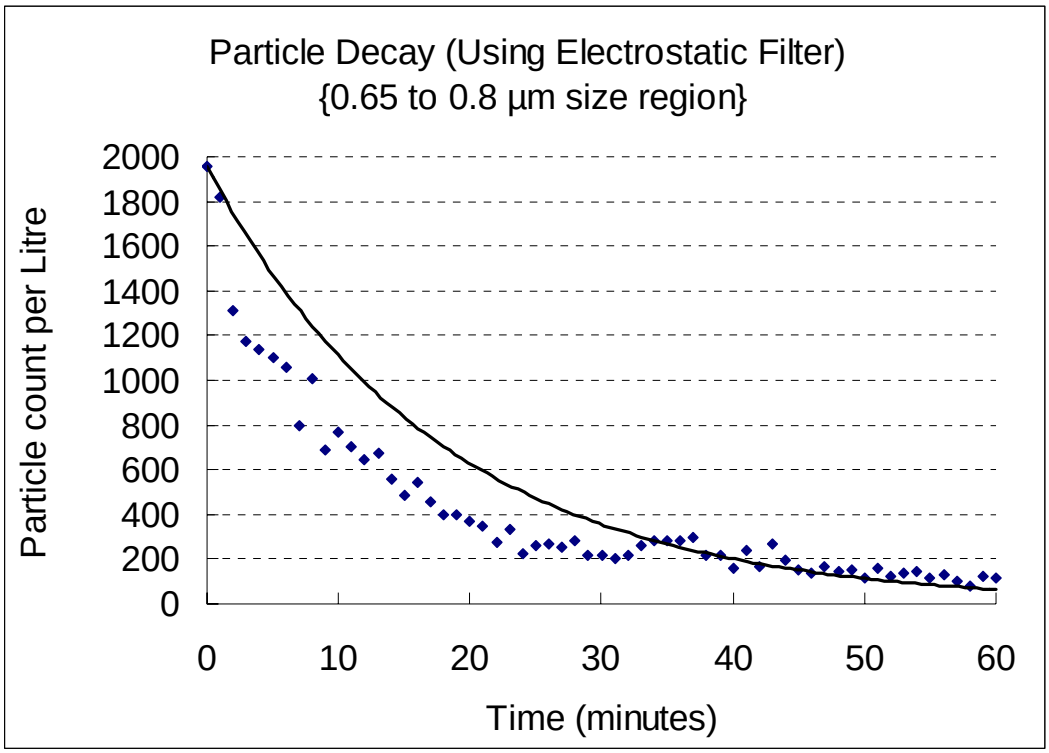

Figure A2.59 Particle decay profile in trial 3, 0.65 μ m to 0.8 μ m particle size range

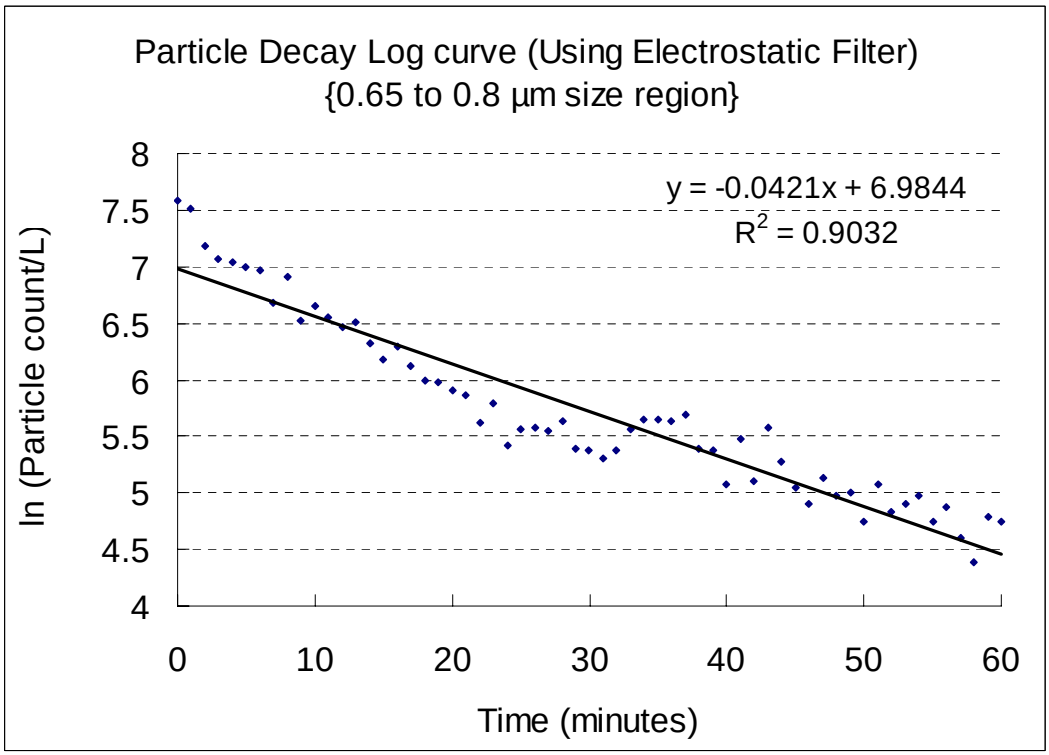

Figure A2.60 Natural log curve for trial 3, 0.65 μ m to 0.8 μ m particle size range

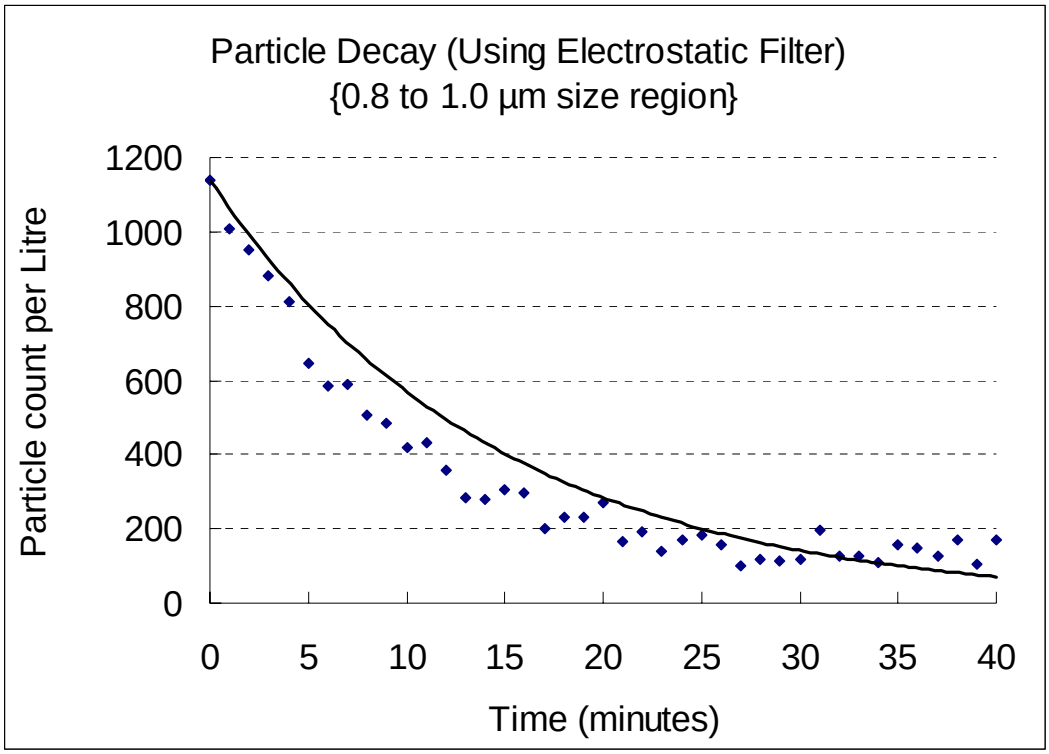

Figure A2.61 Particle decay profile in trial 3, 0.8 μ m to 1.0 μ m particle size range

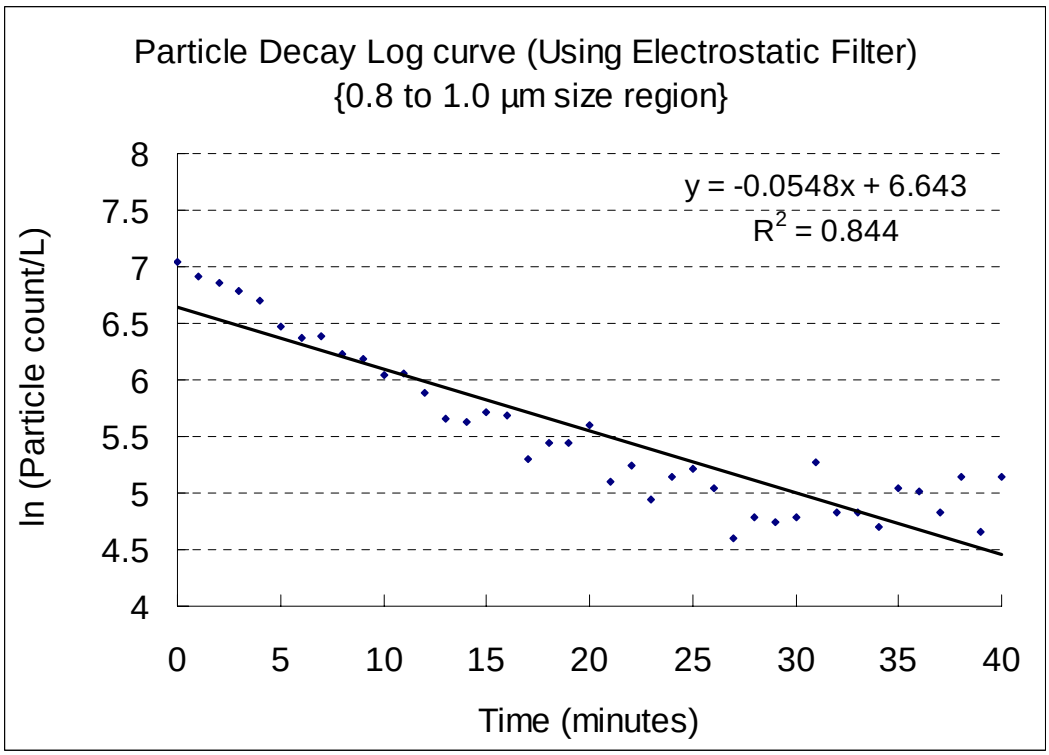

Figure A2.62 Natural log curve for trial 3, 0.8 μ m to 1.0 μ m particle size range

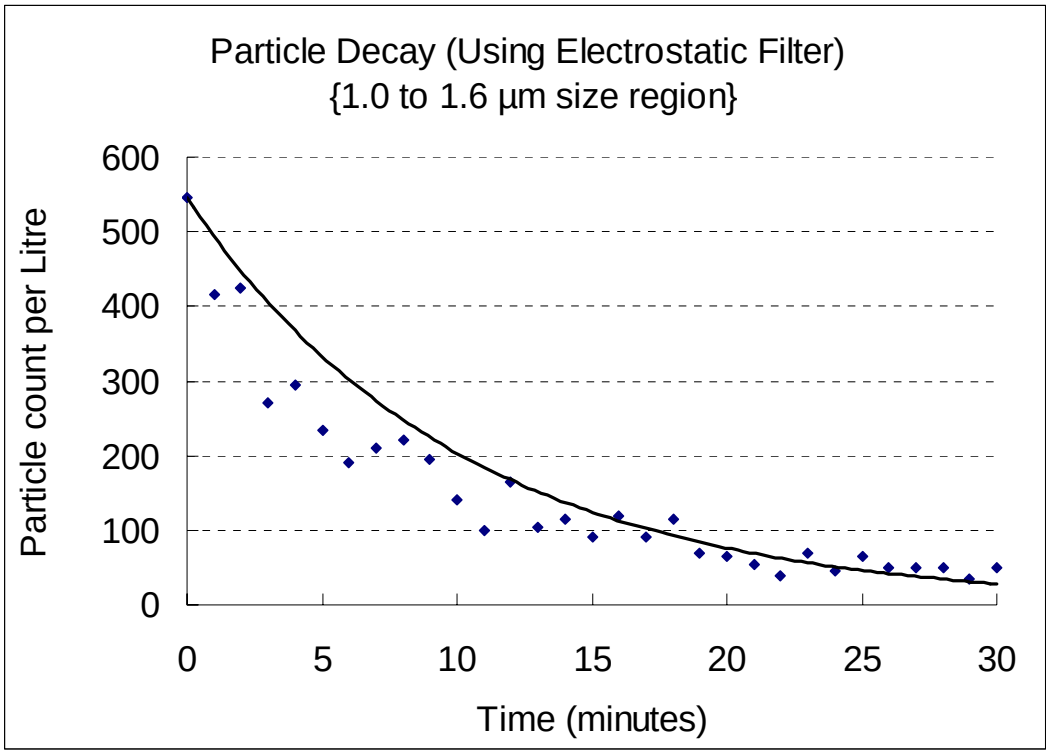

Figure A2.63 Particle decay profile in trial 3, 1.0 μ m to 1.6 μ m particle size range

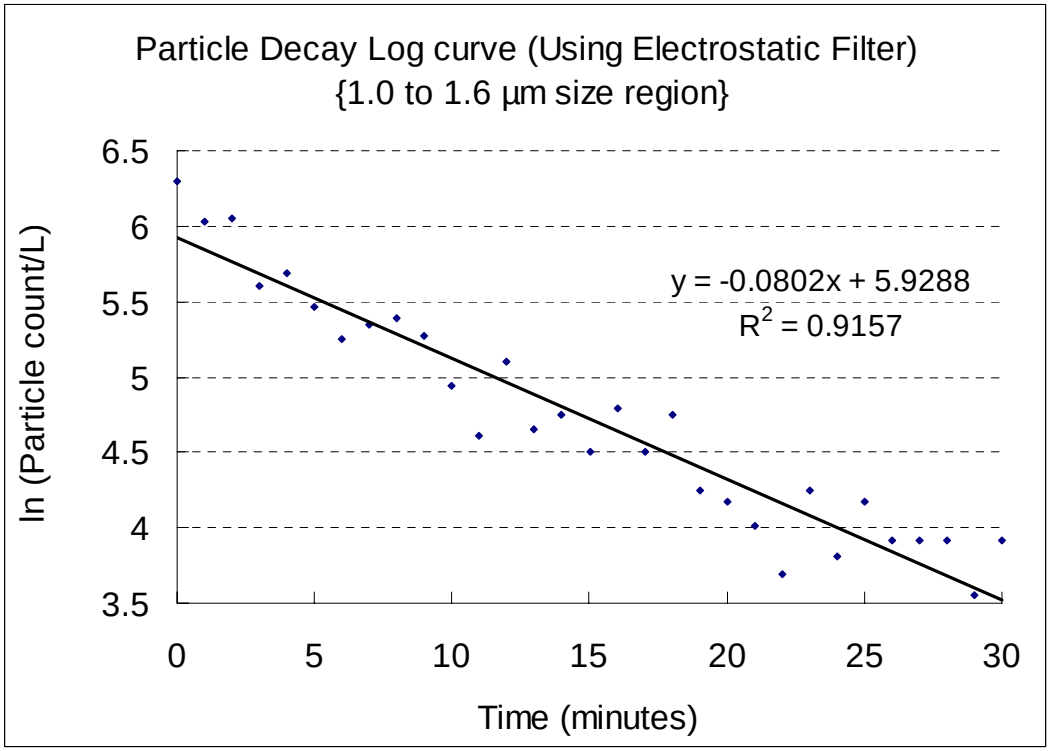

Figure A2.64 Natural log curve for trial 3, 1.0 μ m to 1.6 μ m particle size range

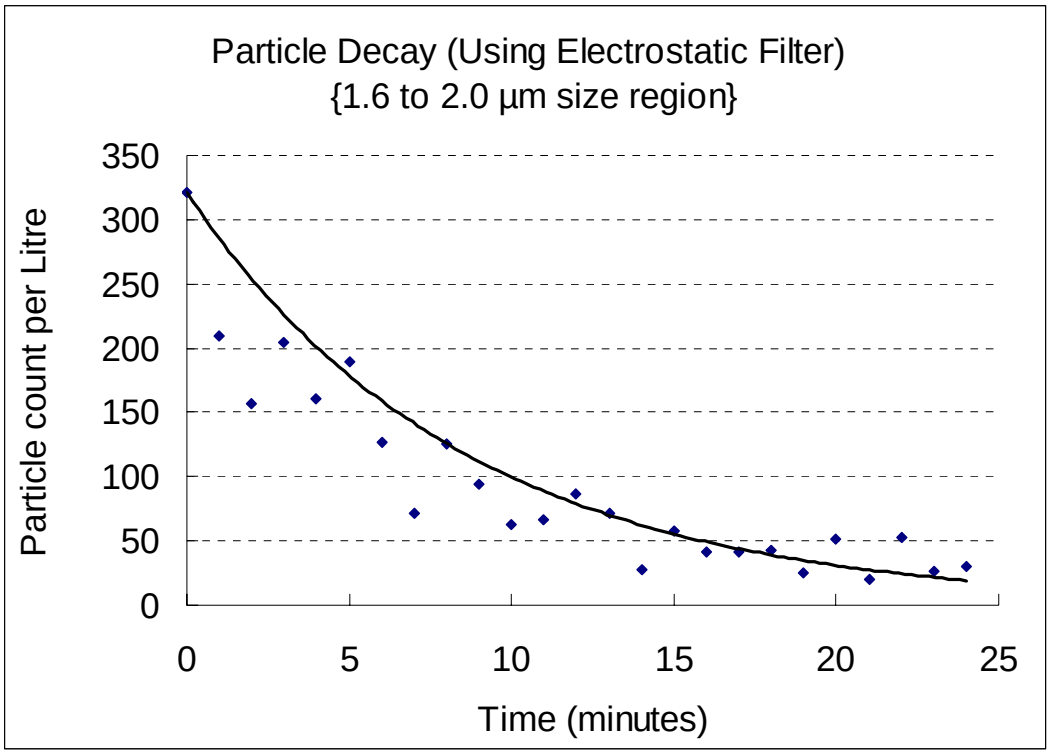

Figure A2.65 Particle decay profile in trial 3, 1.6 μm to 2.0 μm particle size range

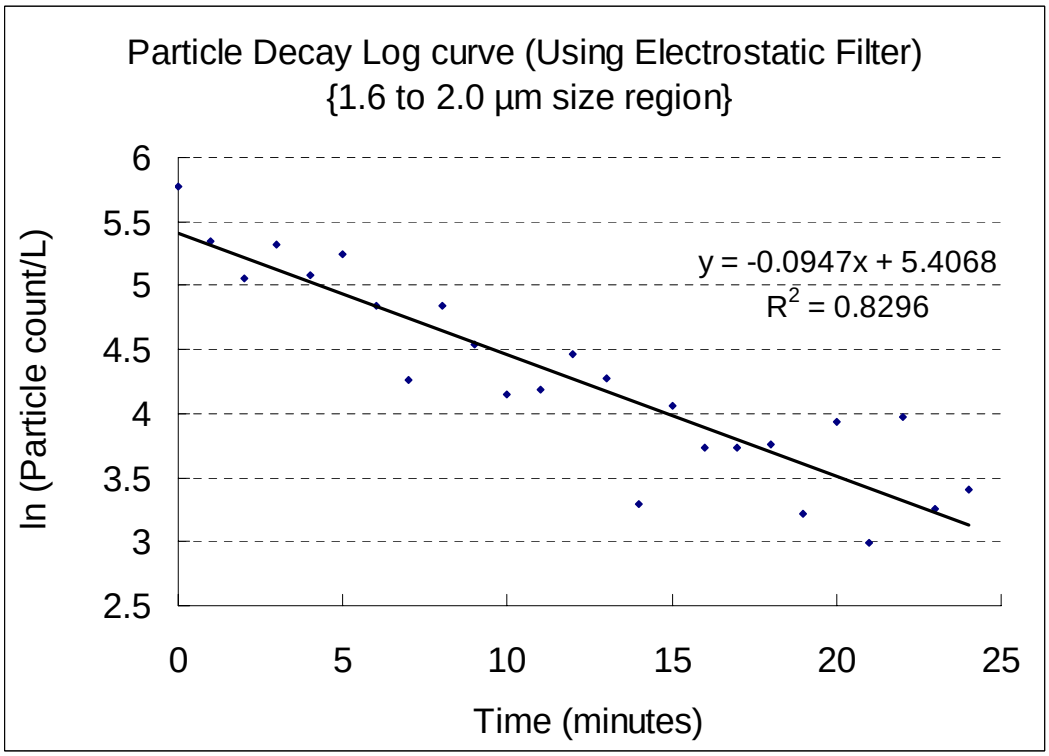

Figure A2.66 Natural log curve for trial 3, 1.6 μm to 2.0 μm particle size range

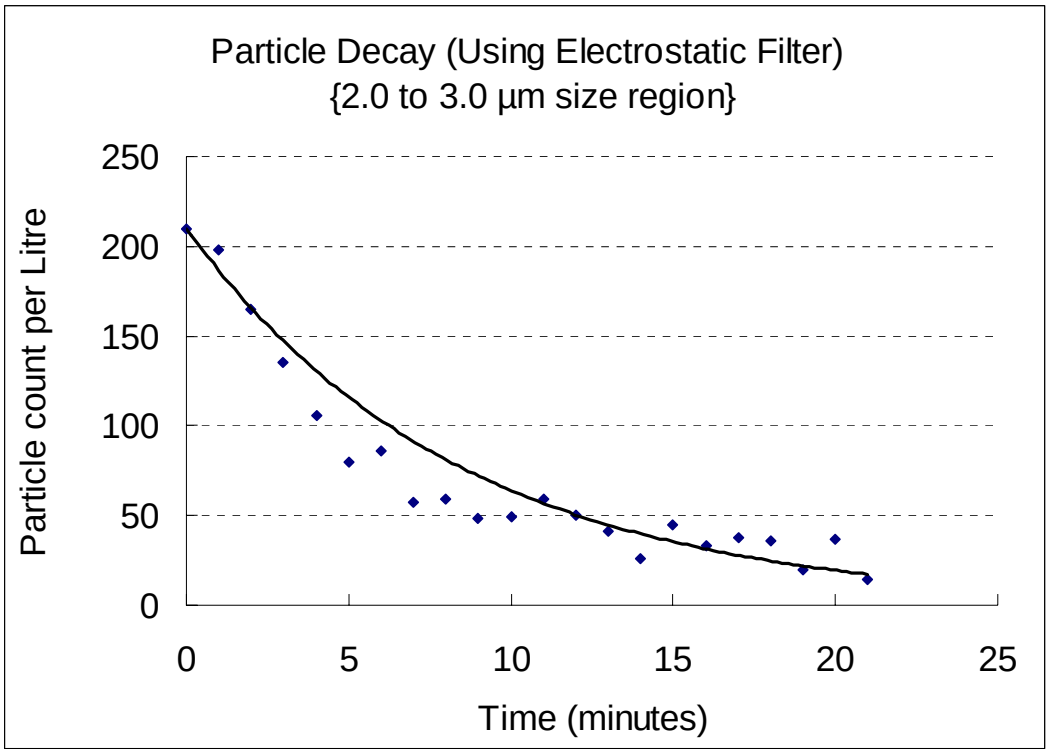

Figure A2.67 Particle decay profile in trial 3, 2.0 μ m to 3.0 μ m particle size range

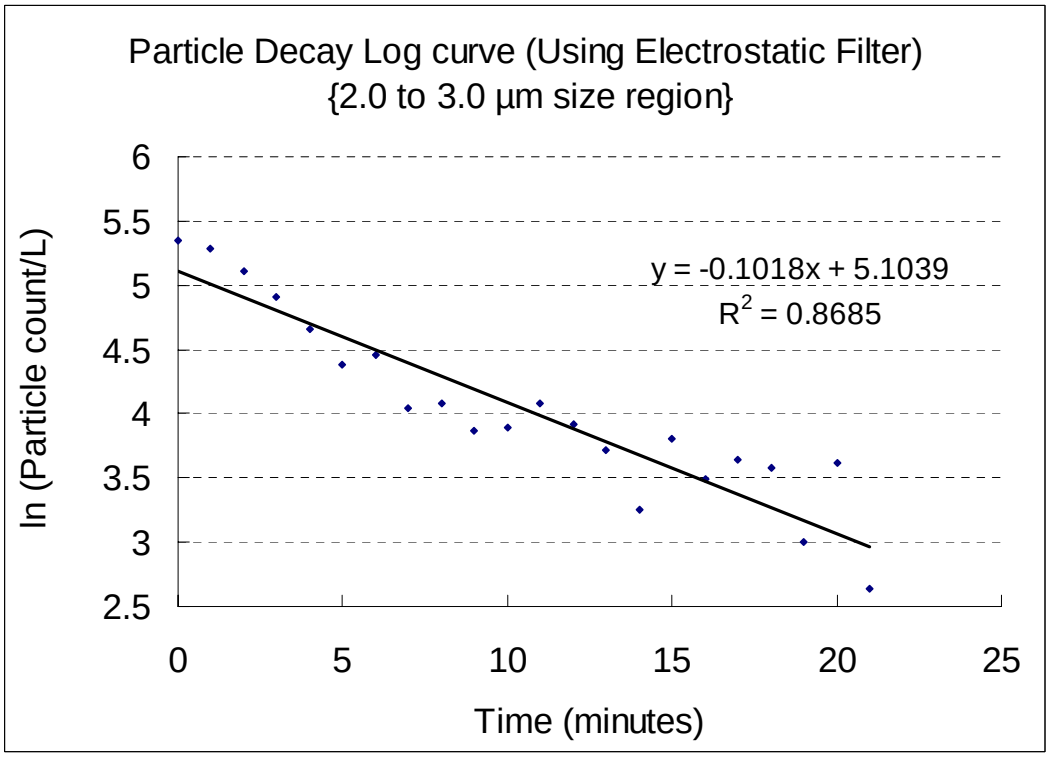

Figure A2.68 Natural log curve for trial 3, 2.0 μ m to 3.0 μ m particle size range

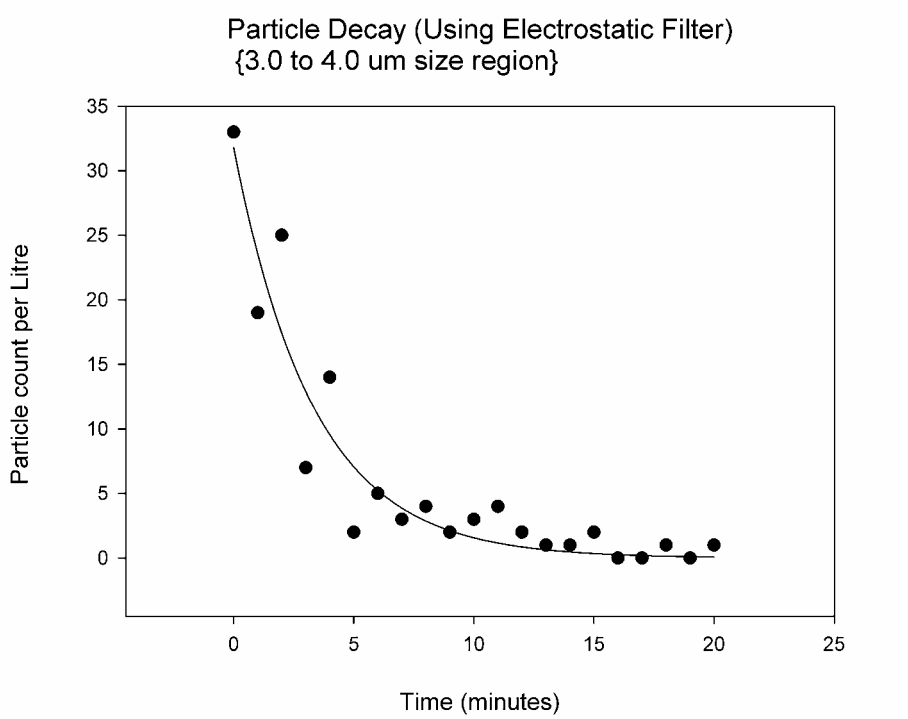

Figure A2.69 Particle decay profile in trial 3, 3.0 μ m to 4.0 μ m particle size range

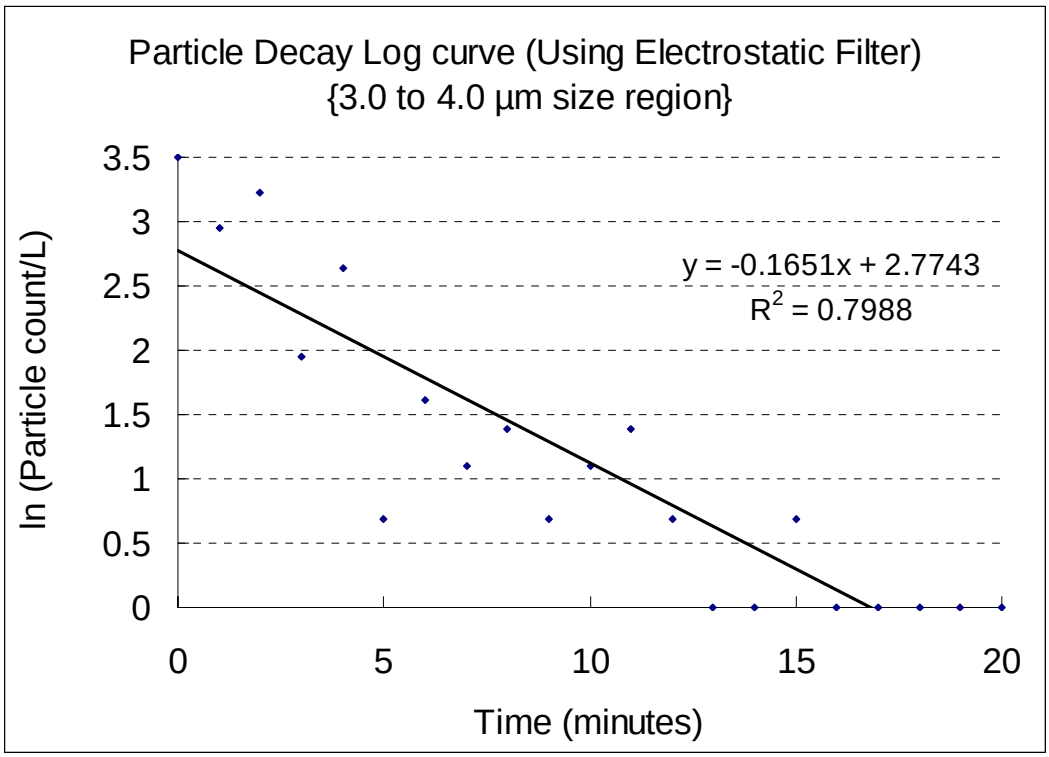

Figure A2.70 Natural log curve for trial 3, 3.0 μ m to 4.0 μ m particle size range

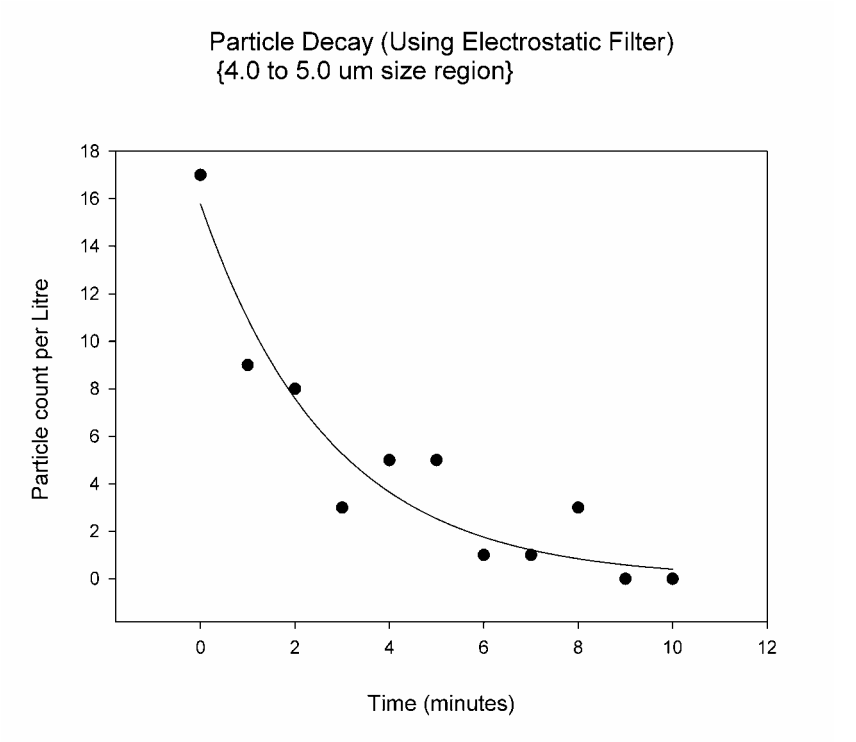

Figure A2.71 Particle decay profile in trial 3, 4.0 μ m to 5.0 μ m particle size range

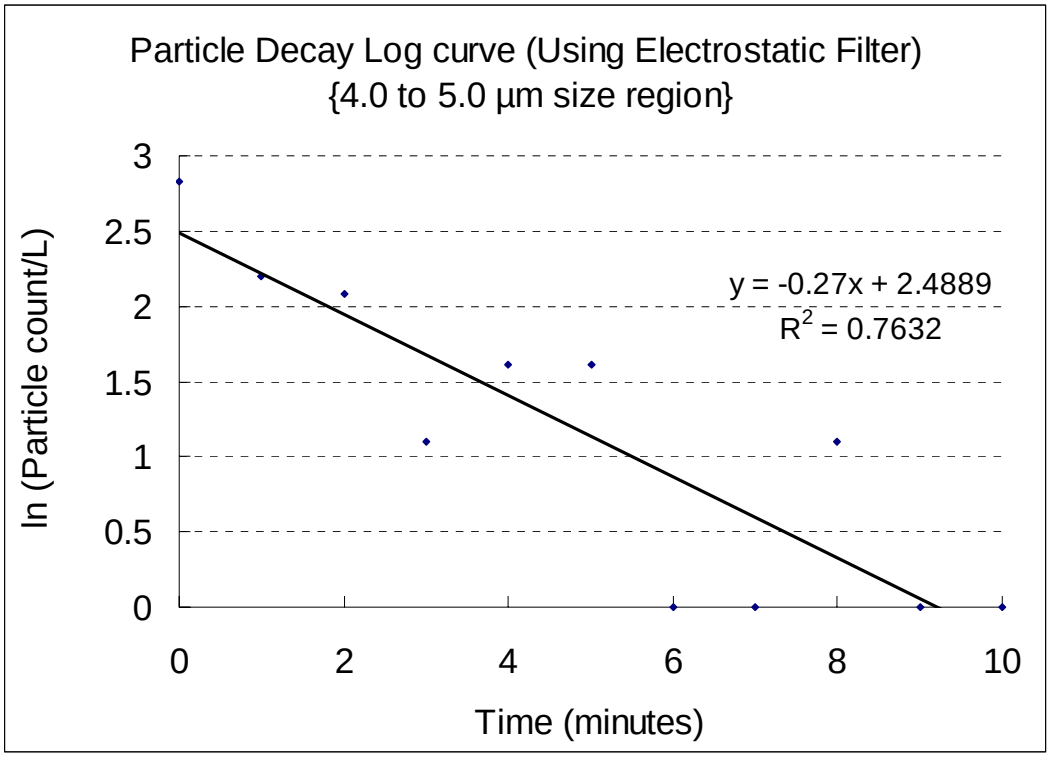

Figure A2.72 Natural log curve for trial 3, 4.0 μ m to 5.0 μ m particle size range

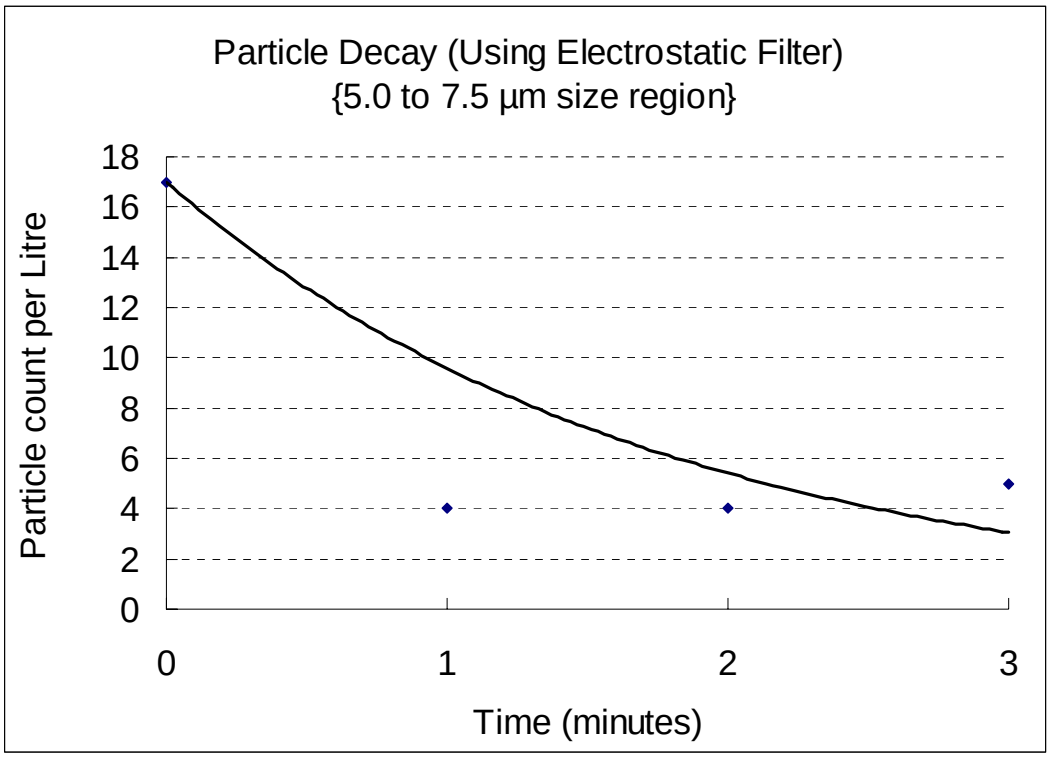

Figure A2.73 Particle decay profile in trial 3, 5.0 μm to 7.5 μm particle size range

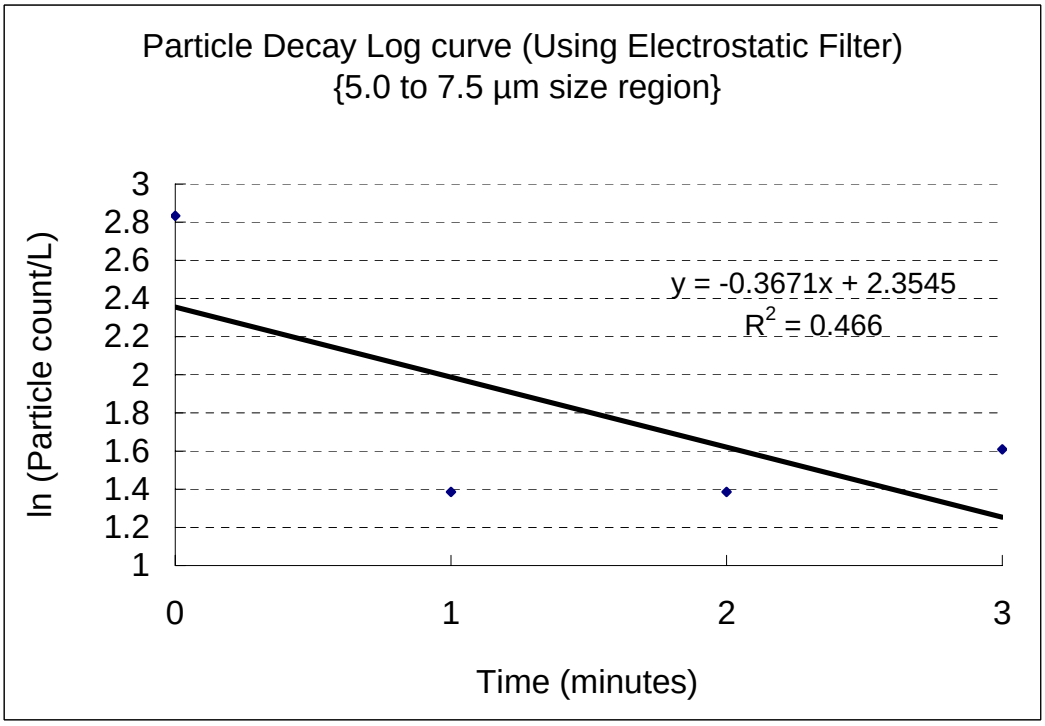

Figure A2.74 Natural log curve for trial 3, 5.0 μm to 7.5 μm particle size range

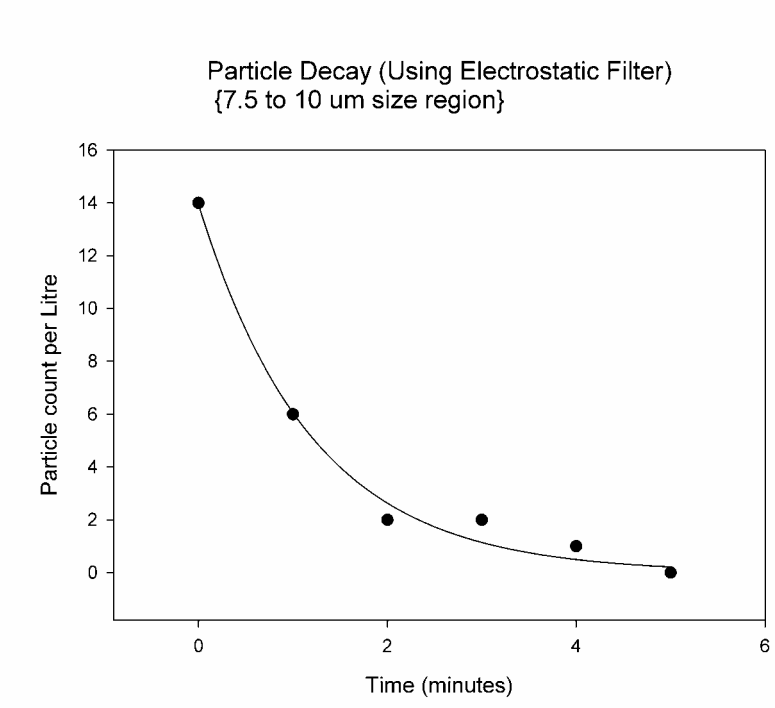

Figure A2.75 Particle decay profile in trial 3, 7.5 μm to 10 μm particle size range

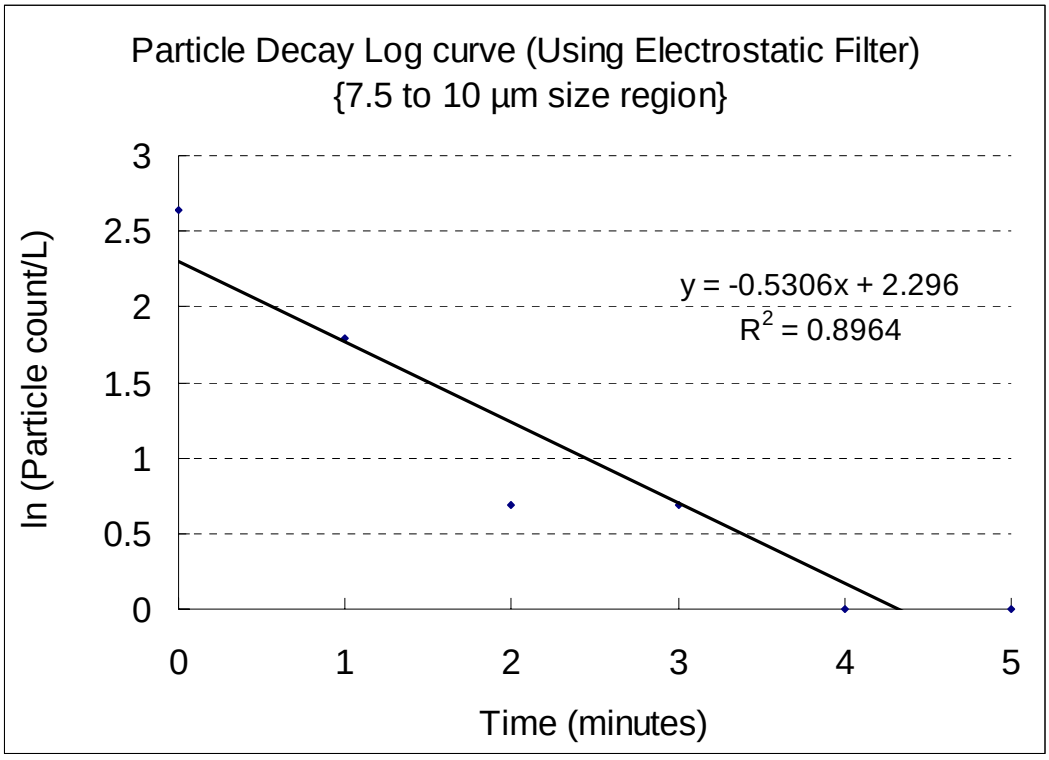

Figure A2.76 Natural log curve for trial 3, 7.5 μm to 10 μm particle size range

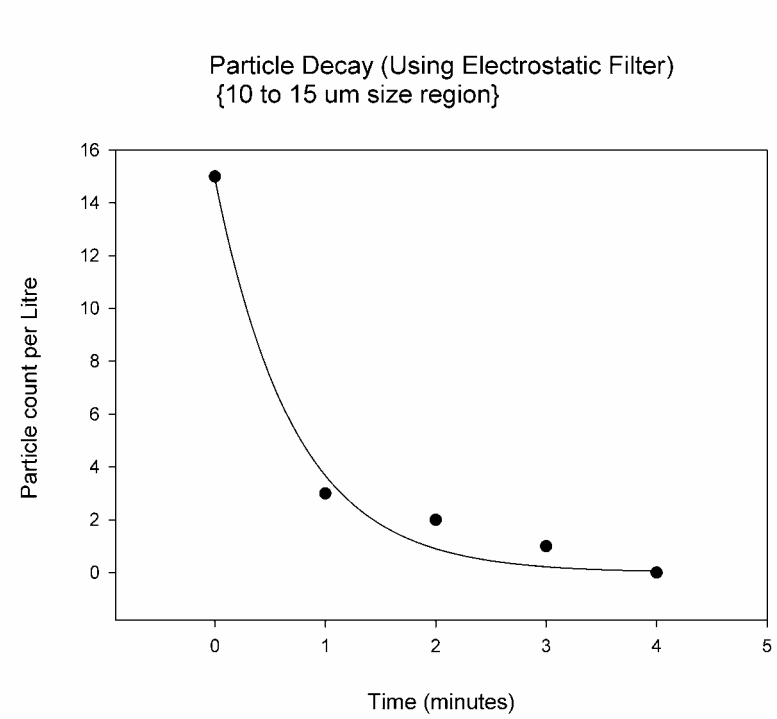

Figure A2.77 Particle decay profile in trial 3, 10 μm to 15 μm particle size range

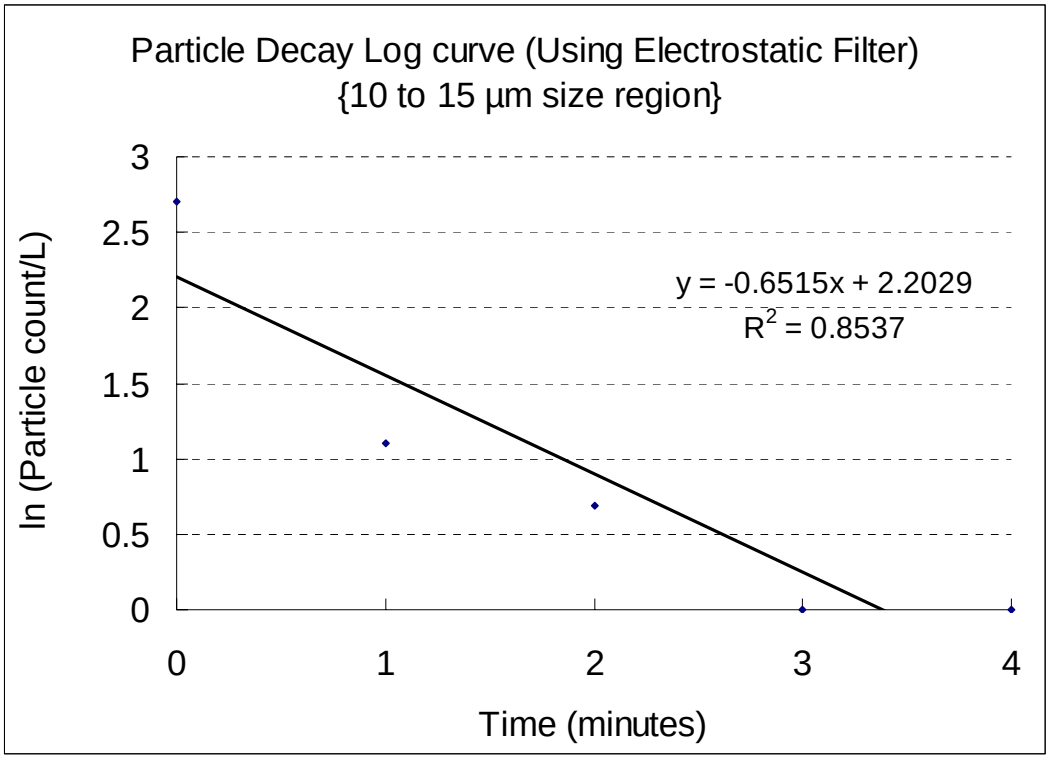

Figure A2.78 Natural log curve for trial 3, 10 μm to 15 μm particle size range