EFFECT OF AIR SPEED ON PARTICLE DEPOSITION RATES IN INDOOR BUILDING

NURUL ATIKAH BINTI AZMI

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ABSTRACT

Particle deposition is an important factor as it significantly influences the pollutant concentration of indoor air and thus people exposure. The goals of this study are to measure the air exchange rate at different air speed conditions studied and determine the optimum air speed condition for particle deposition rates toward better indoor air quality. The air exchange rate was measured by using a tracer gas method. The depositions of three ranges of particle sizes $PM_{(0.3-1.0)}$, $PM_{(1.0-2.5)}$ and $PM_{(2.5-10.0)}$ were assessed by measuring the number of indoor particle and its concentration for each of air speed conditions studied. Other than that, the environmental parameters were evaluated by using an instantaneous measurement of indoor air quality meter. In order to enhance the current understanding of the mechanism involving particle decay and deposition, measurement were made in an experimental bare room, 20.16 m^3 in volume with four different air speed conditions including only air conditioner on, only fan on, both air conditioner and fan on and both air conditioner and fan off. About 10cm^3 of ethyl alcohol was sprayed as a particle generator for each condition studied. The finding of this study shows that air exchange rate varies from 0.89 h^{-1} to 2.19 h^{-1} at different air speed conditions studied. By considering only well mixed conditions, the increased air exchange rates from 1.45 h^{-1} to 2.19 h^{-1} had resulting the increased of mean particle deposition rates from 0.14 h^{-1} to 0.42 h^{-1}. Besides that, this study also shows there was little effect of mixing of the condition only fan on with air speed (0.5-0.19) m/s which shows the lowest deposition rate at 0.14 ± 0.15 (mean ± standard deviation for all respective pairs) compared to other air speed conditions. The highest deposition rates among four conditions studied shows on the condition of both air conditioner and fan off (< 0.1 m/s) at 0.53 ± 0.2. In the context of air flow present by induced convection currents, the condition of only air conditioner on with air speed (0.1-0.14) m/s on shows greatest deposition rate at 0.42 ± 0.31, while the condition of both air conditioner and fan on with air speed (0.2-0.24) m/s shows greater deposition rate which is 0.4 ± 0.23 as compared to only fan on with air speed (0.15-0.19) m/s which shows deposition rate at 0.14 ± 0.15. The optimum condition of air speed for particle deposition rate shows on the condition of only air conditioner on with 0.42 ± 0.31. Higher particle deposition rates also shows on $PM_{(0.3-1.0)}$ with 0.62 ± 0.21 as compared to 0.31 ± 0.20 deposition rates for $PM_{(1.0-2.5)}$ and 0.20 ± 0.12 deposition rates for $PM_{(2.5-10.0)}$. The environmental factors such as temperature and relative humidity also affect the particle deposition rate. By not considering the conditions of both air conditioner and fan off, the increasing of temperature have decreasing the particle deposition rate from 0.42 ± 0.31 to 0.14 ± 0.15 while the increasing of relative humidity in this study have increasing the deposition rate from 0.14 ± 0.15 to 0.42 ± 0.31. As conclusions, it can be concluded that air exchange rate does not influenced by different air speed conditions and that the condition of air conditioner on is the best condition in the building.

ABSTRAK

Pemendapan zarah adalah faktor penting kerana ia dapat mempengaruhi kepekatan pencemaran udara dalaman dan sekaligus pendedahan kepada manusia. Matlamat kajian ini adalah untuk mengukur kadar pertukaran udara pada keadaan kajian kelajuan udara yang berbeza dan menentukan keadaan kelajuan udara optimum untuk kadar pemendapan zarah ke arah kualiti udara dalaman yang lebih baik. Kadar pertukaran udara dalam kajian ini telah diukur dengan menggunakan kaedah pengesanan gas. Pemendapan tiga julat saiz zarah $PM_{(0.3\text{-}1.0)}$, $PM_{(1.0\text{-}2.5)}$ dan $PM_{(2.5\text{-}10.0)}$ dinilai dengan mengukur jumlah zarah dan kepekatannya bagi setiap keadaan kelajuan udara yang dikaji. Selain daripada itu, parameter persekitaran telah dinilai dengan menggunakan ukuran terus dari meter kualiti udara. Dalam usaha untuk meningkatkan kefahaman semasa mekanisme yang melibatkan pereputan zarah dan pemendapan, pengukuran telah dibuat dalam satu bilik eksperimen kosong, dengan isipadu 20.16 m^3 bersama empat keadaan kelajuan udara yang berbeza termasuk hanya penghawa dingin huka, hanya kipas buka, kedua-dua penghawa dingin dan kipas buka dan kedua-dua penghawa dingin dan kipas tutup. Lebih kurang 10 cm^3 etil alkohol telah disembur sebagai penjana zarah untuk setiap keadaan yang dikaji. Dapatan kajian ini menunjukkan bahawa kadar pertukaran udara berbeza daripada 0.89 h^{-1} kepada 2.19 h^{-1} pada keadaan keadaan kelajuan udara yang berbeza. Dengan mempertimbangkan hanya keadaan percampuran udara yang baik, peningkatan kadar pertukaran udara dari 1.45 h^{-1} kepada 2.19 h^{-1} telah mengakibatkan peningkatan min kadar pemendapan zarah dari 0.14 h^{-1} kepada 0.42 h^{-1}. Selain itu, kajian ini juga mendapati sedikit kesan pencampuran keadaan dimana hanya kipas dibuka pada kelajuan udara (0.5-0.19) m/s yang menunjukkan kadar pemendapan yang paling rendah pada 0.14 ± 0.15 (min ± sisihan piawai bagi semua pasangan masing-masing) berbanding dengan keadaan kelajuan udara yang lain. Kadar pemendapan tertinggi di kalangan empat keadaan kelajuan udara yang dikaji ditunjukkan pada keadaan kedua-dua penghawa dingin dan kipas tutup (< 0.1 m / s) pada kadar 0.53 ± 0.2. Dalam konteks aliran udara dengan arus perolakan terarah, keadaan penghawa dingin buka dengan kelajuan udara (0.1-0.14) m/s pada pertunjukan tahap pemendapan terbesar pada kadar 0.42 ± 0.31, manakala keadaan kedua-dua penghawa dingin dan kipas buka dengan kelajuan udara (0.2-0.24) m/s menunjukkan kadar pemendapan yang lebih besar iaitu pada kadar 0.4 ± 0.23 berbanding hanya kipas dibuka dengan kelajuan udara (0.15-0.19) m/s yang menunjukkan kadar pemendapan pada kadar 0.14 ± 0.15. Keadaan optimum kelajuan udara untuk kadar pemendapan zarah ditunjukkan pada keadaan penghawa dingin buka dengan kadar pemendapan 0.42 ± 0.31. Kadar pemendapan partikel yang lebih tinggi juga menunjukkan pada $PM_{(0.3\text{-}1.0)}$ dengan kadar 0.62 ± 0.21 berbanding 0.31 ± 0.20 kadar pemendapan bagi $PM_{(1.0\text{-}2.5)}$ dan 0.20 ± 0.12 kadar pemendapan bagi $PM_{(2.5\text{-}10.0)}$. Faktor-faktor persekitaran seperti suhu dan kelembapan juga mempengaruhi kadar pemendapan zarah. Dengan tidak mempertimbangkan keadaan kedua-dua penghawa dingin dan kipas tutup, peningkatan suhu telah meningkatkan kadar pemendapan zarah dari 0.42 ± 0.31 kepada 0.14 ± 0.15, manakala peningkatan relatif kelembapan telah meningkatkan kadar pemendapan zarah dari 0.14 ± 0.15 kepada 0.42 ± 0.31. Sebagai kesimpulan, dapat disimpulkan kadar pertukaran udara tidak dipengaruhi oleh keaadaan kelajuan angin dan keadaan penghawa dingin pada keadaan adalah yang terbaik di dalam bangunan.

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LIST OF ABBREVIATIONS

ACGIH	American Conference for Governmental Industrial Hygienists
AER	Air Exchange Rate
ASTM	American Society for Testing and Materials
Cfm	Cubic feet per minute
CO_2	Carbon dioxide
DOSH	Department of Occupational Safety and Health
IAQ	Indoor Air Quality
ICOP	Industry Code of Practice
PM	Particulate Matter
SPSS	Statistical Package for the Social Sciences
WHO	World Health Organization

CHAPTER 1

1.1 INTRODUCTION

This chapter will be briefly explained about the background of the study, problem statement, research objectives, research question and research hypotheses. Besides that, the scope and significant of the study, conceptual framework and lastly operational definitions are also be discussed in this chapter.

1.2 STUDY BACKGROUND

"Indoor air quality" refers to the quality of the air in residential, schools, offices, or others building environment, especially as it relates to the health and comfort of building occupants. Ordinary indoor environments contain a wide variety of particle arising from both indoor and outdoor sources (Thatcher et al., 2002). Most pollutants affecting indoor air quality come from sources inside buildings, although some originate outdoors (U.S. EPA, 2008). Typical pollutants of concern include combustion products such as carbon monoxide; particulate matter; cooking fumes and environmental tobacco smoke; substances of natural origin such as radon; biological agents such as molds; pesticides; lead; asbestos; ozone (from some air cleaners); and various volatile organic compounds from a variety of products and materials. Indoor concentrations of some pollutants have increased in recent decades due to the factors such as energy-efficient building construction and increased use of synthetic building materials, furnishings, personal care products, pesticides, and household cleaners (U.S. EPA, 2008).

A healthy indoor environment is important to human being. Based on the statistical summary on buildings and their impact on the environment by U.S. Environmental Protection Agency (2009), average of Americans spend approximately

90 percent of their time indoors or about three quarters of our time awake, where the concentrations of some pollutants are often 2 to 5 times higher, and occasionally more than 100 times higher than outdoor levels. The predictions of indoor particle pollution levels become a subject of great interest for the evaluation of health risks and comfort in building. Indoor particle concentrations often exceed outdoor concentrations (Monn, 2001) and it is a major contributor to total personal exposures (He et al., 2005).

The particles in indoor environments can be transported by a series of physical and chemical processes such as infiltration, exfiltration, deposition, coagulation, resuspension and formation. Particle deposition rate gives significant impact to indoor environments, as it is considered being a dominant mechanism of losses of particles suspended in the indoor air (Sverak, 2004). The understanding of deposition as a removal process is useful for accessing human health impact from indoor exposure to particle (Thatcher et al., 2002). Particle deposition to indoor surfaces has a beneficial effect on indoor air quality, as it results in reduced inhalation exposures (Afshari et al., 2008). Thus, the phenomenon of particle deposition provides crucial information about human exposure in indoor environment.

The first attempt to model particle deposition indoors was introduced by Corner and Pendlebury (1951). Later on, many recent experimental studies have been performed on deposition of particles for indoor environment (He et al., 2005; Afshari et al., 2007; Zhao and Wu, 2007; Afshari et al., 2008; Zhang and Chen, 2009; Wang, 2012). The deposition of particle in indoor spaces depends on many factors such as particle physical characteristics, indoor airflow and building surface coverings as described in Lai (2002) and Lai and Nazaroff (2005). Indoor particles are deposited onto all available surfaces. In a typical room, the deposition surfaces include the floor, walls, ceiling, and furniture (Hussein, 2005)

In the building, the ventilation system (air speed) cannot be avoided. One approach to improve indoor air quality is through the selection of surface materials with the ability to remove indoor particles by increased particle deposition (Afshari et al., 2008). The sticky surfaces resulting in higher deposition than smooth ones while the larger the surface area will higher the probability of particle deposition (Weschler et al., 2003).

1.3 PROBLEM STATEMENT

Particle deposition is an important factor as it significantly influences the pollutant concentration of indoor air and thus people exposure (El Hamdani et al., 2008). The amount of airborne particle content in indoor environments can be highly variable in terms of space and also in terms of time (Fromme, 2012). As a ventilation system (air speed) is a part of indoor environment, it is including as factor that contributing to the particle deposition rates. Therefore, this research will be conducted to study the effect of variety air speed conditions as the parameters contributing to particle deposition rates.

1. 4 RESEARCH OBJECTIVES

1.4.1 To measure air exchange rate at different air speed conditions.

1.4.2 To determine the optimum air speed condition for particle deposition rates toward better indoor air quality.

1.5 RESEARCH QUESTIONS

1.5.1 What are the air exchange rates at different air speed conditions?

1.5.2 What is the optimum condition of air speed on particle deposition rates towards better indoor air quality?

1.6 RESEARCH HYPOTHESES

1.6.1 The different air speed conditions, the different value of air exchange rate.

1.6.2 If particle deposition rate is high, the optimum air speed condition is obtained.

1.7 SCOPE OF STUDY

An experimental study is carried out to assess the effect of air speed on particle deposition rates in indoor building. In this study, the air exchange rates are measured to determine the particle deposition rates. This study is carried out in a single room using four different air flow conditions (air conditioner on with fan off; fan on with air conditioner off; air conditioner on with fan on; and air conditioner off with fan off). Figure 1.1 shows conceptual framework of the study.

1.8 SIGNIFICANCE OF STUDY

The mechanical ventilation system such as fan and air conditioner are commonly use in the building of non-industrial workplace like offices. The ventilation system used to provide indoor thermal comfort to occupants. The study on the effect of air speed to particle deposition in indoor environment has a beneficial effect on indoor air quality. The result obtained from the study is helpful in controlling and reducing the impact of human inhalation exposure to indoor particle (Afshari et al., 2008), especially for fine size of particles as it poses a greater probability to penetrate into deeper part of respiratory and contain high levels of trace element and toxins. Other than that, this study will propose the best air speed condition in order to improve the indoor air quality in the buildings.

1.9 OPERATIONAL DEFINITION OF VARIABLE

1.9.1 Indoor Air Quality (IAQ)

Indoor air quality (IAQ) refers to the air quality within and around buildings and structures. Indoor air quality can be improved through the selection of surface materials with the ability to remove indoor particles by increased particle deposition (Afshari et al., 2008).

1.9.2 Deposition

Deposition is the transport from the air to surfaces of substances in solid, liquid or vapor form. In particular coarse particles, the deposition increases with a rising draught in the room and an increasing room area and it also varies depending on the degree of interior decoration (Fromme, 2012).

1.9.3 Deposition Rate

Deposition rate is defined as the number of particles depositing per unit surface area per unit time (m^{-2} s^{-1}). The larger the surface area, the higher probability of the particle deposition rate (Weschler, 2003).

1.9.4 Air Exchange Rate

Air-exchange rate is a function of building characteristics including the type of ventilation systems used, number of doors and windows, cracks in the building, as well as of the prevailing meteorological conditions. As the concentrations of pollutants indoor sources increases, the air exchange rate decreases (Weschler, 2003)

1.9.5 Tracer Gas Method

Tracer gas refer to gas that is mixed with air and measured in very small concentrations in order to study air movement. Tracer gas technique is used to obtain air change rate (ASTM, 2006).

1.9.6 Air Speed

Air speed is flow of air especially the motion of air currents around an object. In indoor environments, particle deposition is strongly dependent on the presence and speeds of any air flows in (Morawska and Salthammer, 2003).

1.10 CONCEPTUAL FRAMEWORK

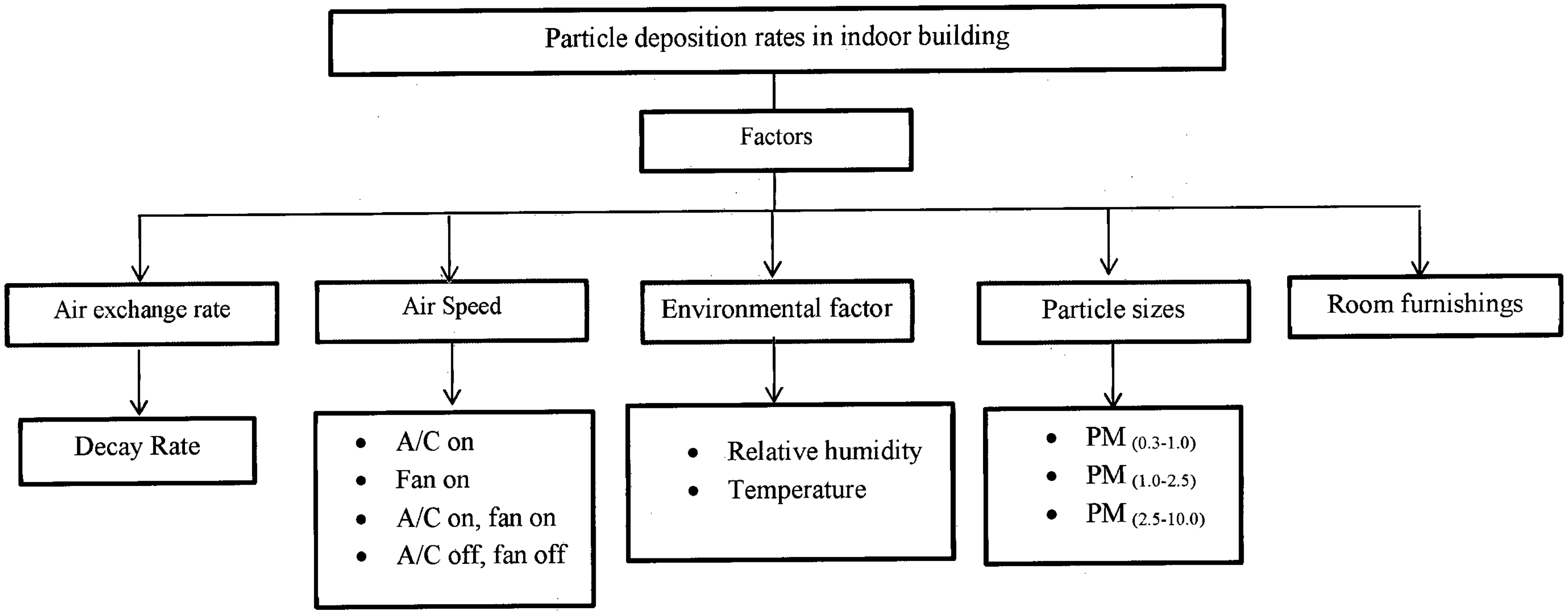

Figure 1.1: Conceptual framework of the effect of air speed on particle rates in indoor building

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This literature review will discuss about the previous related study and researches related to the effect of air speed on particle deposition rates in indoor building. The sources of the review are extracted from journals, articles, reference books and internet. The purpose of this section is to provide additional information and relevant facts based on past researches which related to this project.

2.2 INDOOR PARTICLES

As a result of a change of life style and work habits, people stay in industrial countries spend more than 90% of their time inside buildings. Exposure to air pollutants in indoor environment contributes to human health risk and it is important of risk-reduction approach should be taken. An indoor particle concentration is depends on the penetration of outdoor particles into the indoor environment and on the intensity of indoor aerosol sources (Estokava, 2010). Apart from that, the factors such as deposition of the particle and air exchange rate also affect indoor particle concentrations (Abt et al., 2000). The activities in indoor environments such as the deposition and suspension of house dust, cooking and cleaning activities or smoking can make a considerable contribution to the respective pollution situation (Fromme, 2012).

Particulate matter is one of the contaminants in indoor environment (DOSH, 2010). Particulate matter or referred as aerosol is a complex mixture of extremely small particles and liquid droplets that suspended in the air. Also known as particle pollution, the particulate matter is made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles. The flow of indoor aerosols is affected by the structural system of a building, material characteristics, the air exchange rate and the operating mode of indoor environment in the presence of inhabitants (Estokava, 2010). Particulate matter is one of the most important indoor air pollutants involved in a number of adverse health effects, such as premature deaths and increased mortality of infants and other parts of sensitive population.

Particles have irregular shapes and their aerodynamic behavior is expressed in terms of the diameter of an idealized sphere. The sampling and description of particles is based on this aerodynamic diameter, which is usually simply referred to as 'particle size'. The aerodynamic sizes of particles determine how the particles are transported in air and how they can be removed from it. These sizes also show how far they get into the air passages of the respiratory system. Thus, size of particles is directly linked to the potential factor of adverse effect on human health. U.S. Environmental Protection Agency (U.S. EPA) is concerned about particles that are 10 micrometers in diameter or smaller because those are the particles can penetrate to lower region of lung. Once inhaled, these particles can affect the heart and lungs and cause serious health effects. Additionally, size of particles provides the information on the chemical composition and its sources. U.S. Environmental Protection Agency (2013) groups particle pollution into two categories, which is inhalable coarse particle (PM_{10}) and fine particle ($PM_{2.5}$). The comparison sizes of particulate matter shown in Figure 2.1.

Coarse particles (PM_{10}) are particles have an aerodynamic diameter ranging between 2.5 µm to more than 10 µm (U.S. EPA, 2003). They are formed by mechanical disruption such as crushing, grinding and abrasion of surfaces, evaporation of sprays, and suspension of dust. PM_{10} is composed of aluminosilicate and other oxides of crustal elements (Fierro, 2000). The major sources of PM_{10} including fugitive dust from roads, industry, agriculture, construction and demolition, and fly ash from fossil fuel combustion. The lifetime of PM_{10} is from minutes to hours, and its can travel varies distance from <1km to 10 km. Besides that, fine particles ($PM_{2.5}$) have an aerodynamic diameter equal to or less than 2.5 μm (U.S. EPA, 2003). They differ from PM_{10} in origin and chemistry. These particles are formed from gas and condensation of high-temperature vapors during combustion (Fierro, 2000), and they are composed of various combinations of sulfate compounds, nitrate compounds, carbon compounds, ammonium, hydrogen ion, organic compounds, metals (Pb, Cd, V, Ni, Cu, Zn, Mn, and Fe), and particle bound water. The major sources of $PM_{2.5}$ are fossil fuel combustion, vegetation burning, and the smelting and processing of metals. Their lifetime is from days to weeks and travel distance ranges from 100s to >1000s km.

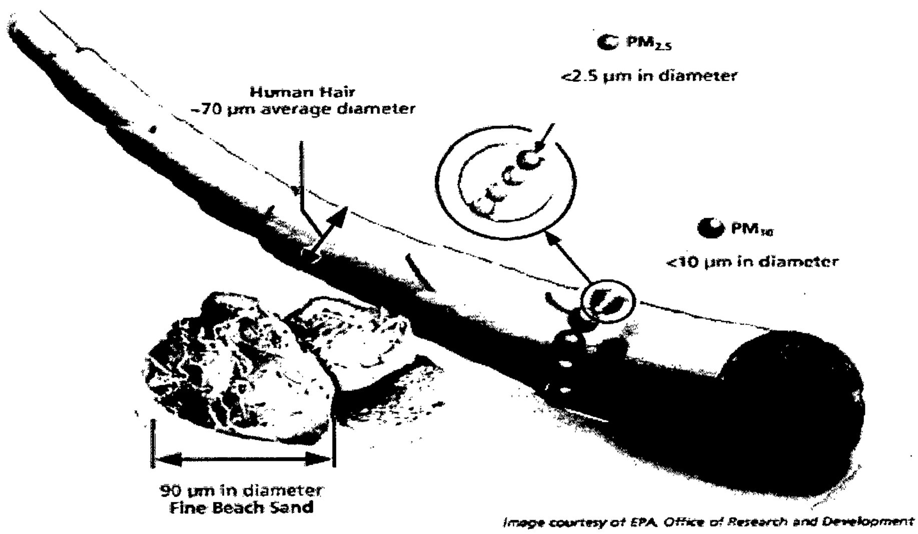

Figure 2.1: Comparison of PM sizes

Source: U.S. EPA (2003)

The American Conference of Governmental Industrial Hygienists (ACGIH) separates particulate matter into three categories, including inhalable, thoracic and respirable particles (ACGIH, 1997). However, Occupational Safety and Health Administration (Malaysia) have only considered of inhalable and respirable dust. Inhalable particles have 50% cut-point of 100 μm. These dust particles are hazardous when deposited anywhere in the respiratory tract. Besides that, thoracic particles are dust particles having 50% cut-point of 10 µm. It is hazardous when deposited anywhere within the lung airways and gas-exchange regions. Last but not least, respirable particles having 50% cut-point of 4 µm which hazardous when it deposited anywhere in the gas-exchange regions (alveolus) of the lung. The inhalation exposure in indoor environment can be reduced by increasing the particle deposition rate. The selection of surface materials with an ability to remove indoor particles and increased particle deposition will improve the indoor air quality (Afshari et al., 2008).

2.3 INDOOR PARTICLES DEPOSITION

The particles in indoor environments can be transported by a series of physical and chemical processes such as infiltration, exfiltration, deposition, coagulation, resuspension and formation. The deposition of particles on surfaces is based on different physical mechanisms such as gravitation and diffusion (Fromme, 2012). Apart from the deposition speed, this process is described as deposition rate. The process of particle deposition is strongly influenced by the particle diameter and reaches a minimum for particles with an aerodynamic diameter of approximately 0.4 µm (Long et al., 2001). However, there is a considerable variation range (Morawska & Salthammer, 2003; Miguel et al., 2005; Hussein et al., 2009). The particle deposition, in particular of coarse particles depending on environmental condition in the room, area of the room and also varies depending on the degree of interior decoration (Fromme, 2012).

The hazardous influence of particle is depending on its penetration and deposition into human respiratory system. The finer particles pose the greatest threat to human health. This is because they can travel deepest into the human lungs (Health Canada, 2012). The range size of particles may exists from 0.005 µm to 100 µm in diameter compared to the average size of human hair is 60 µm. Short-term exposure to fine particulate matter may cause shortness of breath, eye and lung irritation, nausea, light-headedness, and possible allergy aggravations (U.S. EPA, 2012). Exposure to particulate matters for long time in a building may cause respiratory diseases such as bronchial asthma and respiratory inflammation (Han et al., 2011). On 2003, Weschler et al. state that house dust situated, inter alia, on the surfaces of furniture can also contribute to route of exposure via the skin (dermal intake). According to WHO (1999), dusts may affect the skin directly by the absorption through skin, causing various types of dermatitis, which are a widespread and often serious problem, or even skin cancer.

2.3.1 Theoretical Modeling of Indoor Particle Deposition Rates

The first attempt to model particle deposition indoors in an enclosure with turbulent airflow was introduced by Corner and Pendlebury (1951). Many experimental studies have been conducted by researchers on significant modifications and enhancements of model particle deposition indoors. Their effort was summarized by Lai and Nazaroff (2000) as shown in Table 2.1. Then, Lai and Nazaroff (2000) developed a model for particle deposition to a smooth surface which includes the effects of Brownian and turbulent diffusion and gravitational settling. They present results in term of horizontal, vertical, and spherical surfaces.

Riley et al. (2001) developed a model to investigate the deposition portion of the model for predicting indoor particle concentrations which incorporated size-dependent removal mechanisms. Since there are no published experimental data for particles with aerodynamic diameters less than 0.06 µm, they applied the smooth indoor surface particle deposition theory of Lai and Nazaroff (2000) in order to estimate deposition for these ultrafine particles. As the result of wide range of deposition value obtained experimentally, it is difficult to determine which of the deposition models predicts indoor deposition most accurately and which model parameters most accurately reflect real indoor conditions (Thatcher et al., 2001).

2.3.2 Measured of Indoor Particle Deposition Rates

Particle deposition to indoor surfaces will reduce the concentration of indoor airborne particle in the indoor environment. For this reason, understanding particle deposition loss rates under typical indoor conditions is important for assessing human health impacts from exposure to indoor particles. Many experiments have been performed regarding the particle deposition in the indoor environment (Xu et al., 1994; Byrne et. al., 1995; Thatcher and Layton, 1995; Fogh et al., 1997; Abt et al., 2000;

Vette et al., 2001; Mosley et al., 2001, and Thatcher et al., 2002). The results of these eight studies show a wide degree of variability in particle deposition rate for any given particle size. This variability is due to the variations in the conditions of particle deposition rates were measured. Factors such as airflow conditions, furnishings, surface-to-air temperature differences, surface roughness, electrostatic charges, particle type and measurement methods may all be expected to affect the measured deposition rate.

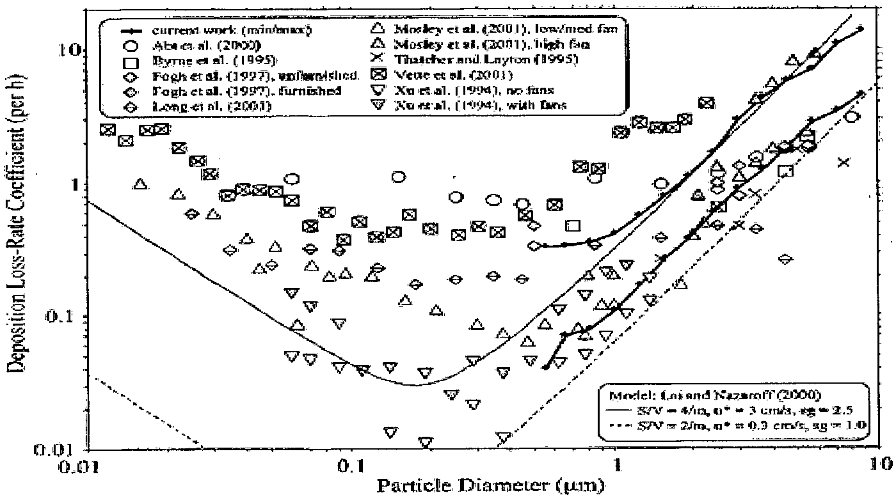

Figure 2.2: Deposition loss rates for full-scale rooms and residences

Source: Thatcher et al. (2002)

Figure 2.2 shows a comparison of results from the eight studies which were conducted under a variety of conditions to study the deposition rates, while Table 2.2 shows detail results from those studies. Xu et al. (1994) measured deposition loss rates of environmental tobacco smoke under conditions of still and actively mixed airflow using unfurnished in 36.5 m^3 full-scale room. Byrne et al. (1995) performed the experiment to determine deposition loss rates for monodispersed porous silica and indium acetylacetonate, in a volume of 8 m^3 smooth walled aluminum chamber mixed with a small fan. Thatcher and Layton (1995) carried out the experiment to measure deposition loss rates for resuspended particles within a single residence.

Table 2.1: Summary of model developments for particle deposition from turbulent flow in enclosures

Investigators	Expressions	Comments
Corner and Pendlebury (1951)	$\varepsilon_p = K_e y^2$ $K_e = \kappa^2 \frac{dU}{dy}$	The first published analytical work. Velocity gradient, dU/dy, evaluated based on drag-force balance for flat plate.
Crump and Seinfeld (1981)	$\varepsilon_p = K_e y^n$ $K_e = 0.4 \frac{dU}{dy}$	Exponent *n* is arbitrary. Analyzed overall depositional loss for vessel of arbitrary shape. Velocity gradient dU/dy, evaluated based on energy dissipation rate (Okuyama et al., 1977).
McMurry and Rader (1985)	$\varepsilon_p = K_e y^2$	Extension of Crump and Seinfeld (198I) theory to include electrostatic attraction. Turbulence intensity parameter, K_e, was treated as an empirical parameter obtained by fitting experimental results.
Nazaroff and Cass (1985)	$\varepsilon_p = K_e y^2$ $K_e = \kappa^2 \frac{dU}{dy}$	Follows work of Corner and Pendlebury, incorporating the effects of thermophoresis.
Shimada et al. (1989)	$\varepsilon_p = K_e y^{2.7}$ $K_e = 7.5 \sqrt{\frac{2\varepsilon}{15\upsilon}}$	Incorporates the effect of particle inertia.
Benes and Holub (1996)	$\varepsilon_p = K_e \delta^2 \left(\frac{y}{\delta}\right)^n$ $\delta = \frac{L}{\sqrt{Re}}$ $K_e = \kappa^2 \frac{dU}{dy}$	Eliminated dimensional problems associated with non-integer value of *n*. Expression for δ based on theory for laminar boundary layer. Re based on the velocity at tip of stirrer blade. Velocity gradient, dU/dy, evaluated based on work of Okuyama et al. (1986).

Source: Lai and Nazaroff (2000)

Fogh et al. (1997) measured deposition loss rates for monodispersed porous silica particles in four houses, with and without furnishings. Abt et al. (2000) measured deposition loss rates after cooking events (oven cooking, toasting, and sautéing) in several houses. Vette et al. (2001) measured deposition decay rate in a furnished residential building using ambient particles. Mosley et al. (2001) performed their deposition loss rates experiment in an unfurnished 19 m^3 room using oil droplets created using a monodispersed-aerosol generator. Thatcher et al. (2002) determined deposition losses for oil droplets in a single room and they found that both furnishing level and mean air speed significantly affected particle deposition rates for the aerodynamic particle diameters studied (0.5 to 10 mm).

Abadie et al. (2001) studied experimentally the deposition loss rate coefficient for several wall textures in a small cubic chamber ($0.216m^3$). Three different particle sizes which are 0.7, 1, and 5.0 µm injected into a box whose internal faces are covered by a texture to be tested, and then mechanically stirred by a fan. The decay of particles was directly monitored while the deposition on the wall inferred indirectly from the measurement. Lai et al., (2002) performed an experimental in a test chamber with volume $8m^3$ to study the particle deposition under well-stirred conditions using monodisperse tracer aerosol particles in the range of 0.7 to 5.4 µm.

On 2005, He et al. carried out the study investigating indoor air in residential houses in Brisbane, Australia to quantify the particle deposition rate of size classified particle in the size range from 0.015 to 6 µm. Zhao and Wu (2007) studied on the influences of flow conditions near the wall surfaces, surface roughness and particle concentration distribution on particle deposition indoors. Besides that, the correlation between amount of carpet and deposition of particles in 21 apartments has been studied by Afshari et al. (2008). Zhang and Chen (2009) predict the particle deposition in enclosed environments by using v'^2-f turbulence model with a modified Lagrangian method. Wang (2012) performed the experiment in a small-scale acrylic chamber to quantify the deposition rate constants of size-classified particles on typical indoor surface materials which affected by the degree of surface roughness.