OPTIMISATION OF INDOOR ENVIRONMENTAL QUALITY AND ENERGY CONSUMPTION WITHIN OFFICE BUILDINGS

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KEYWORDS

Building energy consumption

CO₂

Deep bag (DB) filter

Electrostatic (ES) filter

I/O ratio

Indoor air quality

Indoor environmental quality

Mechanically ventilated office building

Multi-component model

Particle number (PN)

Particle number size distribution (PNSD)

PM₂.₅

Ultrafine (UF) particle
ABSTRACT

Epidemiological studies have consistently shown that ultrafine (UF) particles, measured in terms of particle number (PN) concentrations, may be even more toxic to human health than PM$_{2.5}$. In urban environments, high outdoor particle concentrations strongly influence indoor concentrations. Heating, ventilation and air conditioning (HVAC) systems are commonly used to control air pollutant levels indoors and provide thermal comfort for occupants in office buildings, however these systems also require a large amount of energy to operate. Considering these two, often contradictory, requirements, the optimisation of HVAC systems aims to minimise energy consumption and maximise indoor environmental quality. However, particles, especially UF particles, are yet to be taken into account when optimising HVAC systems. This is due to a lack of information on, and a limited understanding of, indoor and outdoor particle concentrations in mechanically ventilated buildings, in particular office buildings.

This thesis aimed to investigate particle characteristics and dynamics inside and around office buildings, together with their relationship to each other and the factors which affect them. Based on the above, a multi-component model, including an indoor PN model, was developed and applied to optimise indoor environmental quality and energy consumption in the investigated office buildings. The study was designed to: (i) quantify and assess the vertical profile of particle concentration around buildings; (ii) quantify and assess the influence of ventilation/filtration on indoor particle concentration; and (iii) develop and apply a multi-component model to evaluate indoor air quality and energy usage under different operation scenarios, in office buildings strongly affected by high outdoor particle sources. The main outcomes of the thesis can be summarised as follows:

In the first paper (chapter 3), the influence of vehicle emissions and nucleation on particle characteristics (particle number size distribution - PNSD and PM$_{2.5}$ concentration) at different
heights around three urban office buildings located next to busy roads in Brisbane, Australia was assessed. The results showed that both PNSD and PM$_{2.5}$ concentration around the building envelopes were not only influenced by vehicle emissions, but also by new particle formation, and that they exhibited variability across the three different office buildings. These findings highlight important new information in relation to the typically under-valued role of new particle formation in the urban atmosphere and its potential to affect large numbers of people, due to the high density and occupancy of urban office buildings, and the fact that the vast majority of people’s time is spent indoors. Therefore, it is important to consider the effects of these particles when selecting air intake locations and appropriate filter types during the design or upgrade of mechanical ventilation systems in urban office buildings.

The influence of ventilation and filtration on indoor particle dynamics in office buildings was evaluated in the second paper (chapter 4). In this study, the in-situ efficiency of deep bag and electrostatic filters was quantified. Then the influence of ventilation systems using these filters on indoor particle concentrations was assessed using both experimental measurements and modelling for different indoor and outdoor particle source scenarios, in the same three office buildings mentioned above. The highest PN and PM$_{2.5}$ concentrations in one of the office buildings were due to the proximity of this building’s HVAC air intakes to a nearby busway, as well as the higher outdoor ventilation rate for this building. On the other hand, the lowest PN and PM$_{2.5}$ concentrations in another building were due to the utilisation of both outdoor and mixing air filters in its HVAC system. Indoor PN concentrations were strongly influenced by outdoor levels and were significantly higher during rush-hours and nucleation events, compared to working-hours on the measured days, for all three buildings. This is the first time that the influence of new particle formation on indoor particle concentrations has been identified and quantified. This finding also highlights the potentially under-appreciated role of nucleation in generating particles that can penetrate inside office buildings and affect large number of people working there. A dynamic model for indoor PN concentration was
used in this study, and it performed well when outdoor air was the main source of indoor particles and there was less uncertainty regarding indoor source emissions, or when the ventilation system was turned off. Modelling results also revealed that using both mixing air and outdoor air filters can significantly reduce indoor particle concentration in buildings where indoor air was strongly influenced by outdoor particle levels.

In the third paper (chapter 5), a multi-component model was developed based on the dynamic indoor PN concentration model, an indoor CO\textsubscript{2} mass balance model and an energy usage model. This multi-component model was employed to assess the potential improvement of indoor air quality and energy savings under different ventilation conditions in office buildings where indoor particles were strongly influenced by high outdoor particle concentrations from vehicle emissions or new particle formation. When running the ventilation system according to optimal conditions and using outdoor air filtration, average indoor particle number (PN) concentration decreased by up to four times, while indoor CO\textsubscript{2} concentration and energy consumption were not significantly different compared to the normal operation conditions used during the summer months. However, the benefits of running the system according to this configuration were even higher during the winter months. In terms of indoor air quality, both average indoor PN and CO\textsubscript{2} concentrations decreased by 42% and 23%, respectively, while potential energy savings due to free cooling could reach as high as 96% when compared to the normal operating conditions used during winter. Application of such a model for the operation of HVAC systems can help to significantly improve indoor air quality and energy conservation in air-conditioned office buildings strongly influenced by high outdoor particle levels.

The significant contributions of this thesis include: (i) an improved understanding of particle characteristics (PNSD and PM\textsubscript{2.5}) around building envelopes under the influence of vehicle emissions and nucleation events; (ii) an improved understanding of indoor particle characteristics and dynamics inside mechanically ventilated office buildings; (iii)
acknowledgement of the role of nucleation events in producing particles, and their influence on the urban environment (this is the first time that the effect of new particle formation on the vertical profiles of particle concentrations around building envelopes and PN concentration inside office buildings has been identified and quantified); (iv) the first multi-component model consisting of indoor PN and CO₂ concentration, thermal comfort and energy usage, which can be applied to optimise HVAC systems in mechanically ventilated office buildings; and finally (iv) provision of scientific and practical information on which to base the selection, location and operation of filters and outdoor air intakes in a building’s HVAC system, in order to optimise its operation, in terms of energy conservation and improvements in indoor environmental quality.
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LIST OF PUBLICATIONS


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STATEMENT OF ORIGINAL AUTHORSHIP

The work contained in this thesis has not been previously submitted for any degree at any university. To the best of my knowledge and belief, this thesis contains no material previously published or written by other person, except where due reference is appropriately made.

Sign: ..

Date: 01/11/2013
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1 General Introduction

1.1 Background and Motivation of the Study

In most urban environments, vehicle emissions and new particle formation are the dominant source of outdoor particles ((Perez et al., 2010; Pey et al., 2008; Shi et al., 2001; Shi and Harrison, 1999; Shi et al., 1999; Wahlina et al., 2001) and (Cheung et al., 2011; Cheung et al., 2012; Pey et al., 2009), respectively). Ambient air quality legislation regulates airborne particulate matter, in terms of particle mass concentration, expressed as PM$_{2.5}$ and PM$_{10}$ (mass concentrations of particles smaller than 2.5 $\mu$m and 10 $\mu$m respectively), and to date, these are also the most common parameters measured for research purposes. However, the majority of particles emitted by vehicles, in terms of number, belong to the ultrafine size range (UF < 0.1 $\mu$m). UF particles contribute very little to PM$_{2.5}$ and PM$_{10}$, but they contain the majority of toxins emitted by combustion sources. Epidemiological research has consistently shown an association between fine (< 2.5 $\mu$m; PM$_{2.5}$) particle concentrations and increases in both respiratory and cardiovascular morbidity and mortality (Davidson et al., 2005; Pope, 2000; Pope et al., 2004; Pope Iii C and et al., 2002; Schwartz and Neas, 2000). The health effects of UF particles are less well understood, thought recent research indicates that they may be equally or more detrimental than those of PM$_{2.5}$ and PM$_{10}$ (Franck et al., 2011; Oberdorster, 2000; Oberdörster et al., 2005; Oberdörster et al., 2004).

Significant population growth and urbanisation has been experienced by most large cities in the world, including capital cities in Australia, where population growth was by 17% between 2001 and 2011, faster than the remainder of Australia (11%) (Statistics, 2011). New approaches to land and urban planning are needed in order to accommodate significant population growth, however such approaches, which include transit oriented urban development, can increase the number of public and residential developments located close to transport corridors. Given that outdoor particles can penetrate the building envelope via doors,
windows, building structure leakages and mechanical ventilation systems, the exposure of building occupants to outdoor particles is on the rise.

In Australia, most public buildings are equipped with mechanical heating, ventilation and air conditioning (HVAC) systems. The function of these systems is to remove pollution generated indoors from the indoor environment, to filter outdoor air supplied to the building, and to provide the required thermal comfort conditions within the building. However, mechanical ventilation systems always require considerable amounts of energy to operate. Many efforts have been made to optimise building HVAC systems, but most studies have focused on indoor thermal comfort and energy consumption (e.g. Al-Sanea and Zedan (2008), Chowdhury et al. (2008), Freire et al. (2008), Taylor et al. (2008), Conceição et al. (2009)). Some studies also considered indoor air quality, but only indoor CO₂ concentration was taken into account (Atthajariyakul and Leephakpreeda, 2004; Congradac and Kulic, 2009; Kavgic et al., 2008; Mathews et al., 2001; Nassif et al., 2008; Wong et al., 2008a; Wong et al., 2008b).

An urban environment is characterised by the presence of a large number of roads, bordered on either side by buildings of various sizes. Changing building heights and small local structures in street canyons can generate very complex wind patterns and turbulence, which result in localised areas that experience low windflow. Vehicle movement, together with wind induced turbulence and efficient mixing, can lead to inconsistencies in the vertical profile of particle concentrations around building envelopes, which has been reported regularly in scientific literature.

The contribution of outdoor and indoor particle sources to the concentration of indoor particles varies and depends on many factors, including the type of particle source, the location of air intakes, air exchange rate in the building and the type of filters used. Besides dominant outdoor sources in the urban environment consisting of vehicle emissions and new particle formation, printing, vacuum cleaning, and occupants and their activities were recently
reported as the main sources of indoor particles in office buildings. Ventilation systems that utilise filter media can reduce indoor particle levels which originate from both outdoor and indoor sources. However, information on the impact of such systems on indoor particle concentration, especially fine and UF particles in office buildings, is very limited.

Given that fine and UF particles are ubiquitous, emitted from both indoor and outdoor sources and may lead to adverse health effects, they could be considered just as, or even more dangerous than many other indoor pollutants. However, due to a lack of information regarding the characteristics and dynamics of particles in and around office buildings, fine and UF particle concentrations have yet to be considered in the optimisation of building HVAC systems.

1.2 Overall Aims of the Study

The main goal of this research project was to develop a tool that will allow building designers and managers to maximise indoor environmental quality while minimising energy consumption to provide better indoor office environments in order to protect the health of building occupants within mechanically ventilated office buildings located in high outdoor particle concentration areas.

The overall aims of this study were to:

- Contribute to knowledge regarding the characteristics and dynamics of particles around building envelopes.
- Improve scientific understanding of the influence of ventilation/filtration on indoor particle concentration in office buildings, which use HVAC systems.
- Provide scientific and practical information for the design, upgrading and operation of building HVAC systems.

1.3 Specific Objectives of the Study

The following specific objectives were implemented to achieve the above study aims.
• Quantify and assess the vertical profiles of PNSD and PM$_{2.5}$ concentrations around three urban office buildings located close to busy roads in Brisbane, Australia.

• Quantify and assess the influence of ventilation/filtration on indoor particle concentrations in these buildings.

• Develop and apply a multi-component model to evaluate indoor air quality and energy consumption in mechanically ventilated office buildings.

1.4 Account of Scientific Progress Linking the Research Papers

This thesis is presented as a collection of three papers that have been published or submitted for publication in international peer-reviewed journals.

The first paper (chapter 3) focused on the investigation of factors that influenced outdoor particle concentration vertical profiles around urban office buildings. This study was conducted in three office buildings located close to busy traffic roads in Brisbane. The results showed that both PNSD and PM$_{2.5}$ concentration around building envelopes were not only influenced by vehicle emissions, but also by new particle formation. Interestingly, PN concentration in the size range < 30 nm and total PN concentration increased with increasing height up to 65% and 46%, respectively, during nucleation events. These findings highlight important new information in relation to the typically under-valued role of new particle formation in the urban atmosphere and its potential to affect large numbers of people, due to the high density and occupancy of urban office buildings, and the fact that the vast majority of people’s time is spent indoors. Therefore, it is important to consider the effects of these particles when selecting air intake locations and appropriate filter types during the design or upgrade of mechanical ventilation systems in urban office buildings.

The relationship between indoor and outdoor particle concentration in mechanically ventilated office buildings was discussed in the paper 2 (chapter 4). In this study, both experimental measurements and modelling were applied to evaluate the influence of ventilation/filtration on
indoor particle concentration. The results showed that the location of air intakes and the utilisation of filters in a building's HVAC system can have a strong influence on indoor particle concentrations. On the other hand, indoor PN concentration was found to be influenced not only by vehicle emissions, but also by new particle formation. This finding once again draws attention to the role of particle formation in the urban atmosphere and its potential effects on the health of building occupants, since they spend most of their daytime hours inside the office. An existing dynamic indoor PN concentration model was modified for the purpose of this study and its performance was evaluated. The 24 h modelling results showed that the model performed well when outdoor air was the main source of indoor particles, with less uncertainty in the presence of indoor source emissions, or when the ventilation system was turned off. The modelling results also revealed that using both mixing and outdoor air can significantly reduce the effect of high outdoor particle concentrations on indoor particle levels. This work provides a scientific basis for the selection and location of appropriate filters and outdoor air intakes, during the design of new, or upgrade of existing building HVAC systems. The results also serve to provide a better understanding of indoor particle dynamics and behaviours under different ventilation scenarios in office buildings.

The development of a multi-component model to optimise indoor environmental quality and energy consumption in mechanically ventilated office buildings was presented in the paper 3 (chapter 5). In this paper, the dynamic indoor particle concentration model from the second paper was combined with an indoor CO₂ mass balance model to provide a complete indoor air quality model. An energy model based on optimal outdoor air ventilation rate and optimal indoor temperature was also developed and combined with the previous models to give the final multi-component model, which was developed for the purpose of optimising indoor environmental quality and energy consumption in office buildings located close to areas with high outdoor particle concentrations.
Throughout this thesis, new information on the characteristics, dynamics and behaviour of particles in and around office buildings is reported, particularly in relation to the previously under-valued role of new particle formation in urban environments. For example, this study identified and quantified the influence of such nucleation events on particle concentrations around and inside office buildings, for the first time. In addition, the location of air intakes and the utilisation of filters in a building’s HVAC system were found to have a significant impact on indoor particle levels and the first multiple-component model for optimising indoor environmental quality and energy consumption of HVAC systems in office buildings was developed. The modelling results showed that building HVAC systems significantly improved indoor environmental quality and increased energy savings in office buildings when operated with both mixing and outdoor filters. Overall, the findings of this work have provided scientific and practical information on the selection, location and operation of filters and air intakes in a building’s HVAC system, for use when designing or upgrading the mechanical ventilation systems in urban office buildings. These results also serve to provide a better understanding of particle characteristics and behaviours both in and around office buildings, which have implications for studies of both human exposure and aerosol particle science.

1.5 References


2 Literature Review

2.1 Introduction

This part of the thesis reviews literature related to the subject of this research and contains five separate parts. The first part presents a discussion of outdoor particles around building envelopes and their penetration inside buildings. The second part discusses the dynamics of indoor particles and issues related to their models. The third part relates to indoor thermal comfort. While issues related to energy consumption and conservation, and the optimisation of a building’s HVAC system are discussed in part four. In the fifth and final part of this review, gaps in the existing knowledge base are explored.

2.2 Vertical profile of outdoor particles around urban office building envelopes

Ambient particles in urban environments are mainly contributed by vehicle emissions (Perez et al., 2010; Pey et al., 2008; Shi et al., 2001; Shi and Harrison, 1999; Shi et al., 1999; Wahlina et al., 2001) and nucleation events (Pey et al., 2009). In terms of number, these particles generally belong in the ultrafine size range (< 0.1 µm). Ultrafine particles (UFP) contribute very little to PM$_{2.5}$ and PM$_{10}$, however they contain the majority of toxins emitted by combustion sources (Morawska et al., 2008).

An urban environment is characterised by a large number of streets bordered on either side by buildings of various sizes. Changing building heights and small local structures in street canyons can generate very complex wind patterns and turbulence, which result in some localised areas experiencing low wind-flow. Furthermore, vehicle movement and wind can induce turbulence, thus leading to efficient mixing, which has the potential to influence particle concentrations at different heights (Morawska and Salthammer, 2003).

Outdoor particles can penetrate inside the building via doors, windows, building structure leakages, and especially via mechanical ventilation systems. Therefore, it is important to understand the vertical profiles, concentrations and dynamics of particles around the
envelope, in order to locate the optimal position for outdoor air intakes and best mitigate the penetration of particles indoors. Moreover, such information is relevant to developing a better understanding of the complex nature of particles in urban street canyons and their relationship to pedestrian exposure at ground level. The reviews outlined below summarise the results of experimental studies on particle concentrations around building envelopes.

TSP concentrations were measured at heights of 5, 15 and 35 ft in Houston, Texas, US by Bullin et al. (1985). The results showed that vertical TSP was nearly flat and very strong vertical mixing occurred due to large vertical wind speeds. Horvath et al. (1988) measured diesel particles using the tracer method at street and rooftop levels (27 m higher) in Vienna, Austria and reported that the diesel mass concentration at 27 m was 83% of the street value.

Vertical profiles of PM$_{2.5}$ and PM$_{10}$ up to 2.88 m above street level were quantified by Micallef and Colls (1998) in London, UK. The results showed that PM$_{2.5}$ and PM$_{10}$ concentrations at a height of 0.81 m were 12% and 35% higher than those at 2.88 m, respectively. In a research conducted by Rubino et al. (1998), the vertical profile of PM$_{10}$ emitted from motor vehicles was also investigated. The measurements were conducted at different heights, upwind and downwind of the surrounding envelopes of an office building within the city centre of Milan. The building was 100m high and located in an open square with high traffic densities in the surrounding streets. The result showed a steady decrease in PM$_{10}$ concentration with increasing height.

Chen and Mao (1998) investigated TSP and PM$_{10}$ concentrations beside open windows on the 2$^{nd}$ (3.5 m), 7$^{th}$ (24.5 m) and 14$^{th}$ (49 m) floors of a building in Taipei, Taiwan. The highest concentration was found on the 2$^{nd}$ floor, which sharply decreased on the 7$^{th}$ floor and remained at similar levels up to the 14$^{th}$ floor. In a later study by Chan and Kwok (2000), the vertical concentration gradients of TSP, PM$_{10}$ and PM$_{2.5}$ were investigated by measurements conducted on the face of four buildings in Hong Kong, with different surroundings, including
street canyons and open streets. Different vertical concentration gradients were observed for each of the different surroundings. For example, for the buildings adjacent to a street canyon, decreases in particle concentration were found to be exponential with increasing height, however the coefficient of exponential decrease differed between the two street canyon sites, and also differed in relation to particle mass fractions.

Recently, Kalaiarasan et al. (2009) measured PM$_{2.5}$ concentration levels at various heights out the front of two high-rise buildings in Singapore. These buildings were located in close proximity, within 30 m, and along a busy major expressway. Particle samples were collected at three representative levels: the lower, middle and upper levels of the buildings. Experimental results showed that PM$_{2.5}$ concentration was highest at the middle level of both buildings when compared to those measured at the upper and lower levels during typical days.

The influence of vehicle emissions from a freeway on particle number (PN) concentration around 3 high-rise buildings in Brisbane, Australia was investigated by Morawska et al. (1999). Two of these buildings were located relatively far from the freeway (80 and 210 m, respectively), while the other was a lot closer (15 m). The investigations showed that PN concentrations at different heights were not significantly different at the buildings far away from the main road. However, PN concentrations around the building envelope that was close to the main road were much higher than those in the immediate vicinity of the road.

Väkevä et al. (1999) monitored particle number concentrations at street and rooftop levels in Lahti, Finland. The authors used two instruments for the study: a TSI ultrafine condensation particle counter (UCPC) for measurements at street level at a height of 1.5 m, and a TSI condensation particle counter (CPC) for rooftop measurements at height of approximately 25 m. The concentrations measured at different heights by the two instruments were found to be well correlated, while the absolute values differed significantly from each other. The mean
concentration measured by the UCPC at 1.5 m and by the CPC at 25 m was $3.9 \times 10^4$ and $1.08 \times 10^4$ p cm$^3$, respectively.

The vertical profiles of concentrations of sub-micrometer particles for three high-rise buildings in Brisbane, Australia were investigated by Hitchins et al. (2002). The results showed that there was a clear decrease in concentration with height when measurements were conducted at the front of the buildings (facing the street), which were located 5, 15 and 80 m from a major road. The PN concentrations decreased by around 50 to 60% between ground level and rooftop level. Measurement made at the side and the rear of one building showed a 140% increase in concentration at a height of 80 m compared to the ground level.

Longley et al. (2004) measured total PN concentrations at different heights in an asymmetric street canyon with busy one-way traffic in central Manchester, UK. Total PN concentrations at 17 m were generally half of those at 4 m during the day and the gradient was reduced significantly at night. Similarly, Li et al. (2007) also measured total PN concentrations at different heights in an asymmetric street canyon in Shanghai, China, and showed that PN concentrations decreased by 72% and 85% at a height of 38 m compared to those at 1.5 m when the wind blew perpendicularly and parallel to the street canyon, respectively. Furthermore, PN concentrations were measured at street and rooftop levels in a street canyon in Cambridge, UK (Kumar et al., 2009). The study reported that street PN concentrations were about 6.5 times higher than those at rooftop level.

Besides vehicle emissions, the influence of photochemical aerosol particle formation from local vehicle emissions on the vertical profile of PN concentrations is also of significance. For example, Vakeva et al. (1999) reported that new particle production via photochemical nucleation is stronger at rooftop level than at street level, as a result of two factors: (i) the concentrations of condensable gases are higher and (ii) the concentrations of pre-existing particles are smaller at rooftop level compared to street level. Using the ratios of PN
concentrations in the size range \(< 30\) nm and \(30 – 300\) nm (N\(_{<30}\)/N\(_{30-300}\)) to indicate the rate of production of new particles, Kumar et al. (2009) also reported that the production of nucleation mode particles at rooftop level was stronger than at street level. Clement et al. (2001) and Boy and Kulmala (2002) suggested that high solar radiation and low existing particle concentration are necessary for new particle formation, an hypothesis that is supported by the findings of the two previous studies.

A relationship between PN and particle mass concentrations has also been reported for urban background sites, as well as in street canyons. During a study of the physical properties of particles in the atmosphere of a UK urban area, Harrison et al. (1999) found a significant linear correlation between PN and PM\(_{10}\) concentrations at an urban background location \((r^2 = 0.44; \ n = 44\) for 24 h data). In another study in a busy street canyon in Manchester, UK, Longley et al. (2003) determined that the linear correlation \((r^2)\) between ultrafine PN and PM\(_{2.5}\) concentrations was 0.51.

2.3 Indoor particles and their affected factors in office buildings

2.3.1 Penetration of outdoor particles

The high concentration of outdoor particles around building envelopes can penetrate inside via both controlled (air intakes) and uncontrolled ventilation (doors, windows and air leakage through the building envelope). In a study conducted in an office building in Helsinki, Finland, Koponen et al. (2001) found that outdoor particles were the main source of indoor particles when the building's ventilation system was turned both on and off. Morawska et al. (2009) found that indoor PN and PM\(_{2.5}\) concentrations were governed by outdoor air and were significantly affected by the location of the HVAC system's air intakes. The outdoor PN and PM\(_{2.5}\) concentrations measured near the air intake were reduced by 35% and 55%, respectively, by relocating the intakes from street level to rooftop level.
### 2.3.2 Indoor particle sources

Indoor particle concentration is governed by the temporal and spatial variation of indoor sources and sinks, as well as indoor activities. In a study conducted in four houses in Boston, USA, Abt et al. (2000a) identified that the movement of people was one of the most important indoor sources, and strongly contributed to indoor particle mass in the range 0.7 to 10 µm. They also quantified the source emission rate due to building occupant movement, which was found to be $16.26 \pm 3.67 \, \mu m^3 \, cm^{-3} \, h^{-1}$, and was comparable to other indoor sources, such as cooking and cleaning (Abt et al., 2000b).

In another study conducted at 9 houses in Boston, USA, Long et al. (2000) quantified the emission rate of vigorous walking and vacuuming, and determined their contribution to coarse (PM$_{10}$), fine (PM$_{2.5}$) and ultrafine (PM$_{0.1}$) particle fractions. The results showed that both activities mainly emitted particles in the size ranges of 0.7 to 10 µm. In relation to vacuum emissions, Corsi et al. (2008) reported that vacuum cleaning significantly contributed to coarse particle concentration but not fine particle mass. More recently, vacuum cleaning has been found to not only increase fine and coarse particle mass concentrations, but it also generates a large amount of UFPs, in terms of number concentration. PN emission rates from vacuum cleaners ranged from $4.0 \times 10^6$ to $1.1 \times 10^{11}$ p min$^{-1}$, while PM$_{2.5}$ emissions were between $2.4 \times 10^{-1}$ and $5.4 \times 10^3 \mu g \, m^{-3}$ (Knibbs et al., 2011).

Many studies have also reported that laser printers make a significant contribution to indoor particle levels, especially in office buildings where laser printers are widely used nowadays, including He et al (2007), Schipp et al. (2008), Morawska et al. (2009a), He et al. (2010) and Mc Garry et al. (2011). In particular, He et al. (2007) investigated indoor air quality in a large open-plan office and found that the particles generated from printers significantly influenced indoor submicron particle number concentrations. Based on measurements of particle concentrations in the immediate vicinity of the printers after a short printing job, the printers were classified into four classes: non-emitter, low-emitter, medium-emitter and high-emitter.
In addition, the emission rates of the low, medium and high-emitters were tested in a chamber and quantified as $9.54 \times 10^9$ p min$^{-1}$, $92.8 \times 10^9$ p min$^{-1}$ and $159 \times 10^9$ p min$^{-1}$, respectively, for 50% of toner coverage.

Moulds are another indoor particle source and numerous health consequences have been reported as a result of human exposure to these particles (Cummings et al., 2008; Ratard et al., 2006). The causes of mould growth in buildings include inadequate ventilation, poor maintenance, water intrusion and the use of HVAC systems (Kemp et al., 2003).

Furthermore, VOCs can react with ozone to form secondary organic aerosols, which is a potentially large source of indoor particles that are harmful to human health (Waring et al., 2010). The main sources of VOCs in office buildings are building materials, ventilation systems, and occupants and their activities (Zuraiemi et al., 2004). Ongwandee et al. (2011) have reported that some VOC concentrations inside office buildings have risen due to low ventilation rates and the tightening of buildings.

2.3.3 Influencing factors

2.3.3.1 Ventilation/Filtration

Morawska and Salthammer (2003) and Nazaroff (2004) reported that indoor particle concentration was influenced by building ventilation systems, in particular, their outdoor ventilation rate and filtration. Regarding the influence of filtration on indoor particle concentration, Fisk et al. (2000) reported that the utilisation of air filters can significantly reduce indoor number concentration of submicron (from 0.3 to > 5 µm) particles, particularly high efficiency filters, which can dramatically reduce I/O particle concentration ratios by up to 95%.

Four types of filters, including pre-filters, cartridge filters, deep bag filters and HEPA filters were tested in a commercial building by Lam et al. (2006). In order to achieve an ultra low respirable suspended particle (RSP) level of less than 20 µg m$^{-3}$, it suggested removing RSPs.
simultaneously from both the return air and outdoor air supply using a filter with an efficiency that exceeds 80%. It also showed that outdoor air filtration had a significant influence on the steady state indoor RSP concentration when the effective cleaning rate was governed by the return air filter. They also found that higher efficiency filters increased the static drop of the air fan.

To assess the impact of different filters on indoor submicron (from 0.3 to > 5 µm) particle concentration in an office building, Zuraimi and Tham (2009) compared the efficiency of media and electrostatic filters, as well as a combination of the two, where the media filter worked as a pre-filter on the electrostatic filter. The results showed that the efficiency of the electrostatic filter was significantly higher than the media filter for cleaning fine particles, and the use of combination filters significantly enhanced overall efficiency compared to the use of the electrostatic filter alone.

Based on the investigation of indoor PN and PM$_{2.5}$ concentrations in a radio station surrounded by busy roads, Morawska et al. (2009b) reported that the redesign of the HVAC system, including the installation of a pre-filter section (on the rooftop air intake) and the upgrade of the air filter section of the AHU, can increase the overall efficiency of the system in removing particles from approximately 58% to 86%. In order to evaluate the influence of filtration and ventilation on the reduction of indoor submicron particle concentrations, Jamriska et al. (2000) measured PN concentrations up-stream and down-stream of the air-handling system, consisting of deep bag filters and air-conditioning unit, and reported that the average overall filtration efficiency of the air-handling system was approximately 34%.

Hanley et al. (1994) conducted fractional efficiency tests for different filter types in the laboratory, including deep bag (pocket) and electrostatic (electronic air cleaner) filters. The tested size ranges ranged from 0.01 to 3 µm. The results showed that the fractional efficiency was highly particle size dependent, and the efficiency increased for larger and smaller
particles. The increase in efficiency for large particles was due to an increase in the effectiveness of the filtration processes for collecting particles via the physical mechanisms of inertial impaction and interception. On the other hand, the increase in efficiency for smaller particles resulted from diffusion process. Increases in the fractional efficiency of both deep bag and electrostatic filters were found when dust-loading increased. Another electrostatic filter efficiency test was conducted under laboratory conditions by Jamriska et al. (1998). The fractional efficiency showed a maximum for particles in the size range 40 to 50 nm, with a large drop in the filtration efficiency below 30 nm and a steady decrease for particles larger than 60 nm.

2.3.3.2 Deposition

The process of particle deposition has a very important influence indoor particle fate and concentration. The sink of indoor particles on any indoor surface can significantly reduce airborne particle levels. Many studies have investigated indoor particle deposition, however most of them focused on residential houses (Abt et al., 2000b; He et al., 2005; Long et al., 2001; Thatcher et al., 2002; Thatcher and Layton, 1995) or naturally ventilated office buildings (Smolík et al., 2005). Of relevance to air-conditioned office buildings was the calculation of overall loss rate based on the effect of surface deposition and coagulation by Jamriska et al. (2000).

2.3.3.3 Infiltration

In mechanically ventilated buildings, outdoor air can be introduced indoors by fans (ventilation) and it can also penetrate indoors via building envelopes, doors and windows. The penetration of outdoor air can change the buildings air exchange rate, which not only has an impact on the buildings energy consumption, but also on indoor air quality, including indoor particle concentration. Therefore, it is important to understand and quantify this phenomenon. Based on laboratory-based experiments, Liu and Nazaroff (2003) quantified penetration factors through cracks and gaps for seven different building materials: aluminium, brick,
concrete, plywood, redwood lumber, pine lumber, and strand board. The penetration was measured for particle size range of 0.02 to 7 µm under two pressure differences of 4 and 10 Pa. Two crack heights of 0.25 and 1 mm, and two crack lengths of 4.3 and 8.9 cm were experimented for aluminium cracks.

2.3.4 Modelling

In order to simulate and predict indoor particle concentration levels, various mathematical models have been developed, ranging from simple to sophisticated, single zone to multi zone, micro-environment to macro-environment, and static to dynamic models. For example, Fisk et al. (2000) and Zuraimi and Tham (2009) applied a static particle mass balance model to assess the influence of ventilation and filtration on indoor submicron particle mass concentration. Fisk et al. denoted that the model provided evidence of significant indoor generation or re-suspension of particles larger than 1 µm, while Zuraimi and Tham found that the effectiveness of electrostatic filters improved as recirculation rate increased.

Jamriska et al. (2000) built a single zone mathematical model, based on a particle number balance equation, to predict both the evolution of total particle number concentration and particle size distribution in a mechanically ventilated office building. In this model, some effect factors were excluded, such as coagulation, condensation and deposition. Later, a dynamic single zone mathematical model was developed to investigate the effect of air ventilation and filtration on sub-micrometer particle concentration in a hypothetical building (Jamriska et al., 2003). This model also assumed that the flow rates of outdoor air and return air were invariant when the ventilation system was operated.

A number balance model was also developed by Matson (2005) to predict variations in PN concentrations in size ranges from 0.01 to larger than 1 µm inside a building. The model did not take into account the influence of the filtration and indoor sources. However, this study suggested the ventilation operated with lower air change rates to decrease indoor PN concentration when outdoor particle concentrations were relatively high.
Several multi-zone models have also been developed to date. For example, Miller and Nazaroff (2001) applied material-balance models that incorporated both a multi-zone representation of the indoor environment and a time-/size-resolved prediction of concentration of environmental tobacco smoke particle in multi-zone environments. Nazaroff and Cass (1989) also developed a general mathematical model to predict the concentration and fate of particulate matter (PM) in indoor air. The model accounted for the effects of ventilation, filtration, deposition, direct emission and coagulation. It was a sophisticated model that required a lot of work to validate. In addition, Li et al. (2008) presented a state-space model to predict the concentration and the fate of PM in the indoor air of a multi-zone building. The ordinary differential equations used to describe the dynamic behaviour of PM were expressed as a state equation by introducing vector-matrix notation.

Besides macro models, several micro models, mainly based on computational fluid dynamics (CFD) techniques, were also developed. Zhao and Wu (2009) built a model, called the particle filter group model, to simulate particle fate in ventilation systems. The model took into account the interactions between particle transport in ventilation ducts and rooms and particle spatial distribution. The CFD technique was applied to predict particle fate in the ventilation room. Similarly, Zhao et al. (2009) used an improved drift flux (CFD) model to analyse the dispersion of different sized UFPs in two typical indoor environments that where equipped with mixing and displacement ventilation systems, respectively. Bolster and Linden (2009) also used reduced analytical integral models and a numerical model to compare contaminant transport in a traditional “mixing” system with two low-energy displacement ventilation models.

Several models were developed to predict particle concentration indoor. Some of the models were simple, however major factors influenced indoor particles were usually not taken into account. On the other hand, some of them were complex and requested massive information for their input data and validation.
In order to assess the performance of indoor air quality (IAQ) models, quantitative and qualitative tools are provided by ASTM Standard D5157 (ASTM-1997, 2008). The statistical tools used for evaluating the accuracy of the model predictions include: (i) the correlation coefficient of predictions compared to measurements (r), for which the value should be 0.9 or greater; (ii) the line of regression between the predictions and measurements, which should have a slope (b) between 0.75 and 1.25, and an intercept (a) less than 25% of the average measured concentration; and (iii) the normalised mean square error (NMSE), for which the value should be less than 0.25. At the same time, the bias of the model was measured based on (i) normalised fractional bias of the mean concentration (FB), for which the value should be 0.25 or lower; and (ii) fractional bias based on the variance (FS), for which the value should be 0.5 or lower. These indicators were applied to evaluate an experimental model that used to predict PN concentrations in a single-zone residential house (Emmerich and Nabinger, 2001).

2.4 Indoor thermal comfort

2.4.1 Main indoor thermal comfort parameters

According to Auliciems and Szokolay (1997), a person’s thermal comfort levels are affected by a number of variables, which can be grouped into three main sets: environmental (including air temperature, air movement, humidity, radiation), personal (including metabolic or activity rate, clothing) and contributing factors (including food and drink, acclimatisation, body shape, subcutaneous fat, age and gender). Of these, air temperature is considered to be the most important environmental factor.

2.4.2 Optimal temperature in office buildings

Niemela et al. (2002a) reported that thermal neutrality in call centre’s in Finland was estimated to range from 21 to 25 °C in summer, and labour productivity in the call centre decreased by 5-7 % when the air temperature exceeded 25 °C. In addition, the authors reported that productivity increased when indoor temperature rose from 11 °C to 15 – 18 °C,
combined with a reduction in contamination and better lighting conditions (Niemelä et al., 2002b).

In research conducted in Brisbane, de Dear and Auliciems (1985) observed and predicted neutral temperatures in air-conditioned commercial buildings during the summer. Observed neutral temperature was determined based on a seven-point voting scale using the probit regression technique. On the other hand, predicted neutral temperature was calculated based on the predicted mean vote (PMV) model, by iterating the PMV program while increasing or decreasing the operating temperature by 0.1 °C towards the point of neutrality until PMV equalled zero. The observed and predicted neutral temperatures were 23.8 °C and 25.1 °C, respectively.

Similarly, a thermal comfort study conducted in the San Francisco Bay Area, USA also indicated that observed neutral temperatures were lower than predicted ones in both winter (22.0 °C vs. 24.4 °C) and summer (22.6 °C vs. 25 °C) (Schiller, 1990). Another study conducted in Townville’s air-conditioned office buildings reported that observed neutral temperatures were about 24.2 °C and 24.6 °C during the dry and wet season, respectively. In addition, the observed neutral temperature in Darwin office buildings ranged from 23.9 °C to 24.2 °C, depending on the season (Auliciems and de Dear, 1986).

2.5 Optimisation of a building’s HVAC system

Due to the finite supply of energy and recent discoveries in relation to climate change, the conservation of energy is attracting a lot of attention worldwide. Regarding to this issue, many studies have been conducted in order to help improve energy savings in the building sector, especially in HVAC buildings. However, these studies mainly focused on energy consumption and indoor thermal comfort (e.g. Al-Sanea and Zedan (2008), Chowdhury et al. (2008), Freire et al. (2008), Taylor et al. (2008), Conceição et al. (2009)), with only a handful using indoor CO₂ concentration as an indoor air quality indicator.
Energy consumption in air-conditioned office buildings is significantly impacted by efforts to maintain low indoor CO₂ concentrations. In a study of the relationship between energy consumption and indoor air quality in air-conditioned offices, Wong et al. (2008) found that when indoor CO₂ concentration increased from 1000 ppm to 1200 ppm, the percentage of thermal energy savings was about 30%. In contrast, an additional 56% of thermal energy would be required to reduce indoor CO₂ concentration to 800 ppm. Mathews et al. (2001) used CO₂ concentration as an indicator when simulating the control of fully integrated building HVAC systems. In this study, the authors used a recommended indoor CO₂ level of 900 ppm and CO₂ control was expected to have a small effect on the energy efficiency of the building. Congradać and Kulic (2009) also conducted a simulation to demonstrate the energy savings that can be made when using CO₂ concentration as a control in a standard HVAC system. The results showed that energy savings were higher when a higher indoor CO₂ concentration was used.

In summary, higher indoor CO₂ concentrations were used in many HVAC control systems, in order to save energy in air-conditioned office buildings. However, recent studies have shown that high indoor CO₂ can significantly affect the health and performance of the buildings’ occupants. For example, in a study on the symptoms and productivity losses related to Sick Building Syndrome in an air-conditioned office space, Wargocki et al. (2000) reported that increasing the ventilation rate resulted in a lower percentage of subjects who were dissatisfied with the air quality, as well as those who experienced the sensation of dryness of mouth and throat. Wargocki (2004) also found that increasing outdoor air supply rate and replacing filters had positive effects on the health, comfort and performance of the building’s occupants.

A study on the effects of temperature and outdoor air ventilation rate on the performance of call centre operators was conducted by Tham (2004). The results showed that performance significantly improved when both outdoor ventilation rate and indoor temperatures were either higher or lower. Seppanen et al. (2006) also quantified the relationship between work
performance and outdoor ventilation rates. The results showed a 1-3% improvement in average performance per 10 l s\(^{-1}\) person\(^{-1}\) increase in outdoor ventilation rate. The rate of increase in performance was faster when the ventilation rate was lower than 20 l s\(^{-1}\) person\(^{-1}\), but was not significant when the ventilation rate was over 45 l s\(^{-1}\) person\(^{-1}\).

Fisk et al. (2004) estimated the health, energy and economic benefits of an economiser ventilation system that increased outdoor air ventilation rate during more mild weather. The study showed that increasing outdoor air supply not only resulted in energy savings due to free cooling, but it also led to a reduction in sick leave, the estimated value of which was significantly higher than the estimated reductions in cost due to energy savings.

2.6 Gaps in Knowledge and Recommendations for Future Research

2.6.1 Particle concentrations around building envelopes

- Inconsistent findings of vertical profiles of particle mass concentrations around building envelopes. Some research concluded that concentrations decreased with increasing height, including Horvath et al. (1988), who showed that diesel particle mass concentration decreased by 17% at 27 m compared to street level. Micallef and Colls (1998) found that PM\(_{10}\) and total suspended particle (TSP) concentrations at a height of 0.8 m above the ground floor were about 35% higher than those at a height of 2.9 m, while Rubino et al. (1998) reported a decrease in the concentrations of PM\(_{10}\) with increasing height, and the concentration on the leeward side of the building was consistently lower than on the windward side. Chan and Kwok (2000) also found that the relationship between decreases in particle mass concentrations and height was exponential in a street canyon and linear for open sites. However, other studies have shown a decrease in particle mass concentrations up to certain heights, with concentrations remaining somewhat constant beyond that. In particular, Chen and Mao (1998) reported that PM\(_{10}\) concentrations on the seventh and fourteenth floors were comparable, after sharply decreasing from the second floor to the seventh floor.
Additionally, Kalaiarasan et al. (2009) found that PM$_{2.5}$ concentrations were highest around the middle floors when compared to those measured at the upper and lower floor of high-rise buildings. In contrast, Bullin et al. (1985) reported a vertical TSP profile that was nearly flat.

- **Limitations of PN studies, and a lack of studies on PNSD vertical profiles.** In contrast to particle mass, only a handful studies have measured PN concentrations around the building envelope. Vakeva et al. (1999) monitored PN concentrations at street and rooftop levels, and showed that the concentrations at 1.5 m were significantly higher than those at 25 m. Hitchins et al. (2002) also observed a decrease in PN concentrations with height when measured at the front of a high rise building 80 m from road, but the opposite was true when PN concentrations were measured at the rear of the building. Longley et al. (2004) noted that total number concentrations at 17 m were generally half of those measured at 4 m during the day, and the gradient was reduced significantly at night when measurements were conducted in an asymmetric street canyon. Similarly, Kumar et al. (2009) found that PN concentrations at street level (0.2-2.6 m high) were about 6.5 times higher than those at rooftop level (20 m). Other research conducted by Li et al. (2007) showed that PN concentrations decreased by 72 % and 85 % at a height of 38 m compared to 1.5 m, when the wind blew parallel and perpendicular the street canyon, respectively.

- **Limited understanding on the influence of new particle formation on particle concentration vertical profiles.** Vakeva et al. (1999), Li et al. (2007) and Kumar et al. (2009) discussed the influence of photochemical aerosol particle formation relative to local vehicle emissions on the vertical profile of PN concentrations. However, local emissions are not the only thing can influence new particle formation in urban areas, and it is also important to consider wind direction and air masses from different
regions (Stanier et al., 2004; Qian et al., 2007; Hussein et al., 2008; Salma et al., 2011; Cheung et al., 2011).

- **Lack of information on the correlation of PNSD and PM$_{2.5}$ around building envelopes.** A relationship between PN and particle mass concentrations has been reported for urban background sites, as well as street canyons. For example, Harrison et al. (1999) found a significant linear correlation between PN and PM$_{10}$ concentrations at an urban background location ($R^2 = 0.44$). Similarly, Longley et al. (2003) determined that the linear correlation ($R^2$) between ultrafine PN and PM$_{2.5}$ concentrations in a street canyon was 0.51. However, there may be a difference in correlations between PNSD and particle mass concentration around a building envelope, due to the influence of a number of factors, such as emission sources, building height and particularly, the difference in particle size ranges.

### 2.6.2 Particles and related issues in office buildings

- **Limited understanding on the influence of ventilation/filtration on indoor particle dynamics in office buildings.** Not many studies on the influence of ventilation/filtration on indoor particle dynamics in air-conditioned office buildings.

- **Limited information on in-situ filter efficiency.** Several studies have quantified the efficiency of dry-media and electrostatic filters used in mechanically ventilated office buildings, but they mainly focused on particles in the size range > 300 nm (Fisk et al., 2000; Zuraimi and Tham, 2009). Others studied UFPs but their investigations were conducted in laboratories, not on real-world buildings (Hanley et al., 1994; Jamriska et al., 1998).

- **No information on the influence of new particle formation on indoor particle concentrations.**
2.6.3 Relationship between indoor particle concentrations, thermal comfort and energy consumption within office buildings

- Limited studies on the optimisation of both indoor air quality and thermal comfort, in conjunction with energy consumption.
- To date, no studies have considered particle concentration or both particle and CO₂ concentration as indicators when investigating the optimisation of building HVAC systems for thermal comfort and energy consumption.

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Vertical Particle Concentration Profiles around Urban Office Buildings

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3 Vertical Particle Concentration Profiles around Urban Office Buildings

Abstract

Despite its role in determining both indoor and outdoor human exposure to anthropogenic particles, there is limited information describing vertical profiles of particle concentrations in urban environments, especially for ultrafine particles. Furthermore, the results of the few studies performed have been inconsistent. As such, this study aimed to assess the influence of vehicle emissions and nucleation formation on particle characteristics (particle number size distribution - PNSD and PM$_{2.5}$ concentration) at different heights around three urban office buildings located next to busy roads in Brisbane, Australia, and place these results in the broader context of the existing literature. Two sets of instruments were used to simultaneously measure PNSD, particle number (PN) and PM$_{2.5}$ concentrations, respectively, for up to three weeks at each building.

The results showed that both PNSD and PM$_{2.5}$ concentration around building envelopes were influenced by vehicle emissions and new particle formation, and that they exhibited variability across the three different office buildings. During nucleation events, PN concentration in size range of < 30 nm and total PN concentration increased (7 – 65% and 5 – 46%, respectively), while PM$_{2.5}$ concentration decreased (36 – 52%) with height.

This study has shown an under acknowledged role for nucleation in producing particles that can affect large numbers of people, due to the high density and occupancy of urban office buildings and the fact that the vast majority of people’s time is spent indoors. These findings highlight important new information related to the previously overlooked role of particle formation in the urban atmosphere and its potential effects on selection of air intake locations and appropriate filter types when designing or upgrading mechanical ventilation systems in urban office buildings. The results also serve to better define particle behaviour and
variability around building envelopes, which has implications for studies of both human exposure and particle dynamics.

*Keywords*: Ultrafine particle, particle number size distribution, particle number, PM$_{2.5}$, building envelope.

### 3.1 Introduction

Epidemiological research has consistently shown an association between fine (< 2.5 µm; PM$_{2.5}$) particle concentrations and increases in both respiratory and cardiovascular morbidity and mortality (Pope, 2000; Davidson et al., 2005; Schwartz and Neas, 2000). The health effects of ultrafine (< 0.1 µm) particles are less well known, however research to date indicates that they may be equally or more detrimental than those of PM$_{2.5}$ and PM$_{10}$ (Oberdorster, 2000; Franck et al., 2011).

Ultrafine particles make only a minor contribution to particle mass, but often constitute up to ~90% of particle number (PN), with these figures being reversed for fine particles (Morawska et al., 2008). The amount of fine and ultrafine particles in the urban atmosphere is mainly influenced by vehicle exhaust emissions during the traffic peak hours (Pey et al., 2008; Perez et al., 2010) and new particle formation by photochemical reactions (Pey et al., 2009).

Outdoor particles can penetrate the building envelope via doors, windows, building structure leakages, and especially via mechanical ventilation systems. It is therefore important to understand the vertical profiles, concentrations and dynamics of particles around the envelope in order to locate the optimal position for outdoor air intakes, and best mitigate the penetration of particles indoors. Moreover, such information is relevant to developing a better understanding of the complex nature of particles in urban street canyons and their relationship to pedestrian exposure at ground level.
To-date, studies investigating vertical profiles of particle mass concentrations around building envelopes has yielded inconsistent findings. Some research concluded that concentrations decreased with increasing height, including Horvath et al. (1988) who showed that diesel particle mass concentration decreased by 17% at 27 m compared to street level. Micallef and Colls (1998) found that PM\textsubscript{10} and total suspended particle (TSP) concentrations at a height of 0.8 m above the ground floor were about 35% higher than those at a height of 2.9 m, while Rubino et al. (1998) reported a decrease in the concentrations of PM\textsubscript{10} with increasing height, and the concentration on the leeward side of the building was consistently lower than on the windward side. Chan and Kwok (2000) also found that the relationship between decreases in particle mass concentrations and height was exponential in a street canyon and linear for open sites. However, other studies have shown a decrease in particle mass concentrations to certain heights, with concentrations remaining somewhat constant beyond that. In particular, Chen and Mao (1998) reported that the PM\textsubscript{10} concentrations on the seventh and fourteenth floors were comparable, after sharply decreasing from the second floor to the seventh floor. Additionally, Kalaiarasan et al. (2009) found that PM\textsubscript{2.5} concentrations were highest around the mid-floors when compared to those measured at the upper and lower floor of high-rise buildings. Bullin et al. (1985) reported a vertical TSP profile was nearly flat.

In contrast to particle mass, only a handful studies have measured PN concentrations around the building envelope. Vakeva et al. (1999) monitored PN concentrations at street and rooftop levels, and showed that the concentrations at 1.5 m were significantly higher than those at 25 m. Hitchins et al. (2002) also observed a decrease in PN concentrations with height when measured at the front of a high rise building 80 m from road, but this was the opposite when measured at the rear of this building. Longley et al. (2004) noted that total number concentrations at 17 m were generally half of those at 4 m during the day and the gradient was reduced significantly at night when measurements were conducted in an asymmetric street canyon. Similarly, Kumar et al. (2009) found that PN concentrations at street level (0.2-2.6 m
high) were about 6.5 times higher than those at rooftop height (20 m). Other research conducted by Li et al. (2007) showed that PN concentrations decreased by 72 % and 85 % at a height of 38 m compared to that at 1.5 m when the wind blew parallel and perpendicularly the street canyon. Vakeva et al. (1999), Li et al. (2007) and Kumar et al. (2009) also discussed the influence of the photochemical aerosol particle formation relative to local vehicle emissions on vertical profile of PN concentrations. However, not only the local emissions but also other air mass from different regions, travelling with the wind direction can influence new particle formation in urban areas (Stanier et al., 2004; Qian et al., 2007; Hussein et al., 2008; Salma et al., 2011; Cheung et al., 2011).

In addition to research surrounding building envelopes, some studies have quantified the vertical profiles of particle concentrations in urban areas. Imhof et al. (2005) has shown that PN concentrations 60 m downwind of a highway decreased when measured at heights of 5 – 30 m. Zhu and Hinds (2005) quantified the vertical particle concentrations measured 50 m downwind of an elevated highway and reported that the PN concentrations increased within the first 5m from the ground, then decreased at higher levels. He and Dhaniyala (2012) measured vertical profiles of PN concentrations at heights between 0.55 to 10 m at distances 15, 50, and 100 m from a highway. Their results have shown that vertical profiles of particle concentrations vary with wind speed, direction and distance from the highway.

A relationship between PN and particle mass concentrations has also been reported for urban background sites, as well as in street canyons. For example, Harrison et al. (1999) found a significant linear correlation between PN and PM\textsubscript{10} concentrations at an urban background location ($R^2 = 0.44$). Similarly, Longley et al. (2003) determined that the linear correlation ($R^2$) between ultrafine PN and PM\textsubscript{2.5} concentrations in a street canyon was 0.51. However, there may be a difference in correlations between particle number size distribution (PNSD) and particle mass concentration around a building envelope due to the influence of different
factors, such as emission sources, building height, and especially, the difference in particle size ranges.

Due to the inconsistent findings of previous studies, there is a lack of clear knowledge regarding PNSD, the factors affecting it, and its relationship with particle mass. The characteristics, variability and role of particle vertical profiles in both indoor and outdoor human exposure in and around urban buildings remains poorly understood. To contribute towards addressing these knowledge gaps and inform the limited experimental evidence base currently underlying numerous modelling studies, we aimed to: (1) assess the variation of PNSD, PN and PM$_{2.5}$ concentrations by simultaneous measurements at the rooftop and street levels of three urban office buildings; (2) quantify vertical profiles of PNSD and PM$_{2.5}$ concentration and analyse the influence of vehicle emissions and nucleation events on these vertical profiles; (3) quantify and interpret differences between PNSD and PM$_{2.5}$ concentration at different levels; and (4) place the results in the context of broader literature and seek to identify if location-independent trends exist for vertical profiles of PN and PM$_{2.5}$.

3.2 Experimental methods

3.2.1 Setting

Our research was conducted in the subtropical city of Brisbane, which is the capital city of Queensland, Australia. Detailed information on the topography and meteorology of this region is described in Cheung et al. (2011). The major air pollution sources found in the Central Business District (CBD) are inner-city traffic emissions, and aircraft, ship and industrial emissions transported from the lower reaches of the River, located approximately 15-18 km NE of the CBD.

We selected three urban office buildings, located close to busy roads with different terrains. Building A is ~17 m high, located on relatively flat ground with unrestricted access and ~7 m from a busway, which is a bus-only roadway with a daily traffic volume of about 900 buses.
Building B is ~77 m high, located in the centre of the CBD and surrounded by other high rise buildings and busy city roads with a daily traffic volume of about 11,000 vehicles. Building C is ~25 m high, located ~7 m from a freeway with a daily traffic volume of about 110,000 vehicles. There are some high rise buildings to the rear of this building. The locations of Buildings A, B and C are shown in Figure 3.1.

![Figure 3.1. Locations of Buildings A, B, and C in Brisbane.](image)

### 3.2.2 Instrumentation

Two TSI 3934 Scanning Mobility Particle Sizers (SMPSs) were used for measuring PNSD in the range 8.5 – 400 nm. Each SMPS is comprised of a TSI 3071 Electrostatic Classifier (EC) that classifies particles according to their electrical mobility, and a TSI 3010 Condensation Particle Counter (CPC). The duration of each scan was 180 seconds. The PN concentrations in the range 6 – 3000 nm were measured using two TSI 3781 CPCs at an averaging interval of 10 seconds.
Two TSI 8520 DustTrak aerosol monitors, each with a 2.5 µm inlet were used to measure PM$_{2.5}$ concentrations at an averaging interval of 30 seconds. It should be noted that the DustTrak operates based on a light scattering technique where the amount of scattered light is proportional to the volume concentration of the aerosol. The DustTraks used to measure PM$_{2.5}$ concentrations in this study were not calibrated against gravimetric readings, however this was not necessary since it was the relative values rather absolute values that were the subject of our analyses.

3.2.3 Sampling sites and measurement procedures

Two sets of instruments were used to measure PNSD, PN and PM$_{2.5}$ concentrations. One measured continuously at the highest level (usually on the rooftop), which was designated as the reference site for each building. The second set measured simultaneously at one of the lower levels. The air sampled from outdoors (i.e. outside the plant room) was delivered to the instruments via a 1 m long conductive tubing, with an inner diameter of 6 mm. The locations of all outdoor air sampling points were carefully considered to avoid the influence of nearby exhaust air from the HVAC system, if any. A flow splitter was used in cases where several instruments sampled air from the same location. Measurements were performed continuously for at least 24 hours and under different wind conditions at each of the lower level sites. The measurement campaign at each building ranged from two to three weeks. The specific measurement procedures for each of the three buildings are described below.

**Building A**: One set of instruments continuously measured at the reference site located on the top level (level 3) 14.5 m above the ground, 8.5 m above and 7 m away from the busway. The second set was rotated between the ground floor, level 1 and level 2 at the front of the building (facing the busway), at heights of ~1.5, 6.5 and 10.5 m above ground, respectively (see Figure 3.2). The measurements were performed from the 22 July to the 16 August 2009, during the Australian winter period.
Figure 3.2. Schematic diagram of Building A showing the location of the sampling points.

Building B: The reference site was located on the rooftop, about 78.5 m above road level, and one set of instruments sampled continuously at this location. The second set simultaneously sampled at 1.5 m above and ~ 5 m from the roadway, as shown in Figure 3.3, since there were no other access points available at other levels due to the tight glass wall structure of the building. Measurements were performed from the 14 to the 30 January 2010, during the Australian summer period.

Figure 3.3. Schematic diagram of Building B and the location of the sampling points.
Building C: One set of instruments sampled continuously at the reference site, which was located 21.5 m above the ground, and 13.5 m above and 7 m away from the freeway. The second set was moved between sites located at heights of ~1.5 m, 5.5 m, 9.5 m and 21.5 m (levels 1, 2, 3 and 6, respectively) on the opposite side of the building to the reference site (the rear of the building). The sampling sites and building layout are shown in Figure 3.4. Measurements were performed from the 24 June to the 16 July 2010, during the Australian winter period.

Figure 3.4. Schematic diagram of Building C showing the location of sampling points.

3.2.4 Meteorological data

Meteorological parameters, including wind speed, wind direction, temperature and relative humidity corresponding to each measurement campaign were obtained from the Queensland Bureau of Meteorology weather station located in Brisbane CBD between 1 to 5 km east to south east of the measurement sites. Global solar radiation was collected at the Queensland Department of Environment and Resource Management site, about 10 to 14 km south of the measurement sites. A summary of the meteorological data is provided in Table 3.1.
Table 3.1. Average meteorological conditions (± standard deviation)

<table>
<thead>
<tr>
<th>Meteorological parameters</th>
<th>Building A</th>
<th>Building B</th>
<th>Building C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed (m s⁻¹)</td>
<td>1.7 ± 1.2</td>
<td>2.4 ± 1.3</td>
<td>1.3 ± 1.1</td>
</tr>
<tr>
<td>Solar radiation intensity (W m⁻²)</td>
<td>204 ± 209</td>
<td>343 ± 429</td>
<td>123 ± 203</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>15.7 ± 4.4</td>
<td>26.6 ± 3.2</td>
<td>15.2 ± 3.4</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>68.9 ± 18.8</td>
<td>63.7 ± 13.8</td>
<td>69.6 ± 13.1</td>
</tr>
</tbody>
</table>

3.2.5 Identification of nucleation event

Morawska et al. (2008) has shown that motor vehicle emissions are the major source of air pollution in urban environments. Particles from vehicle emissions are classified as either primary or secondary. The primary particles are generated directly from engines and range in size from 30 – 500 nm. The secondary particles are formed via nucleation in the atmosphere after emissions from the tailpipe and are generally below 30 nm.

In order to identify nucleation events, contour plots of data based on a 24-hour period, from 0:00 – 24:00, were visually analysed. Criteria proposed by Dal Maso et al. (2005) and Hussein et al. (2008) were then applied to identify nucleation events. These criteria are: (i) a distinctly new mode of particles must appear in the size distribution; (ii) the mode starts in size range of < 30 nm; (iii) the mode prevails over a time period of hours; and (iv) the new mode shows signs of growth. In urban environments, nucleation events have been observed both with and without particle growth (Cheung et al., 2011; Gao et al., 2009; Park et al., 2008). Therefore, an event where the nucleation mode particle number concentrations increased during the day, but the particles did not grow larger during the event period, as indicated by a near constant Geometric Mean Diameter (GMD) value, was also considered as a nucleation event. Atmospheric conditions during the events were also recorded to identify the preconditions for nucleation process.
3.2.6 Data analyses

In order to compare PN concentrations in different size ranges at street and rooftop levels, PN concentrations were classified into the following size ranges: 8.5 – 30 nm, 30 – 50 nm, 50 – 100 nm, 30 – 100 nm, 100 – 300 nm and 30 – 300 nm. The number of particles within each range was referred to as \( N_{<30} \), \( N_{30-50} \), \( N_{50-100} \), \( N_{30-100} \), \( N_{100-300} \) and \( N_{30-300} \), respectively.

Vertical profiles of PNSD and PM\(_{2.5}\) concentrations for each building were determined by normalising measured concentrations to the reference site. These were calculated as the ratio of concentrations measured at the different levels to the corresponding concentration at the reference site. Following this, the mean ratios of normalised concentrations were shifted so that the lowest height of each building was 1.0. This allowed trends of increasing or decreasing concentrations to be interpreted as values larger or smaller than one.

Statistical analyses included the Student’s t-test to assess differences in mean particle concentrations between different heights and time periods. Paired PNSD and PM\(_{2.5}\) concentrations corresponding to different heights at each building were analysed using the linear correlations. The 5% level was taken to indicate statistical significance in all cases.

3.3 Results and discussion

3.3.1 Variation of PNSD at rooftop and street levels

Whilst ‘rooftop level’ refers to the reference site at each building, the ‘street level’ varied for each building depending on the height of the busy road close by. For example, the height of level 1 at Building A is approximately the same height as the nearby busway, and therefore, the measurements conducted at level 1 are considered to be ‘street level’ measurements. Similarly, the ground floor of Building B (close to city street level) and level 3 of Building C (close to the freeway) are also referred to as ‘street level’.

To interpret the daily pattern of PNSD at rooftop and street levels of each building, PNSD spectra and average daily PN concentrations for \( N_{<30} \), \( N_{30-50} \), \( N_{50-100} \), \( N_{30-100} \), and \( N_{100-300} \) were plotted.
against time of the day for Buildings A, B and C (see Figure 3.5, Figure 3.16-S1 and Figure 3.17-S2, respectively). In general, PNSD trends at rooftop and street levels were similar at each building.

At the rooftop and street levels of Building A, PN size fraction concentrations increased in the early morning and late afternoon. However, the concentrations in the morning were higher than those in the afternoon. During the middle of the day (noon) and early afternoon, \( N_{<30} \) repeatedly increased while other particle size concentrations remained constant or decreased. At Building B, \( N_{<30} \) increased significantly during the early afternoon, while other particle size range concentrations decreased at both the rooftop and street levels. Similar to Building A, all particle size concentrations at Building C increased in the early morning and late afternoon, while only \( N_{<30} \) increased again around noon.

Daily mean variations of PN size fraction concentrations increased in the early morning and late afternoon at Buildings A and C. Traffic flows on the streets close to the sampling sites also showed corresponding peaks during these times, which indicate the influence of vehicle emissions on increased particle concentrations during the rush hours. In contrast, \( N_{<30} \) concentration increased at noon, while other particle size ranges remained constant or decreased at both the rooftop and street levels of all three buildings. In addition, the traffic flow rates decreased around midday. This could suggest the occurrence of new particle formation during this period. A detailed analysis and discussion of the influence of vehicle emissions and new particle formation on particle concentrations is provided in the following section.
3.3.2 Influence of vehicle emissions and new particle formation on PNSD and PM$_{2.5}$ concentrations at rooftop and street levels

3.3.2.1 Influence of vehicle emissions on PN and PM$_{2.5}$ concentrations at rooftop and street levels

The days that did not meet at least one of the criteria for the nucleation event definition were defined as a non- or unclear nucleation event day. Based on this, there were 19, 8, and 20 days...
that were classified as non- or unclear nucleation event at Building A, B, and C, respectively. Weekdays characterised by non- or unclear nucleation events were selected to assess the influence of vehicle emissions on the PN and PM$_{2.5}$ concentrations at the rooftop and street levels of each building. Examples of PNSD spectra, PN and PM$_{2.5}$time series plots at the rooftop and street levels of Buildings A, B and C, as well as their ratios are presented in Figure 3.6, Figure 3.7, Figure 3.18-S3, Figure 3.19-S4, Figure 3.20-S5 and Figure 3.21-S6, respectively. Statistical results are given in Table 3.2.

From Figure 3.7 it can be seen that both PN and PM$_{2.5}$ concentrations peaked at the rooftop and street levels of Building A during the early morning on 7 August 2009. However, PN concentration at the rooftop level was significantly higher than at street level, while the opposite was the case for PM$_{2.5}$. The bus ramp located close to Building A may explain the higher PN and PM$_{2.5}$ concentrations in the morning rush hours compared to those in the afternoon rush hours. About 75% (157/209) of buses during the morning rush hour have to ascend an uphill ramp, and these would have greater emissions than those during the afternoon rush hours that predominantly travel downhill.

PN concentration at the rooftop and street levels of Building B on 18 January 2010, fluctuated according to the wind conditions during the day. However, both PN and PM$_{2.5}$ concentrations at street level were significantly higher than those at the rooftop level during the morning and afternoon rush hours when the wind blew from SW and NE directions. This can be explained by the one-way city street immediately adjacent to the lower sampling site at Building B, which had a traffic flow from the SW to the NE and therefore both SW and NE winds blew parallel the street. Given that the NE wind blew against the traffic flow, it was classified as up-canyon wind, while the SW wind was classified as down-canyon wind. Both PN and PM$_{2.5}$ concentrations at the rooftop and street levels were significantly higher during up-canyon wind (in the afternoon) compared to down-canyon wind (in the morning) (refer to Table 3.2 for comparative results) and ratios between the street and rooftop levels for both PN and
PM$_{2.5}$ concentrations were also significantly higher during the up-canyon wind compared to the down-canyon wind.

At Building C, PN and PM$_{2.5}$ concentrations at the roof top level were significantly higher than those at street level during the morning rush hours on 6 July 2010. Low dispersion due to low wind speed ($v = 0.31 \pm 0.29$ m s$^{-1}$) during this time might explain why the particle concentrations at the rooftop sampling point, which was closer to the freeway, were higher than those at the opposite sampling point at street level. During the afternoon, a WNW wind blew almost parallel to the freeway and the building, resulting in a better dispersion of pollutants on both sides of the building and also being the likely explanation why the PN and PM$_{2.5}$ concentrations were not significantly different at the rooftop and street levels ($p$-values of 0.06 and 0.45, respectively).

In summary, time series of PN and PM$_{2.5}$ concentrations and their ratios between the rooftop and street levels showed clear diurnal variation. As expected, vehicle emissions strongly influenced both PN and PM$_{2.5}$ concentrations at both levels, especially during the rush hours at all three buildings. Similarly, building topography, distance to the emission sources, and wind speed and direction also had an observed effect on particle concentrations at the 3 buildings.

Table 3.2. Average particle concentrations at the rooftop and the street levels of Buildings A, B and C during the rush-hours.

<table>
<thead>
<tr>
<th>Site</th>
<th>Level</th>
<th>PN ($\times 10^3$ p cm$^{-3}$) (Mean ± 95% CI)</th>
<th>PM$_{2.5}$ (µg m$^{-3}$) (Mean ± 95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Morning Afternoon $p$</td>
<td>Morning Afternoon $p$</td>
</tr>
<tr>
<td>Building A</td>
<td>Rooftop</td>
<td>18.7 ± 1.21 9.99 ± 0.73 &lt; 0.01</td>
<td>42.9 ± 1.74 10.1 ± 0.62 &lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>Street</td>
<td>14.5 ± 0.85 7.56 ± 0.43 &lt; 0.01</td>
<td>78.5 ± 3.69 11.8 ± 0.86 &lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>$p$</td>
<td>&lt; 0.01 &lt; 0.01</td>
<td>&lt; 0.01 &lt; 0.01</td>
</tr>
<tr>
<td>Building B</td>
<td>Rooftop</td>
<td>5.01 ± 0.37 5.82 ± 0.64 &lt; 0.05</td>
<td>8.51 ± 0.48 9.6 ± 0.27 &lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>Street</td>
<td>6.04 ± 0.65 7.21 ± 0.69 &lt; 0.05</td>
<td>19.6 ± 1.14 22.0 ± 1.22 &lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>$p$</td>
<td>&lt; 0.01 &lt; 0.01</td>
<td>&lt; 0.01 &lt; 0.01</td>
</tr>
<tr>
<td>Building C</td>
<td>Rooftop</td>
<td>18.6 ± 1.21 8.56 ± 0.65 &lt; 0.01</td>
<td>19.0 ± 0.51 8.00 ± 0.67 &lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>Street</td>
<td>12.5 ± 1.70 8.12 ± 0.52 &lt; 0.01</td>
<td>17.7 ± 0.79 8.20 ± 0.56 &lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>$p$</td>
<td>&lt; 0.01 0.06</td>
<td>&lt; 0.05 0.45</td>
</tr>
</tbody>
</table>
Figure 3.6. PNSD spectra at Building A on a week day characterised by the non- or unclear nucleation events.
Figure 3.7 Average particle concentrations and their rooftop to street level ratios at Building A on a week day characterised by the non- or unclear nucleation events.

3.3.2.2 Influence of new particle formation on PNSD and PM$_{2.5}$ concentration at rooftop and street levels

Based on the inclusion criteria for nucleation identification, we observed 7 events during a 3 weeks measurement campaign at Building A, 9 events during a 2 weeks measurement campaign at Building B and 3 events during a 3 weeks measurement campaign at Building C. The frequency of nucleation events at Building B (measured during summer) was clearly higher than those at Buildings A and C (measured during winter), which is in agreement with the findings of Qian et al. (2007) and Mejia and Morawska (2009). A summary of the
conditions observed during the nucleation events is provided in the Supplementary Table 3.4-S1.

Representative nucleation events were selected to analyse the influence of new particle formation on PNSD at the rooftop and street levels of each building, to assess their likely sources and impact on vertical profiles. PNSD spectra, time series’ of \(N_{<30}\), \(N_{30-100}\) and PM2.5 concentrations, as well as ratios of PN and PM\(_{2.5}\) concentrations at the rooftop and street levels of Buildings A, B and C are presented in Figure 3.8, Figure 3.9, Figure 3.22-S7, Figure 3.23-S8, Figure 3.24-S9 and Figure 3.25-S10, respectively. The results of statistical tests are presented in Table 3.3.

\(N_{<30}/N_{30-300}\), which is the ratio between nucleation mode and accumulation mode PN concentration, was used by Kumar et al. (2009) to evaluate the rate of production of new nucleation mode particles. When analysed together with \(N_{<30}\), which indicates nucleation mode PN concentration, it is possible to assess the strength of new particle formation at the different levels of each building. From Table 3, it can be seen that both \(N_{<30}\) and \(N_{<30}/N_{30-300}\) were significantly higher at the rooftop level compared to street level at each building, and they were also clearly higher at Building B than at Buildings A and C. Meanwhile the rooftop PM\(_{2.5}\) concentration was significantly lower than the street level PM\(_{2.5}\) at all three buildings.

Based on the higher values of \(N_{<30}\) and \(N_{<30}/N_{30-300}\) at the rooftop level of each building, we inferred that the production of new nucleation mode particles was stronger at the rooftop level than the street level at all three buildings. Vakeva et al. (1999) reported two important factors that can favour a much greater production of particles by local vehicle emissions: (i) a higher concentration of condensable gases, and (ii) a smaller concentration of pre-existing particles. Additionally, both O Dowd et al. (1999) and Boy and Kulmala (2002) identified the important role of solar radiation on new particle formation. The roles of these factors in initiating the events we observed are discussed below.
Wind direction during the nucleation event at Building A on 3 August 2009, was WNW. In this case, both sampling sites and the busway were on the downwind side of the building. Leuzzi and Monti (1998) modelled the dispersion of a tracer gas emitted from a line source located downwind of a building and reported that high pollutant concentrations occurred at locations corresponding to the vortex on the leeward side of the building. At about 40 m wide and 17 m high, Building A can be considered a wide and low building and therefore the vortex, which entrains the smaller particles or condensable gases emitted from vehicles, probably formed at a level higher than the street level, while the larger or pre-existing particles (mainly attributed to PM$_{2.5}$) remained suspended and stagnated at the lower levels. Therefore, it appears that the stronger nucleation observed at the rooftop compared to the street level was due to higher condensable gas and lower pre-existing particle concentrations.

Leuzzi and Monti (1998) also modelled an upwind line source and reported that low concentrations occurred on the leeward side of the building, with only a small amount of pollutants able to penetrate into the region. During the nucleation event at Building C on 8 July 2010, a SSW wind blew perpendicular to the building from direction of the freeway. Therefore, the rooftop sampling site was upwind and received pollutants directly from the freeway emission sources, while the street level sampling site was located in the lee of the building. This suggests that there were lower concentrations of condensable gases at the street level compared to the rooftop level of Building C and that the higher PM$_{2.5}$ concentrations measured at street level might be due to the stagnation of larger, pre-existing particles on the leeward side of the building.

Based on $N_{<30}$ and $N_{<30}/N_{30-300}$ at rooftop and street levels, we also concluded that the intensity of new particle formation at Building B on 16 January 2010, was clearly stronger than that at Buildings A and C, although the mean solar radiation intensity (W m$^{-2}$) (Mean ± 95% CI) during the nucleation event at Building B was not significantly different compared to Building A (664.3 ± 20.7 vs. 689.4 ± 22.4, $p = 0.36$). At the same time, ratios between rooftop
and street level values for $N_{30}$ and $N_{30-300}$ were significantly lower at Building B compared to those at Building A ($1.15 \pm 0.09$ vs. $1.88 \pm 0.27$, $p < 0.01$; $1.20 \pm 0.14$ vs. $1.84 \pm 0.30$, $p < 0.01$, respectively). The nucleation event observed at Building B occurred on a weekend, when vehicle density was typically low and a strong NE wind ($3.57 \pm 0.32$ m s$^{-1}$) was blowing. The resultant increase in $N_{30}$ but decrease in $N_{30-100}$ suggests that the PN concentrations at the sampling site were not significantly influenced by local vehicle emissions but more likely from upwind air masses. In this case, the air mass was likely to come from an industrial zone about 15-18 km NE of the city. Further analysis and comparison of the data measured at this building was conducted along with data collected from a Queensland Department of Environment and Resource Management station, which is about 10 km SW of the Brisbane city and 25 km SW of the NE Brisbane industrial zone. The results showed similar trends in PN concentrations between the two locations during the NE winds, but not for other wind directions, during the nucleation days. This implies that emissions from the NE Brisbane industrial zone are those which contribute to the PN concentrations in the Brisbane CBD and surrounding areas. Furthermore, a similar phenomenon was identified and reported by Cheung et al. (2011) in the Brisbane region. It should also be noted that newly formed particles at both the rooftop and street levels did not show signs of growth (their GMDs were almost constant during the event). This indicates that the newly formed particles already underwent growth before reaching the monitoring sites and they were likely to be relatively homogeneous in size when reaching Building B after the distance travelled. Furthermore, the NE wind, which would have blown parallel to the street canyon, and minimal turbulence due to the low vehicle density could explain why the difference in PN concentrations ($\times 10^3$ p cm$^{-3}$) between the rooftop and street levels at Building B ($16.9 \pm 1.49$ vs. $15.7 \pm 1.47$; $p < 0.05$) was significant, but not to the same extent observed at Buildings A ($8.16 \pm 1.02$ vs. $4.57 \pm 0.28$; $p < 0.01$) and C ($5.34 \pm 0.45$ vs. $3.31 \pm 0.27$; $p < 0.01$). This new finding contradicts the results reported for Building A and locations
investigated by Kumar et al. (2009), where new particle formation was mainly influenced by local vehicle emissions. This also has implications for modelling urban canyon PN concentrations for both planning and exposure assessment purposes, and indicates the value of location-specific measurements at underpinning these.

In summary, the time series concentrations of $N_{<30}$, $N_{30-100}$ and $PM_{2.5}$, as well as the time series ratios of PN and $PM_{2.5}$ concentrations at the rooftop and street levels showed that new particle formation events influenced and contributed to increases in PN concentrations at both rooftop and street levels at all three buildings. However, the factors that contributed to the observed phenomena were different between the three buildings. At Building A and C, the new particles were mainly formed from local vehicle emissions and therefore, the formation process was expected to depend mainly on local conditions, such as high condensable gas concentrations and solar radiation intensity, together with low pre-existing particle concentrations. Meanwhile at Building B, the newly formed particles were blown in from the direction of a nearby industrial zone and therefore, new particle production was not the result of local sources but was strongly influenced by wind speed, wind direction and the origin of incoming air masses. Detailed consideration of the factors described above should be undertaken prior to modelling urban canyon particle concentrations and profiles, and a ‘one-size-fits-all’ approach is likely to be unable of accounting for the specific determinants at each individual building.

Nucleation events are often studied in the context of their role as physical phenomena, and typically within the context of producing natural and anthropogenic aerosols that may affect climate change. This study has shown an underappreciated role of nucleation in producing particles that can affect large numbers of people, due to the high density and occupancy of urban office buildings and the fact that the vast majority of people’s time is spent indoors.
Table 3.3. Average particle concentrations during the nucleation event days

<table>
<thead>
<tr>
<th>Site</th>
<th>Level</th>
<th>N$_{30}$ ($\times 10^3$ p cm$^{-3}$) (Mean ± 95% CI)</th>
<th>N$<em>{30}$/N$</em>{30-300}$ PM$_{2.5}$ (µg m$^{-3}$) (Mean ± 95% CI)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building A</td>
<td>Rooftop</td>
<td>8.16 ± 1.02</td>
<td>1.76 ± 0.33</td>
<td>11.3 ± 1.11</td>
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<tr>
<td>Street</td>
<td></td>
<td>4.57 ± 0.28</td>
<td>1.01 ± 0.08</td>
<td>19.7 ± 3.50</td>
</tr>
<tr>
<td></td>
<td>p</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Building B</td>
<td>Rooftop</td>
<td>16.9 ± 1.49</td>
<td>4.54 ± 0.52</td>
<td>4.0 ± 0.08</td>
</tr>
<tr>
<td>Street</td>
<td></td>
<td>15.7 ± 1.47</td>
<td>3.92 ± 0.34</td>
<td>7.5 ± 0.65</td>
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<tr>
<td></td>
<td>p</td>
<td>&lt; 0.05</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Building C</td>
<td>Rooftop</td>
<td>5.34 ± 0.45</td>
<td>2.23 ± 0.32</td>
<td>1.67 ± 0.18</td>
</tr>
<tr>
<td>Street</td>
<td></td>
<td>3.31 ± 0.27</td>
<td>1.91 ± 0.24</td>
<td>2.01 ± 0.14</td>
</tr>
<tr>
<td></td>
<td>p</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
</tr>
</tbody>
</table>

Figure 3.8. PNSD spectra at Building A on a nucleation event day.
Figure 3.9. Particle concentrations and their rooftop to street level ratios at Building A during a nucleation event day.

3.3.3 Vertical profiles of particle concentrations

The average vertical profiles of the PNSD and PM$_{2.5}$ for the entire day, rush-hours and during nucleation events at Buildings A, B, and C are presented in Figure 3.10, Figure 3.11 and Figure 3.12, respectively. It should be noted that the data of the nucleation events at Building C were only collected at rooftop and street levels and therefore, constructing a vertical profile based on nucleation events at this building, was not appropriate. However, the measured results at Building C show that the PN concentration at rooftop levels was significantly higher
than at street levels during the event, while the opposite was the case for the PM$_{2.5}$ concentration.

At Building A, the trends of total number concentration (TNC) and N$_{<30}$ were similar. Their concentrations during nucleation events themselves and over 24 hour on the day of nucleation events constantly increased with height ($p < 0.01$). While during the rush-hours, they decreased between 1.5 and 10.5 m, and then increased onward ($p < 0.05$). In contrast, the trends of N$_{30-100}$ and N$_{>100}$ fluctuated and depended on the measurement heights and times. In general, the daily PM$_{2.5}$ concentrations decreased with increasing height, however they stabilised at heights between 6.5 and 10.5 m. During rush-hours, PM$_{2.5}$ concentrations were higher at heights of 6.5 and 10.5 m, but lower at a height of 14.5 m, compared to the daily concentrations ($p < 0.05$). The PM$_{2.5}$ concentrations during the nucleation events were generally lower than the daily concentrations ($p < 0.01$).

At Building B, N$_{30-100}$, N$_{>100}$ and PM$_{2.5}$ concentration at street levels were always higher than those at rooftop levels ($p < 0.05$). The daily and rush-hour TNCs were significantly higher at street level compared to those at rooftop level, but the opposite was the case during the nucleation events ($p < 0.05$). N$_{<30}$ at rooftop level was significantly higher than at street level during the nucleation event ($p < 0.01$), while their daily and rush-hour concentrations were relatively similar ($p$-values of 0.17 and 0.78, respectively).

The daily PNSD and PM$_{2.5}$ concentration decreased with height between 1.5 and 21.5 m at the rear (opposite side facing the road) of Building C ($p < 0.01$), however N$_{30-100}$, N$_{>100}$, PM$_{2.5}$ tended to stabilise at heights between 5.5 and 9.5 m, followed by a less pronounced decrease from 9.5 to 21.5 m. During the rush-hour periods, N$_{30-100}$, N$_{>100}$, TNC decreased from 1.5 to 9.5 m, and then stabilised at heights between 9.5 and 21.5 m. N$_{<30}$ increased at the beginning of the rush-hour period, then decreased from 5.5 to 9.5 m, and finally stabilised onwards. The rush-hour PM$_{2.5}$ followed the PM$_{2.5}$ daily trends and was higher than the daily concentrations.
In general, the trend of TNC followed those of $N_{<30}$ and $N_{30-100}$ during the nucleation event and rush-hours, respectively, while the trends of $N_{>100}$ and PM$_{2.5}$ were similar.

At Building B, the daily and rush-hour PN concentrations at street level were higher than those on the rooftop. This finding is in agreement with the results of previous studies (Hitchins et al., 2002; Kumar et al., 2009; Li et al., 2007; Longley et al., 2004; Väkevä et al., 1999). On the contrary, the daily and rush-hour PN concentrations at Building A increased with height. This is likely to be attributed to the fact that the busway is located close to the building and elevated above ground level, and therefore, it has a stronger influence on the concentrations measured at higher levels compared to Building B. The daily and rush-hour PN concentrations at the rear of Building C decreased with increasing height. This finding is not in agreement with the results reported by Hitchins et al. (2002) based on measurements in Brisbane, where a short time measurement (5 samples during 450 seconds for each level) was conducted. The difference could be due to the highly diurnal variations of influencing factors, such as vehicle emissions, wind speed and wind direction on particle concentrations between the different levels of this building.

The PM$_{2.5}$ concentrations seemed to consistently decrease with height throughout the day and this finding is also in accordance with previous research (Chan and Kwok, 2000; Horvath et al., 1988; Micallef and Colls, 1998; Rubino et al., 1998). However, the PM$_{2.5}$ concentrations at Buildings A and C did not decrease consistently. In the case of the Building A, this may be due to the influence of the proximity of the busway. The sampling points were located on the rear side of Building C and were obstructed by other buildings located behind it, and therefore, some stagnation of air in this region may have influenced the PM$_{2.5}$ concentrations at mid-height levels.

In general, the vertical profiles of the PM$_{2.5}$ concentrations around the building envelopes decreased with increasing height. However, vertical profiles of the PNSD were building-specific and the rate of change with height was different at all three buildings. The results
indicate that it is not only vehicle emissions that influence the particle vertical profiles, but new particle formation as well; while particle number increased, we observed a reduction in particle mass during the nucleation events. These results serve to further define the specific effect of roadway proximity and nucleation formation on the vertical profiles of PN and PM$_{2.5}$ concentrations around building envelopes. Moreover, the highly building-specific nature of the profiles and factors affecting them underscores that, ideally, measurements form the basis of any modelling or planning exercise prior to or after construction of a building. Such an approach, which is currently lacking for the most part, will ensure the greatest model veracity. This has important implications for selecting appropriate sites for the air intakes of building HVAC systems to minimise occupant exposure to combustion products, and also to investigate how street-level exposures may be mitigated via improved design practices.
Figure 3.10. Vertical profiles of PNSD and PM$_{2.5}$ concentration around Building A*.

*Error bars denote one standard deviation
Figure 3.11. Vertical profiles of PNSD and PM$_{2.5}$ concentration around Building B*.

*Error bars denote one standard deviation
3.3.4 Relationship between PNSD and PM$_{2.5}$ concentration

Spearman’s correlation coefficients (rho) for the PNSD and PM$_{2.5}$ concentrations at different heights and different time periods at Buildings A, B and C are presented in Figure 3.13, Figure 3.14 and Figure 3.15, respectively, and Table 3.5-S2. However, as noted, new particle formation data was collected only at the reference site and street level during the measurement campaign of Building C. Therefore, correlations between the PNSD and
PM$_{2.5}$ during the nucleation events at this site were not calculated. In general, the correlation coefficients between N$_{>100}$ and PM$_{2.5}$ were higher, while the correlation coefficients of N$_{<30}$ were usually lower compared to other particle size fractions.

The PNSD and PM$_{2.5}$ correlation coefficients on the rooftop were higher than those at street level at Building B. The difference between correlation coefficients for PN size fractions and PM$_{2.5}$ concentrations at Building A were higher than at Building B. This is likely due to the relative proximity of the particle sources at each level, as well as to the closeness to the busway at Building A. Both daily and rush-hour correlation coefficients of PNSD at the rear of Building C initially increased from the ground to level 3, and then decreased closer to the rooftop.

Correlations between the PNSD and PM$_{2.5}$ were characterised by a significant variability and dependence on particle size fraction, measured height and particle emission sources. The linear correlations for the building envelopes, especially during the rush-hour and nucleation events, fluctuated significantly. This indicates that it is not appropriate to use particle mass concentrations to infer PN concentrations when modelling vertical concentrations around the building envelope and at a street level. This finding, while not a novel observation, adds weight to the existing case for separately considering particle mass and number during any urban modelling or exposure assessment exercise.
Figure 3.13. Relationship between PNSD and PM$_{2.5}$ at different heights for Building A.
Figure 3.14. Relationship between PNSD and PM$_{2.5}$ at different heights for Building B.
3.4 Conclusions

In general, vertical profiles of PM$_{2.5}$ concentrations around building envelopes showed a consistent decrease in concentration with increasing distance from nearby streets. However, vertical profiles of PN size fraction concentrations were building-specific and its rate of change was inconsistent with height. These results are not unexpected, in view of the complex flow patterns around the building envelopes, as well as in the busway and street canyons proximate to some of the buildings. The results of simultaneous measurements indicated that it was not only vehicle emissions but new particle formation was also found to strongly influence the vertical profiles of particle concentrations. Time series ratios of PN and PM$_{2.5}$ concentrations at street and rooftop levels showed clearly diurnal variation. These suggest that
it is impossible to generalise vertical profiles of particle concentrations for all buildings, and that there is a need to conduct measurements or model these vertical profiles for a specific case when planning building morphology and air intake locations. Furthermore, newly formed particles and building-scale variability should also be into account when modelling particle concentrations around the building envelope, and also for urban environments and the exposures that occur within them in general.

The results of this serve to provide better insight into the impact of nucleation and local scale variability on particle concentrations, and will also help to better define particle behaviour and variability around building envelopes, which has implications for studies of both human exposure and particle dynamics.

Acknowledgement

This project was funded by the Queensland Department of Public Works, and the Australian Research Council, through ARC Linkage Grant LP0776542. We would also like to thank the building managers and the security staff at the buildings we investigated and Ms Rachael Appleby from the International Laboratory for Air Quality and Health, for assisting us during the project implementation.

3.5 References


3.6 Supporting information

Figure 3.16-S1. Daily variation of PNSD and PN size fraction concentrations at Building B.
Figure 3.17-S2. Daily variation of PNSD and PN size fraction concentrations at Building C.
Figure 3.18-S3. PNSD spectra at Building B on a week day characterised by the non- or unclear nucleation events.
Figure 3.19-S4. Average particle concentrations and their rooftop to street level ratios at Building B on a weekday characterised by the non- or unclear nucleation events.
Figure 3.20-S5. PNSD spectra at Building C on a weekday characterised by the non- or unclear nucleation events.
Figure 3.21-S6. Average particle concentrations and their rooftop to street level ratios at Building C on a weekday characterised by the non- or unclear nucleation events.
Figure 3.22-S7. PNSD spectra at Building B on a nucleation event day.
Figure 3.23-S8. Particle concentrations and their rooftop to street level ratios at Building B on a nucleation event day.
Figure 3.24-S9. PNSD spectra at Building C on a nucleation event day.
Figure 3.25-S10. Particle concentrations and their rooftop to street level ratios at Building C on a nucleation event day.
<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>Local time</th>
<th>SR (\text{Wm}^{-2})</th>
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<th>WS (\text{Ms}^{-1})</th>
<th>Temp</th>
<th>RH</th>
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* The data in the table present events observed at the reference sites of Buildings A, B and C.
Table 3.5-S2. Spearman’s correlation coefficients ($\rho$) for PNSD and PM$_{2.5}$ concentration around the building envelopes

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* Correlation is significant at the 0.05 level (2-tailed)

** Correlation is significant at the 0.01 level (2-tailed)
Influence of Ventilation and Filtration on Indoor Particle
Concentrations in Urban Office Buildings

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STATEMENT OF JOINT AUTHORSHIP

Title: Influence of ventilation and filtration on indoor particle concentrations in urban office buildings

Authors: Tran Ngoc Quang, Congrong He, Lidia Morawska and Luke D. Knibbs

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Contributed to the development of the experimental design and scientific method; conducted the experiments; collected, analysed and interpreted the data; and wrote the manuscript.

Congrong He
Developed the experimental design and scientific method; conducted the experiments; collected the data; assisted in the analysis and interpretation of the data and the writing of the manuscript.

Lidia Morawska
Developed the experimental design and scientific method; assisted in the interpretation of the data and the writing of the manuscript; and proof reading.

Luke D. Knibbs
Contributed to the development of experimental design and scientific method; conducted the experiments; and contributed to the writing of the manuscript.
4 Influence of Ventilation and Filtration on Indoor Particle Concentrations in Urban Office Buildings

Abstract

There is limited quantitative information about the performance and efficiency of in-situ filters in HVAC systems, especially in relation to ultrafine (<100 nm) particles, and scientific understanding of the influence of ventilation and filtration on indoor particle dynamics in office buildings is incomplete. This study aimed to quantify the efficiency of deep bag and electrostatic filters, and assess the influence of ventilation systems using these filters on indoor fine (< 2.5 µm) and ultrafine particle concentrations in commercial office buildings. Measurements and modelling were conducted for different indoor and outdoor particle source scenarios at three office buildings in Brisbane, Australia. Overall, the in-situ efficiency, measured for particles in size ranges 6 to 3000 nm, of the deep bag filters ranged from 26.3 to 46.9% for the three buildings, while the in-situ efficiency of the electrostatic filter in one building was 60.2%. The average indoor particle number (PN) and PM$_{2.5}$ concentrations ranged from 2.46 to $5.71 \times 10^3$ p cm$^{-3}$ and 5.2 to 6.81 µg m$^{-3}$, respectively, while the daily median I/O ratios of PN and PM$_{2.5}$ were 0.21 to 0.38 and 0.52 to 0.63, respectively. The highest PN and PM$_{2.5}$ concentrations in one of the office buildings (up to 131% and 31% higher than the other two buildings, respectively) were due to the proximity of the building’s HVAC air intakes to a nearby bus-only roadway, as well as its higher outdoor ventilation rate. The lowest PN and PM$_{2.5}$ concentrations (up to 57% and 24% lower than the other two buildings, respectively) were measured in a building that utilised both outdoor and mixing air filters in its HVAC system. Indoor PN concentrations were strongly influenced by outdoor levels and were significantly higher during rush-hours (up to 41%) and nucleation events (up to 57%), compared to working-hours, for all three buildings. An existing dynamic model for indoor PN concentration was used in this study, and it performed well when outdoor air was
the main source of indoor particles, when there less uncertainty regarding indoor source emissions, and when the ventilation system was turned off. Modelling results also revealed that using both mixing air and outdoor air filters can significantly reduce indoor particle concentration in buildings where indoor air was strongly influenced by outdoor particle levels. This work provides a scientific basis for the selection and location of appropriate filters and outdoor air intakes, during the design of new, or upgrade of existing, building HVAC systems. The results also serve to provide a better understanding of indoor particle dynamics and behaviours under different ventilation scenarios, and highlight effective methods to reduce exposure to particles in commercial office buildings.

*Keywords:* Ultrafine particles, indoor, I/O ratio, deep bag filter, electrostatic filter, dynamic model.

### 4.1 Introduction

The association between fine (< 2.5 µm) particle concentrations and increases in respiratory and cardiovascular morbidity and mortality has been reported by many studies (Davidson et al., 2005; Pope, 2000; Schwartz and Neas, 2000; WHO, 2006). Other studies have indicated that the health effects of ultrafine (< 0.1 µm) particles could be even more harmful than those of PM$_{2.5}$ (Franck et al., 2011; Oberdorster, 2000). The concentrations of fine and ultrafine outdoor particles in urban environments are mainly influenced by vehicle exhaust emissions (Harrison et al., 1999; Perez et al., 2010; Pey et al., 2008; Shi et al., 1999) and new particle formation from photochemical reactions (Cheung et al., 2011; Cheung et al., 2012; Pey et al., 2009; Quang et al., 2012). These particles can reach the interior of buildings, especially those located close to busy traffic areas, via penetration through their envelopes (Thornburg et al., 2001), and through mechanical ventilation systems (Koponen et al., 2001; Morawska et al., 2009b; Weschler et al., 1996). Indoor activities, such as movement of building occupants, can also affect and increase indoor particle levels (Abt et al., 2000a; Long et al., 2000). Recent research has indicated that laser printers, a widely-used piece of office equipment, can make a
significant contribution to indoor particle levels (He et al., 2007; He et al., 2010; McGarry et al., 2011; Morawska et al., 2009a; Schripp et al., 2008).

The filtration systems of mechanically ventilated buildings can reduce indoor particle concentrations which originated both outdoors and indoors (Hanley et al., 1994; Hinds, 1999; Jamriska et al., 2003). Several studies have quantified the efficiency of dry-media and electrostatic filters used in mechanically ventilated office buildings, but they mainly focused on particles >300 nm (Fisk et al., 2000; Zuraimi and Tham, 2009). Other work has focused on ultrafine particle, but these investigations were performed under laboratory conditions, and not in operating buildings (Hanley et al., 1994; Jamriska et al., 1998). Indoor particle deposition can also be an important factor affecting indoor particle levels, with a number studies published on this topic. However, these mainly focused on residential houses (Abt et al., 2000b; He et al., 2005; Long et al., 2001; Thatcher et al., 2002; Thatcher and Layton, 1995) or naturally ventilated office buildings (Smolík et al., 2005). Only one study calculated indoor particle deposition rate in an office building during working-hours (Jamriska et al., 2003). Two studies employed static models to simulate particle concentrations inside office buildings (Fisk et al., 2000; Zuraimi and Tham, 2009). Matson (2005) also built a dynamic model for this purpose, but did not consider the influence of filtration and indoor sources. Another dynamic model was developed by Jamriska et al. (2003) to study particle dynamics in a hypothetical office building, however it was not applied to real buildings.

Currently, there is only limited information on in-situ filter efficiency in mechanically ventilated office buildings, where a substantial proportion of the population spend a large amount of time each day, and the scientific understanding of the factors which impact indoor particle concentrations and occupant exposures in these buildings is incomplete. To help address these gaps in knowledge, and provide information for the selection and location of appropriate filtration media in office building HVAC systems, we aimed to: (1) quantify indoor and outdoor particle concentrations and air exchange rates in three office buildings; (2)
test the in-situ efficiencies of different filter types under real-world conditions; (3) assess the factors that impact on I/O ratios under different ventilation and filtration schemes and particle source scenarios; (4) investigate indoor particle sources; and (5) modify, assess the performance of, and apply a mathematical model to further evaluate the important factors which affect the concentration and dynamics of indoor particles.

4.2 Research methods

4.2.1 Sampling sites – building description

Three urban office buildings in the subtropical city of Brisbane, which is the capital city of Queensland, Australia, were selected for measurements. These buildings, referred to here as A, B and C, were chosen to represent different building heights, ages, ventilation systems and nearby traffic density. Building A is 4storeys, was built in 2008, is ~17 m high and located on relatively flat ground and ~7 m from a busway (a bus-only roadway with a daily traffic volume of about 900 buses). Building B is 18storeys, was built in 1980, is ~77m high, located in the centre of Brisbane City and is surrounded by other high rise buildings and busy city roads, with a daily traffic volume of about 11,000 vehicles. Building C is 6storeys, was built in 1998, is ~25 m high, and located ~7 m from a freeway with a daily traffic volume of about 110,000 vehicles. All three office buildings had a steel frame and glass exterior walls. The floors of the working spaces were fully carpeted, and furnishings included desks, chairs, filing cabinets, desktop computers, laser printers and photocopiers. All of the buildings were non-smoking. Further information on the characteristics and location of these buildings is provided in Quang et al. (2012).

4.2.2 Ventilation systems

Four types of ventilation systems, including three central ventilation systems and one single split system, operated in the buildings studied. A central ventilation system is one in which air is supplied from a central plant room, where fresh outdoor air and recirculation air from the building are mixed, then cleaned and conditioned by deep bag (DB) filters and air handling
units (AHUs), respectively, before being introduced into each office space via ducts. The pockets of a DB filter are formed and sewn by using multiple polyester fibers.

A split system consists of indoor and outdoor units that work together. The outdoor unit consists of condenser coils, which transport the thermal energy from the hot air inside the building to the outdoors. The indoor unit consists of evaporator coils, which collect and remove heat and moisture from the indoor air. Both condenser coils and evaporator coils are connected to the refrigerant lines, which are powered by a compressor.

At Building A, two central ventilation plants were located centrally at the front of each floor to treat and provide supply air to the open plan offices. The flow rates of supplied air were controlled by variable air volume (VAV) boxes located in the office ceilings and AHUs were located in the plant rooms. Outdoor air was taken from air intakes located at the front of each plant room, which were close to the nearby busway. DB filters were located in the air stream of mixed outdoor and recirculation air. Individual office spaces (such as meeting rooms) were conditioned by a separate split system, in which supply air was drawn in directly from outdoors, near the central plant room, and then treated by indoor fan coil units–(FCUs), which contained a basic filter, before being distributed to the space.

At Building B, a central plant room was located on the rooftop level and provided conditioned air for levels 3 to 18. Outdoor air was introduced via air intakes and then mixed with return air from all levels. After the mixed air was filtered and conditioned by DB filters and AHUs, respectively, the treated air was supplied to each floor space via a riser duct system.

In contrast, Building C had one central plant room which was located towards the centre-rear section of each floor. Outdoor air was drawn from air intakes and filtered primarily by electrostatic (ES) filters located in a rooftop plant room, before being supplied to individual plant rooms on each level via raiser ducts. The ES filter was a two stage air cleaner comprising ionising wires and collecting plates that operated at voltages of about 13 and 6.5
kV DC, respectively. In each individual floor’s plant room, the pre-filtered outdoor air was mixed with recirculation air, and then re-filtered and conditioned by DB filters and AHUs, respectively, before being supplied to the offices via a duct system. Schematic diagrams of the HVAC systems at Buildings A, B and C are shown in Figure 4.11-S1.

4.2.3 Instruments and measured parameters

Two TSI 3934 Scanning Mobility Particle Sizers (SMPSs) were used for measuring particle number size distribution (PNSD) in the range 8.5 – 370 nm in the downstream and upstream air flow of each filter device to quantify its efficiency. Each SMPS comprised a TSI 3071 Electrostatic Classifier (EC) that classified particles according to their electrical mobility, and a TSI 3010 Condensation Particle Counter (CPC). The duration of each scan was 180 s. Indoor and outdoor particle number (PN) concentrations in the range 6 – 3000 nm were measured by TSI Model 3025 and 3781 CPCs at an averaging interval of 5 s and 15 s, respectively. Two TSI 8520 DustTrak aerosol monitors, each with a 2.5 \( \mu m \) inlet, were used to measure indoor and outdoor PM\(_{2.5}\) concentrations at an averaging interval of 10 s and 30 s, respectively. It should be noted that the DustTrak operates based on light scattering technique where the amount of scattered light is proportional to the volume concentration of the aerosol, and is not calibrated for measurement of combustion aerosols. In order to obtain representative PM\(_{2.5}\) values, data collected by the DustTraks in this study were corrected against a Thermo Scientific (Franklin, MA) 1405-DF tapered element oscillating microbalance (TEOM), by using an equation obtained by Morawska et al. (2003): \[ \text{PM}_{2.5}(\text{TEOM}) = 0.394 \text{PM}_{2.5}(\text{DustTrak}) + 4.450 \] (with \( r^2 = 0.83 \)).

A TSI model 8525 PTrak was used for mobile measurement of possible indoor PN sources. TSI Model 8552 and 7545 QTraks were used to measure temperature, relative humidity and CO\(_2\) levels inside offices and outdoors, respectively. TSI Model 8705 and 9535 hot wire anemometers were used to simultaneously measure the velocities of outdoor air (OA), return air (RA) and mixing air (MA) in each plant room to determine total flows. The anemometers operated continuously in the center of OA
intake(s), RA outlet(s), and MA intake(s), while the VelociCalc was used to traverse these air intakes and outlets in order to capture the average total flow of OA, RA and MA. All instruments were tested and calibrated in the laboratory before being used for field measurements. Comparative quality assurance tests for all particle instruments were also conducted simultaneously with all instruments co-located and sampling outdoor air during the last day of each field campaign.

4.2.4 Measurement procedures

4.2.4.1 Air exchange rate

Outdoor air exchange rates (AERs) for each office space were calculated based on two methods: the outdoor air flow rate measurement and indoor CO₂ decay measurements. When the HVAC system was turned on, the outdoor air flow rate introduced to each plant room was calculated based on average air velocity, measured at the relative outdoor air intake(s). Then an AER for the relevant office space was estimated based on the following equation:

\[ AER = \frac{Q_{oa}}{V_{room}} \]  \hspace{1cm} (4.1)

in which \( Q_{oa} \) is the outdoor air flow rate (\( m^3 \) h\(^{-1}\)) and \( V_{room} \) is the effective volume of the relevant office space (\( m^3 \)). This equation denotes that the outdoor air flow rate should include the portion penetrated via the building envelope. However, during operation of the ventilation system, the inside air pressure usually remained positive and therefore, in this case, the infiltration portion was considered negligible compared to ventilated outdoor air.

When the HVAC system was turned off outside of work hours, the indoor CO₂ decay method (He et al., 2005; Weichenthal et al., 2008) was applied to calculate outdoor AER (i.e. infiltration) based on real-time measurements of indoor CO₂, according to the following equation:

\[ AER = \frac{\ln C_0 - \ln C_t}{\Delta T} \]  \hspace{1cm} (4.2)
in which $C_0$ is the initial indoor CO$_2$ concentration and $C_t$ is the lower indoor CO$_2$ concentration after the time needed ($\Delta T$) for a continuous decay of well-mixed CO$_2$. To correct for the background contribution of outdoor CO$_2$, ambient concentrations were subtracted from the initial and final measured CO$_2$ concentrations. AERs were estimated between 18:00 to 19:00, when the HVAC system was turned off, occupants had left but CO$_2$ remained mixed throughout the building, and cleaning activities had not yet commenced.

4.2.4.2 Indoor and outdoor air quality

Indoor and outdoor air quality parameters were measured continuously and simultaneously at different levels, and the measurements were conducted up to three weeks at each building. However, air quality variables at the front of the air intakes on the rooftop level and inside the offices on level 3 of each building, which was the level closest to, or most strongly influenced by, particle emissions from the surrounding roads (see Quang et al. (2012)) were used for the purpose of this study. The measurement of indoor and outdoor air quality parameters were conducted continuously and simultaneously at different levels up to three weeks at each building. However, air quality variables inside the offices on level 3 of each building, which was the level closest to, or most strongly influenced by, particle emissions from the surrounding roads (see Quang et al. (2012)) were used for the purpose of this study. Indoor PN, PM$_{2.5}$, and CO$_2$ concentrations, along with temperature and relative humidity, were measured inside the offices by a set of instruments comprising a 3025 CPC, a DustTrak and an 8552 QTrak. The indoor air sampling sites were set up in the middle of the office, at a height of approximately 1.2 m, and their locations were carefully considered to avoid the direct influence of nearby occupants and air outlets.

A second set of instruments, consisting of an SMPS, a CPC 3781 and a DustTrak, was used to measure PNSD, PN and PM$_{2.5}$ concentrations at a location adjacent to the outside air intake on the rooftop level of each building. The air sampled from outdoors (i.e. outside the plant room) was delivered to the instruments via a 1 m long conductive tube, with an inner diameter of 6
mm. The locations of all outdoor air sampling points were carefully selected to avoid the influence of nearby HVAC exhaust air. A flow splitter was to distribute air from the sample point to the instruments. Indoor and outdoor particle concentrations were measured simultaneously and measurements were performed continuously for at least 24 hours at each location.

At the same time, background PN and PM$_{10}$ concentrations corresponding to each measurement campaign were obtained from a Queensland Department of Environment and Heritage Protection air quality station, located at the Queensland University of Technology (QUT station), in Brisbane’s CBD (Central Business District). Background PM$_{2.5}$ concentrations for Brisbane CBD were calculated based on PM$_{10}$ concentrations measured at the QUT station, and ratios of PM$_{2.5}$ and PM$_{10}$ concentrations measured at the South Brisbane station, which is another station belonging to the Queensland Department of Environment and Heritage Protection located about 2 km SSE of the QUT station.

### 4.2.4.3 Filter testing

Tests to measure the particle removal efficiency of the total AHU system (AHS), which consisted of DB filters and the air handler itself, were conducted in the level 3 plant rooms of buildings A and C, as well as in the rooftop plant room of Building B. The ES filter used for outdoor air cleaning at the rooftop of Building C was also tested. Two sets of instruments, including the SMPSs, CPCs and DustTraks, were used to simultaneously measure PNSD, PN and PM$_{2.5}$ concentrations. One set measured upstream, while the other measured downstream of the ES and AHS filters, simultaneously. In addition, the filtration efficiency of a fan coil unit (FCU) in one meeting room of Building A was also tested based on measured PN and PM$_{2.5}$ concentrations at the outdoor air intake (upstream) and the supply air outlet (downstream) of the FCU. All filter tests were performed continuously for at least 1 hour. Based on the measured data, the efficiency of each filter was then quantified using the equation below:
\[ FE = \left(1 - \frac{C_{\text{down}}}{C_{\text{up}}} \right) \times 100\% \]  

(4.3)

in which \( C_{\text{down}} \) is the PN or PM\(_{2.5}\) concentration downstream of the filter (\( p \text{ cm}^{-3} \) or \( \mu g \text{ m}^{-3} \), respectively) and \( C_{\text{up}} \) is the PN or PM\(_{2.5}\) concentrations at the upstream of the filter (\( p \text{ cm}^{-3} \) or \( \mu g \text{ m}^{-3} \), respectively).

### 4.2.5 Investigation of indoor particle sources

Laser printers were recently identified as a sources of indoor particles in office environments (He et al., 2007; He et al., 2010; He et al., 2004; McGarry et al., 2011; Morawska et al., 2009a; Schripp et al., 2008). Similarly, vacuum cleaning has also been reported as an indoor particle emission source in domestic and office locations (Afshari et al., 2005; Corsi et al., 2008; Knibbs et al., 2011; Trakumas et al., 2001). Whilst vacuuming is usually done outside working hours, both laser printer and vacuum cleaner emissions were investigated in all three office buildings, in order to gather information suitable for modeling particle concentrations over 24-h periods.

All laser printers identified during a walk-through survey of the office areas in each building were tested. The TSI PTrak was placed 0.5 m above the printer to measure the background office PN concentration (when the printer was off), as well as PN concentration after the printer had printed one page. Ratios of peak PN concentrations after printing to the background PN concentrations were used to classify the printers into four groups, including: non-emitters (ratio \( \leq 1 \)); low emitters (\( 1 < \text{ratio} \leq 5 \)); medium emitters (\( 5 < \text{ratio} \leq 10 \)); and high emitters (ratio \( > 10 \)) based on the approach of He et al. (2007). The frequency and duration of printing were recorded by the investigators for some of the printers in each office and these data, together with printer emission rates obtained from our previous work (He et al., 2007) were used to simulate particle generation by laser printers in these offices.

In-situ emission rates of vacuums were quantified based on the time-series records of PN concentrations inside office areas and records of evening cleaning activities, when the activity
mainly comprised of vacuuming, by using the following Equation 4.4 presented by He et al. (2004):

\[
Q_s = \frac{V}{60n} \left[ C_{\text{int}} - C_{\text{ino}} \Delta T + (a + \lambda)C_{\text{in}} - aP C_{\text{out}} \right] \quad (4.4)
\]

where \( Q_s \) is the average emission rate (p min\(^{-1} \)), \( V \) is the effective volume of measured enclosure room (cm\(^3 \)), \( n \) is the number of vacuum cleaners that operated simultaneously, \( C_{\text{int}} \) and \( C_{\text{ino}} \) are the peak and initial indoor PN concentrations, respectively (p cm\(^{-3} \)), \( C_{\text{in}} \) and \( C_{\text{out}} \) are the average concentrations of indoor and outdoor PN during the time \( \Delta T \), from initial to peak indoor PN concentration (p cm\(^{-3} \)), \( a \) is the air exchange rate (h\(^{-1} \)), \( \lambda \) is the deposition rate (h\(^{-1} \)), and \( P \) is the penetration factor. The equation was previously applied under natural ventilation conditions, however, it can also be used for quantifying vacuum emission rates in office buildings if the mechanical ventilation system is turned off during cleaning activities, as was the case in this study.

4.2.6 Particle concentration modeling

4.2.6.1 Model modification

A dynamic mathematical model derived by Jamriska et al. (2003) was modified by separating the right hand side of the equation into individual components that contribute to indoor particle concentration at time \( t_i \), including (i) the decay of previous indoor particle concentration at time \( t_{i-1} \), (ii) the contribution of indoor sources, and (iii) the contribution of outdoor sources, respectively. Parameters in each component were modified according to the real conditions in each building and assumed constant within one time step. The new model is presented in Equation 4.5. A schematic of the HVAC system and the model input parameters is shown in Figure 4.1.

\[
C_{\text{in}}^{t_i} = C_{\text{in}}^{t_{i-1}} e^{-\alpha_{t_i} \Delta t} + \int_{t_i}^{t_{i+\Delta t}} \frac{g_{t_i}}{\nu} e^{-\alpha_{t_i} \Delta t} dt + C_{\text{out}}^{t_i} \beta_{t_i} \Delta t \quad (p \ cm^{-3}) \quad (4.5)
\]
In cases where the building was located close to busy traffic areas, and indoor PN concentration was mainly influenced by outdoor sources, the influence of indoor particle sources was omitted, and Equation 4.5 was reduced as follows:

$$C_{in}^{t_i} = C_{in}^{t_{i-1}} e^{-\alpha_{t_i} \Delta t} + C_{out}^{t_i} \beta_{t_i} \Delta t \text{ (p cm}^{-3})$$  \hspace{1cm} (4.6)

where:

- $C_{in}^{t_i}$: indoor PN concentration at time $t_i$ (p cm$^{-3}$)
- $C_{in}^{t_{i-1}}$: indoor PN concentration at time $t_{i-1}$ (p cm$^{-3}$)
- $\Delta t$: time step (h)
- $\alpha_{t_i}$: total removal rate of the indoor PN concentrations
  $$\alpha_{t_i} = \frac{3.6 \times 10^3 k}{V} \left(Q_{RA}^{t_i} F_{EAHS} + Q_{exc}^{t_i} + Q_{Esf}^{t_i} + V \lambda_{t_i} \right) \text{ (h}^{-1})$$  \hspace{1cm} (4.7)
- $k$: mixing factor (unitless) ($k = 1$ if perfect air mixing conditions are assumed)
- $V$: effective volume of the enclosure room (m$^3$)
- $Q_{RA}^{t_i}$: return air flow rate at time $t_i$ (m$^3$ s$^{-1}$)
- $F_{EAHS}$: the overall efficiency of the air handing system filter (decimal)
- $Q_{exc}^{t_i}$: general and local exhaust flow rates at time $t_i$ (m$^3$ s$^{-1}$)
- $Q_{Esf}^{t_i}$: exfiltration flow rate at time $t_i$ (m$^3$ s$^{-1}$)
- $\lambda_{t_i}$: particle deposition rate at time $t_i$ (s$^{-1}$)
- $\Delta t$: time period, in which indoor particles are generated (h$^{-1}$)
- $Q_{OA}^{t_i}$: indoor particle emission rate $I$ at time $t_i$ (p s$^{-1}$)
- $C_{out}^{t_i}$: outdoor PN concentration at time $t_i$ (p cm$^{-3}$)
- $\beta_{t_i}$: total penetration rate of outdoor particle indoor
  $$\beta_{t_i} = \frac{3.6 \times 10^3}{V} \left[Q_{OA}^{t_i} (1 - F_{OA})(1 - F_{EAHS}) + Q_{inf}^{t_i} P_{inf}^{t_i} \right] \text{ (h}^{-1})$$  \hspace{1cm} (4.8)
- $Q_{OA}^{t_i}$: outdoor air flow rate at time $t_i$ (m$^3$ s$^{-1}$)
- $F_{OA}$: the overall efficiency of the outdoor air filter (decimal)
- $Q_{inf}^{t_i}$: infiltration flow rate at time $t_i$ (m$^3$ s$^{-1}$)
- $P_{inf}^{t_i}$: penetration factor via the building envelope at time $t_i$ (unitless)
4.2.6.2 Model performance assessment

The real ventilation conditions, outdoor particle concentrations, and particles generated from printing and vacuum cleaning in each building were used to run the model based on assumptions that the changes in particle concentration due to chemical reactions are negligible and the pollutants are well mixed (Kulmala et al., 1999; Nazaroff and Cass, 1989). Predicted indoor particle concentrations were then compared to measured values in these buildings. Quantitative and qualitative tools for evaluation of indoor air quality (IAQ) models provided by ASTM Standard D5157 (ASTM-1997, 2008) were applied to assess the performance of the model. The statistical tools for evaluating the accuracy of the model predictions include (i) the correlation coefficient of predictions compared to measurements ($r$), for which the value should be 0.9 or greater; (ii) the line of regression between the predictions and measurements, which should have a slope ($b$) between 0.75 and 1.25, and an intercept ($a$) less than 25% of the average measured concentration; and (iii) the normalized mean square error ($NMSE$), for which the value should be less than 0.25. All were used to assess our model outputs. Additionally, the bias of the model was measured based on (i) normalized fractional bias of
the mean concentration \((FB)\), for which the value should be 0.25 or lower; and (ii) fractional bias based on the variance \((FS)\), for which the value should be 0.5 or lower.

### 4.2.7 Estimation of indoor particle deposition rates

Equation 4.6 was applied to estimate indoor particle deposition rates in the office buildings when the ventilation was turned off and indoor particle sources were absent (overnight when no cleaning activities occurred). If the air exchange rate and the penetration factor are assumed to not vary, the equation becomes:

\[
C_{in}^{t_i} = C_{in}^{t_{i-1}} e^{-3.6 \times 10^3 (a + \lambda) \Delta t} + 3.6 \times 10^3 C_{out}^{t_i} a P \Delta t \text{ (p cm}^{-3} \text{)} \tag{4.9}
\]

and the indoor particle deposition rates will be estimated as:

\[
\lambda = -\frac{1}{3.6 \times 10^3 \Delta t} \left( a + \ln \frac{C_{in}^{t_i} - 3.6 \times 10^3 C_{out}^{t_i} a P \Delta t}{C_{in}^{t_{i-1}}} \right) \text{ (s}^{-1} \text{)} \tag{4.10}
\]

where \(C_{in}^{t_i}\) and \(C_{in}^{t_{i-1}}\) are the outdoor and indoor PN concentrations at time \(t_i\), respectively; \(C_{in}^{t_{i-1}}\) is the indoor PN concentration at time \(t_{i-1}\); \(\Delta t\) is the time step; \(a\) and \(P\) are the air exchange rate and penetration factor, respectively, when the ventilation system is turned off.

### 4.2.8 Data analysis

The results from the particle measurements were grouped according to their outdoor and indoor location, along with the time period of the measurements, and 24h average outdoor concentrations were calculated for each building space. The indoor air concentrations were then classified as: (1) HVAC ON and no indoor occupants and activities (6:00 – 8:30 and 17:00 – 18:00, and during the weekend); (2) HVAC ON during working hours (8:30 – 17:00); (3) HVAC OFF and no indoor occupants and activities (18:00 – 19:00, 23:00 – 6:00, and during the weekend); (4) HVAC OFF and cleaning activities (usually from 19:00 to 23:00 on weekdays); (5) during rush-hours (from 6:00 – 9:00 and 16:00 – 19:00 on weekdays); and (6) during nucleation events. The identification of nucleation events during each field
measurement campaign was reported in our previous work (Quang et al., 2012). All statistical analyses (correlation, regression, t-test and One-Way ANOVA) were conducted using SPSS for Windows version 18 (SPSS Inc.). The 5% level was used to indicate statistical significance in all cases.

4.3 Results and discussion

4.3.1 Air exchange rates and CO₂ concentrations

Average air exchange rates (AERs) for level 3 of each building are presented in Table 4.1. As expected, the AERs were markedly higher when the ventilation was turned on compared to when it was off, even with consideration of the different measurement methods used. It is important to note that the ventilation system in Building B was operated in energy saving mode in the summer, which resulted in a significantly lower AER for Building B when the ventilation system was on compared to the other two buildings, where measurements were performed in the winter. This also led to a significantly higher CO₂ concentration (ppm) in Building B (Mean ±SD, 826 ± 91) compared to Buildings A (674 ± 28) and C (675 ± 61) ($p < 0.01$), however the CO₂ concentrations were not significantly different when the ventilation systems were turned off in all three buildings over the weekend (475 ± 6, 467 ± 5 and 481 ± 23 for Buildings A, B and C, respectively) ($p = 0.46$). The overall average CO₂ concentrations in all three buildings were lower than the guideline concentration of 1000 ppm for office buildings, as outlined in the ANSI/ASHRAE 62.1 Standard (ASHRAE, 2010).

Table 4.1. Average air exchange rates (h⁻¹)

<table>
<thead>
<tr>
<th>Site</th>
<th>HVAC ON*</th>
<th>HVAC OFF**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building A</td>
<td>1.19</td>
<td>0.08</td>
</tr>
<tr>
<td>Building B</td>
<td>0.37</td>
<td>0.11</td>
</tr>
<tr>
<td>Building C</td>
<td>0.89</td>
<td>0.12</td>
</tr>
</tbody>
</table>

* Based on ventilated outdoor air flow rates; ** Based on the decay of CO₂ concentrations
4.3.2 Outdoor and indoor particle concentrations

A summary of the descriptive statistics for outdoor and indoor particle concentrations at each building are presented in Figure 4.2 and Table 4.9-S1. In general, overall 24 h average outdoor particle concentrations were significantly higher than indoor concentrations for all three buildings ($p < 0.01$). Apart from PN concentration for Building B, outdoor particle concentrations were also significantly higher than background concentrations measured simultaneously in Brisbane CBD; the results of these comparisons are presented in Table 4.2. Both outdoor PN and PM$_{2.5}$ concentrations for Building A were significantly higher than those for Buildings B and C ($p < 0.01$), while their relevant background concentrations were comparable. This was due to location of Building A’s air intakes, which were sited proximate to the busway, compared to those of Building B and C, which were located on higher rooftop levels (level 18 and level 6, respectively). Indoor PN concentrations in the three buildings were comparable with the PN concentration measured in an office building in Brisbane’s CBD by Jamriska et al. (2000). However, indoor PN and PM$_{2.5}$ concentrations were significantly higher in Building A compared to Buildings B and C ($p < 0.01$). The highest indoor particle concentrations in Building A were the result of higher outdoor particle concentrations and outdoor ventilation rates for this building.

Table 4.2. Comparison of overall 24 h average outdoor particle concentrations at each building with those measured simultaneously in Brisbane’s CBD at a background site

<table>
<thead>
<tr>
<th>Building</th>
<th>PN ($\times 10^3$ p cm$^{-3}$) (Mean ± 95% CI)</th>
<th>PM$_{2.5}$ (µg m$^{-3}$) (Mean ± 95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building A</td>
<td>17.4 ± 1.33</td>
<td>13.9 ± 0.38</td>
</tr>
<tr>
<td>Brisbane CBD</td>
<td>7.42 ± 0.34</td>
<td>8.16 ± 0.17</td>
</tr>
<tr>
<td>$p$</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td>Building B</td>
<td>8.94 ± 1.12</td>
<td>9.5 ± 0.28</td>
</tr>
<tr>
<td>Brisbane CBD</td>
<td>7.65 ± 1.89</td>
<td>6.33 ± 0.34</td>
</tr>
<tr>
<td>$p$</td>
<td>0.25</td>
<td>$&lt; 0.05$</td>
</tr>
<tr>
<td>Building C</td>
<td>11.48 ± 0.58</td>
<td>9.25 ± 0.27</td>
</tr>
<tr>
<td>Brisbane CBD</td>
<td>8.59 ± 0.4</td>
<td>5.7 ± 0.14</td>
</tr>
<tr>
<td>$p$</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
</tr>
</tbody>
</table>
4.3.3 Filter efficiency measurements

4.3.3.1 Central filtration systems

Overall and fractional filter efficiencies for the air handling system (AHS - consisting of a DB filter and an AHU) at Buildings A, B and C, and the ES filter for Building C, are presented in Figure 4.3 and Figure 4.4, respectively. The overall filter efficiency, for Building A ($46.9 \pm 11.6 \%$) was significantly higher than those for Building B ($26.3 \pm 4.1 \%$) and Building C ($26.4 \pm 2.3 \%$) ($p < 0.01$). The higher filter efficiency for Building A was likely to be due to higher dust-loading, because outdoor and indoor particle concentrations at this building were significantly higher than those at Buildings B and C (Hanley et al., 1994). The overall filtration efficiencies of the AHS for each building were comparable to the efficiency of an office building AHU system (34%) with deep-bag filters in Brisbane reported by Jamriska et
al. (2000). This validates the results of both the present study and that performed by Jamriska et al. (2000) to some extent, and further analyses are presented in the following sections.

Fractional efficiencies of the filters decreased with increasing particle size, and reached a minimum for particles approximately 70-110 nm in size, prior to increasing again for larger particle sizes (Figure 4.4). The increase in filtration efficiency for smaller and larger particles is caused by diffusion and impaction processes, respectively (Hanley et al., 1994). The overall filter efficiency for Buildings B and C were not significantly different. However, the fractional filter efficiencies at Building B compared to Building C were respectively higher and lower for 9-60 nm and 60-340 nm particles. These differences are likely to be due to the use of ES filters in Building C, which can significantly reduce the concentration of smaller outdoor particles in the air, before they are transported to the DB filter.

The filtration efficiency of the ES filters in the rooftop plant room of Building C was 60.2 ± 9 %. This result was lower than the results of previous laboratory studies (80 – 95%), which were reported by Jamriska et al. (1998). In addition, the fractional efficiency of the ES filter was at a maximum for particles around 10 nm in size, which then decreased as particle size increased, while laboratory tests for new ES filters showed a maximum efficiency for particles in the size range 40-50 nm, with a large drop in filtration efficiency below 30 nm and a gradual decrease for particles larger than 60 nm (Jamriska et al., 1998).
4.3.3.2 Fan coil unit

Particle concentrations downstream (in the supply air at an air outlet) and upstream (in the outdoor air at an air intake) of a fan coil unit (FCU) were measured for a meeting room in Building A (Figure 4.5). In general, it can be seen that variations in downstream particle concentration followed variations in upstream particle concentrations when the FCU was turned on (indicated by the sharp decrease in indoor temperature), however when the FCU was turned off, the downstream particle concentrations started to decline. The filtration
efficiency of the FCU, including its upstream air duct, was \((21 \pm 14)\%\), which is significantly lower than for the filters in the central plant room of this building \((p < 0.01)\). This implies that directly drawing outdoor air via the FCU, in order to introduce more fresh air into the room, also introduced an increased proportion of outdoor particles than would be expected if the room was ventilated by the central AHU.

Figure 4.5. Time-series of particle concentrations in outdoor air and supply air before, during and after the operation of the FCU.

4.3.4 I/O ratios of particle concentrations

Indoor to outdoor (I/O) ratios of PN and PM\(_{2.5}\) concentrations for different time periods and ventilation scenarios, including: Daily, Cleaning (during cleaning with the HVAC system off), Off/absence (vacant office with the HVAC system off), On/absence (vacant office with the HVAC system on) and Working (during working hours with the HVAC system on), are presented in Figure 4.6 and Table 4.10-S2. The comparisons of I/O ratios during different time periods and ventilation scenarios for each building are presented in Table 4.3, while the
comparisons of indoor particle concentrations and their I/O ratios during nucleation and rush-hour periods with their working-hours periods, respectively are presented in Table 4.4.

Table 4.3. I/O ratios (Mean ± SD) for different time periods and ventilation scenarios for each building

<table>
<thead>
<tr>
<th>Building</th>
<th>Unoccupied HVAC off</th>
<th>HVAC on</th>
<th>p</th>
<th>Unoccupied HVAC off</th>
<th>HVAC on</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>PN 0.34 ± 0.1</td>
<td>0.20 ± 0.03</td>
<td>&lt; 0.01</td>
<td>0.20 ± 0.03</td>
<td>0.34 ± 0.09</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>PM$_{2.5}$ 0.51 ± 0.07</td>
<td>0.38 ± 0.02</td>
<td>&lt; 0.01</td>
<td>0.38 ± 0.02</td>
<td>0.53 ± 0.10</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>B</td>
<td>PN 0.25 ± 0.07</td>
<td>0.20 ± 0.09</td>
<td>&lt; 0.05</td>
<td>0.20 ± 0.09</td>
<td>0.29 ± 0.10</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>PM$_{2.5}$ 0.71 ± 0.08</td>
<td>0.65 ± 0.04</td>
<td>&lt; 0.05</td>
<td>0.65 ± 0.04</td>
<td>0.66 ± 0.10</td>
<td>0.48</td>
</tr>
<tr>
<td>C</td>
<td>PN 0.20 ± 0.03</td>
<td>0.13 ± 0.05</td>
<td>&lt; 0.05</td>
<td>0.13 ± 0.05</td>
<td>0.18 ± 0.05</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>PM$_{2.5}$ 0.76 ± 0.03</td>
<td>0.74 ± 0.1</td>
<td>0.37</td>
<td>0.74 ± 0.01</td>
<td>0.91 ± 0.03</td>
<td>&lt; 0.01</td>
</tr>
</tbody>
</table>

Table 4.4. Indoor particle concentrations and I/O ratios during rush-hours and nucleation events

<table>
<thead>
<tr>
<th>Build.</th>
<th>Concentrations (Mean ± SD)</th>
<th>p</th>
<th>I/O ratio (Mean ± SD)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Working hours</td>
<td>Nucleation</td>
<td></td>
<td>Working hours</td>
</tr>
<tr>
<td>A</td>
<td>PN ($\times 10^3$ p cm$^{-3}$) 3.64 ± 0.52</td>
<td>4.02 ± 0.62</td>
<td>&lt; 0.01</td>
<td>0.30 ± 0.07</td>
</tr>
<tr>
<td></td>
<td>PM$_{2.5}$ ($\mu$g m$^{-3}$) 8.62 ± 0.57</td>
<td>9.0 ± 0.22</td>
<td>&lt; 0.01</td>
<td>0.8 ± 0.09</td>
</tr>
<tr>
<td>B</td>
<td>PN ($\times 10^3$ p cm$^{-3}$) 4.56 ± 3.38</td>
<td>7.14 ± 2.92</td>
<td>&lt; 0.01</td>
<td>0.10 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>PM$_{2.5}$ ($\mu$g m$^{-3}$) 5.22 ± 0.22</td>
<td>5.14 ± 0.02</td>
<td>&lt; 0.01</td>
<td>0.86 ± 0.04</td>
</tr>
<tr>
<td>C</td>
<td>PN ($\times 10^3$ p cm$^{-3}$) 3.4 ± 0.64</td>
<td>4.0 ± 0.52</td>
<td>&lt; 0.01</td>
<td>0.29 ± 0.17</td>
</tr>
<tr>
<td></td>
<td>PM$_{2.5}$ ($\mu$g m$^{-3}$) 5.16 ± 0.3</td>
<td>4.93 ± 0.13</td>
<td>&lt; 0.01</td>
<td>0.86 ± 0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Build.</th>
<th>Concentrations (Mean ± SD)</th>
<th>p</th>
<th>I/O ratio (Mean ± SD)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Working hours</td>
<td>Rush-hours</td>
<td></td>
<td>Working hours</td>
</tr>
<tr>
<td>A</td>
<td>PN ($\times 10^3$ p cm$^{-3}$) 4.08 ± 1.29</td>
<td>4.83 ± 0.68</td>
<td>&lt; 0.01</td>
<td>0.35 ± 0.12</td>
</tr>
<tr>
<td></td>
<td>PM$_{2.5}$ ($\mu$g m$^{-3}$) 6.9 ± 0.29</td>
<td>7.12 ± 0.17</td>
<td>&lt; 0.01</td>
<td>0.63 ± 0.11</td>
</tr>
<tr>
<td>B</td>
<td>PN ($\times 10^3$ p cm$^{-3}$) 2.82 ± 0.93</td>
<td>3.98 ± 0.54</td>
<td>&lt; 0.01</td>
<td>0.19 ± 0.09</td>
</tr>
<tr>
<td></td>
<td>PM$_{2.5}$ ($\mu$g m$^{-3}$) 6.48 ± 0.38</td>
<td>6.79 ± 0.04</td>
<td>&lt; 0.01</td>
<td>0.72 ± 0.04</td>
</tr>
<tr>
<td>C</td>
<td>PN ($\times 10^3$ p cm$^{-3}$) 4.69 ± 3.63</td>
<td>5.08 ± 1.55</td>
<td>&lt; 0.05</td>
<td>0.25 ± 0.22</td>
</tr>
<tr>
<td></td>
<td>PM$_{2.5}$ ($\mu$g m$^{-3}$) 5.55 ± 0.48</td>
<td>6.17 ± 0.29</td>
<td>&lt; 0.01</td>
<td>0.69 ± 0.12</td>
</tr>
</tbody>
</table>
In general, the I/O ratios for both PN and PM$_{2.5}$ concentrations were less than 1, and agree well with the results of other studies conducted in mechanically ventilated buildings (Koponen et al., 2001; Wang et al., 2010; Wu et al., 2012). However, the I/O ratios of PM$_{2.5}$ concentrations were significantly higher than those for PN concentrations for all three buildings ($p < 0.01$). This implies that indoor PN concentration was strongly influenced by high outdoor PN sources, while indoor PM$_{2.5}$ levels were more influenced by sources inside the buildings, which is similar to the previous studies (Abt et al., 2000a; Abt et al., 2000b; Long et al., 2000). Another contribution factor is the lower efficiency of the DB filters for particles at the lower end of the PM$_{2.5}$ range (~0.1 micron).

The I/O ratios for both PN and PM$_{2.5}$ during cleaning had the highest values compared to other time periods at all three buildings ($p < 0.01$). This is not surprising, given that vacuum
cleaner motors can release large amounts of fine and ultrafine particles (Afshari et al., 2005; Géhin et al., 2008; He et al., 2004; Knibbs et al., 2011; Trakumas et al., 2001), and vacuuming can also re-suspend larger size particles (Corsi et al., 2008; Ferro et al., 2004; Vaughan et al., 1999) inside the building.

When the office was vacant, the I/O ratios were significantly lower when the HVAC system was on compared to when it was off, for all three buildings ($p < 0.05$). This shows that the filters not only contributed to preventing the penetration of outdoor particles indoors, but they also served to reduce existing indoor particle concentrations (Jamriska et al., 2003; Zuraimi and Tham, 2009).

The I/O ratios in the presence of the office occupants were significantly higher than those in their absence ($p < 0.05$) for all three buildings. The movement of occupants and the activities they undertake, together with the operation of office equipment, particularly laser printers, have been shown to increase indoor particle concentrations during working hours (He et al., 2007; He et al., 2010; Long et al., 2000; McGarry et al., 2011; Morawska et al., 2009a; Schripp et al., 2008). Further discussion of these factors is provided in Section 4.3.6.3.

When the ventilation system was turned on, the I/O ratios of PN concentration during both the absence and presence of occupants for Building C were significantly lower than those for Buildings A and B ($p < 0.01$). As discussed earlier, the use of the ES filters in Building C markedly reduced the amount of smaller particles which penetrated from outdoors.

The I/O ratios during rush-hours and nucleation events were significantly lower than those during overall working hours on the measurement days, however, the opposite was true for indoor PN concentrations (refer to Table 4.4 for comparative results). In addition, the correlations of indoor and outdoor PN concentration during these periods were very good for all three buildings. These results show that indoor PN was mainly influenced by outdoor
concentrations, and therefore, building occupants were exposed to higher particle concentrations from outdoors during rush-hours and nucleation events.

4.3.5 Investigation of indoor particle sources

A summary of the printer investigations conducted in the offices on level 3 of each building is presented in Table 4.5. These data, together with the printer emission rates reported by He et al. (2007) were used as model input data to quantify the number of particles generated by printing (Table 4.6).

The total emission rates of vacuuming (i.e. the vacuum emission and resuspension) were quantified based on Equation 4.4, using the measured data from Buildings A and C. The calculated emission rates were $5.05 \times 10^{11}$ p min$^{-1}$ and $5.34 \times 10^{11}$ p min$^{-1}$ for Building A and C, respectively. These results are higher than the emission rates from vacuum cleaners reported by Knibbs et al. (2011), Szymczak et al. (2007), and He et al. (2004). However, they are lower than the emission rate obtained by Gehin et al. (2008). Then these emission rates were used for 24-h modeling of indoor particle levels to determine the contribution of cleaning.

Table 4.5. Printer profiles on level 3 of Buildings A, B and C*

<table>
<thead>
<tr>
<th>Building</th>
<th>Total printers</th>
<th>Printer emission classification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Non</td>
</tr>
<tr>
<td>A</td>
<td>15</td>
<td>7</td>
</tr>
<tr>
<td>B</td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>14</td>
<td>1</td>
</tr>
</tbody>
</table>

*The criteria to determine printer emission class was defined in the section 4.2.5

4.3.6 Modeling of indoor PN concentrations

4.3.6.1 Model input parameters

The mathematical model, which was presented by Jamriska et al. (2003) for theoretical studies, was modified to account for the real conditions encountered in each building we assessed. Model input parameters were based on both measured data and those reported in the
literature. The penetration factor was determined based on the experimental measurement by Liu and Nazaroff (2003). As mentioned previously, the exterior walls of all three buildings were made from glass, so the main penetration pathway for outdoor air was cracks in aluminium window frames. The height and the length of cracks was assumed 0.25 mm and 4.3 cm, respectively, which were the lower range in the experiment and were appropriate for the tighter envelope of air-conditioned office buildings. The penetration rate was found to be 0.8 and 0.6 when the ventilation was on (I-O pressure difference $\Delta P = 10$ Pa) and off ($\Delta P = 4$ Pa), respectively.

Particle deposition rates with the ventilation turned on were based on a previous calculation (Jamriska et al., 2003), while rates when ventilation was turned off were quantified based on Equation 4.10 and the measured data in Building B. The measured indoor and outdoor PN concentrations, as well as the ventilation flow rates, filter efficiencies and particle concentrations generated from laser printing and vacuum cleaning in each building were used to run the 24 h model simulations. The input data used in the model are summarised in Table 4.6.

### Table 4.6. Summary of model input parameters

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Sym.</th>
<th>Building A</th>
<th>Building B</th>
<th>Building C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air flow rate (m$^3$ s$^{-1}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outdoor</td>
<td>$Q_{oa}$</td>
<td>0-3.25</td>
<td>0-0.45</td>
<td>0-1.05</td>
</tr>
<tr>
<td>Return</td>
<td>$Q_{ra}$</td>
<td>0-13.8</td>
<td>0-7.25</td>
<td>0-4.85</td>
</tr>
<tr>
<td>Supply</td>
<td>$Q_{sa}$</td>
<td>0-15.8</td>
<td>0-7.7</td>
<td>0-5.9</td>
</tr>
<tr>
<td>Exceed</td>
<td>$Q_{exc}$</td>
<td>0-3.25</td>
<td>0-0.45</td>
<td>0-1.05</td>
</tr>
<tr>
<td>Infiltration</td>
<td>$Q_{inf}$</td>
<td>0.18</td>
<td>0.13</td>
<td>0.14</td>
</tr>
<tr>
<td>Exfiltration</td>
<td>$Q_{ef}$</td>
<td>0.18</td>
<td>0.13</td>
<td>0.14</td>
</tr>
<tr>
<td>Room effective volume (m$^3$)</td>
<td>$V_{room}$</td>
<td>7.94 $\times$ 10$^3$</td>
<td>4.38 $\times$ 10$^3$</td>
<td>4.25 $\times$ 10$^3$</td>
</tr>
<tr>
<td>Mixing factor</td>
<td>$k$</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Filter efficiency (mixing air)</td>
<td>$FE_{AHS}$</td>
<td>0.47</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>Filter efficiency (outdoor air)</td>
<td>$FE_{OA}$</td>
<td>-</td>
<td>-</td>
<td>0.60</td>
</tr>
<tr>
<td>Penetration factor</td>
<td>$P_{bld}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ventilation ON</td>
<td></td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Ventilation OFF</td>
<td></td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Deposition rate (s$^{-1}$)</td>
<td>$\lambda$</td>
<td>4.51 $\times$ 10$^{-5}$</td>
<td>4.51 $\times$ 10$^{-5}$</td>
<td>4.51 $\times$ 10$^{-5}$</td>
</tr>
<tr>
<td>Input parameter</td>
<td>Sym.</td>
<td>Building A</td>
<td>Building B</td>
<td>Building C</td>
</tr>
<tr>
<td>------------------------------------------------------</td>
<td>--------</td>
<td>------------</td>
<td>------------</td>
<td>------------</td>
</tr>
<tr>
<td>Ventilation OFF</td>
<td>2.51 × 10^5</td>
<td>2.51 × 10^5</td>
<td>2.51 × 10^5</td>
<td></td>
</tr>
<tr>
<td>Laser printer emission rate (p min^-1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low emission</td>
<td>9 × 10^9</td>
<td>9 × 10^9</td>
<td>9 × 10^9</td>
<td></td>
</tr>
<tr>
<td>Medium emission</td>
<td>90 × 10^9</td>
<td>90 × 10^9</td>
<td>90 × 10^9</td>
<td></td>
</tr>
<tr>
<td>High emission</td>
<td>150 × 10^9</td>
<td>150 × 10^9</td>
<td>150 × 10^9</td>
<td></td>
</tr>
<tr>
<td>Vacuum cleaner emission rate (p min^-1)</td>
<td>2.02 × 10^{12}</td>
<td>-</td>
<td>2.14 × 10^{12}</td>
<td></td>
</tr>
</tbody>
</table>

4.3.6.2 Model performance assessment

The 24 h modelled and measured PN concentrations for the three buildings are presented in Figure 4.7, Figure 4.8 and Figure 4.9, respectively. Statistical indicators from ASTM D5157 were applied to evaluate the performance of the model, including correlation coefficients of predictions compared to measurements (r), the slope (b) and intercept (a) of the line of regression between the predictions and measurements, normalised mean square error (NMSE), normalised fractional bias of the mean concentration (FB), and fractional bias based on the variance (FS). These indicators were calculated for each building, with the ventilation system turned on and off, and are shown in Table 4.7. All simulations for Building A met the ASTM D5157 indicator criteria, as did those for Buildings B and C when the ventilation system was turned off. When the ventilation system was turned on, the correlation coefficient for Building B was lower than the criterion, as were the correlation coefficient, the slope of the regression line and the normalized mean square error values for Building C. These results indicate that the model performed better when evaluating the 24 h PN concentrations for Building A and the night-time PN concentrations (i.e. when the ventilation system was turned off) for Buildings B and C. This is unsurprising since there are less variables to influence concentration (both in terms of number and intensity) when the ventilation is turned off. It was also found that the accuracy of the predicted concentrations was higher when the main source of indoor particles was from outdoor air, or when ventilation was turned off. Nevertheless, model performance remained serviceable even when the ASTM criteria were unmet, as Table 4.7, Figure 4.8 and Figure 4.9 highlight. This indicates the appropriateness
of this approach for predicting PN concentrations and the factors that influence them in office buildings. Emmerich and Nabinger (2001) also applied the ASTM D5157 standard to evaluate an experimental indoor PN concentration model. However, to the best of our knowledge there is no information available in the literature regarding the use of these criteria for assessment of a theoretical dynamic model for indoor PN concentration.

Table 4.7. Summary of model evaluation indicators based on comparison of measured and modelled results

<table>
<thead>
<tr>
<th>Site</th>
<th>Period</th>
<th>$r$</th>
<th>$a$</th>
<th>$b$</th>
<th>NMSE</th>
<th>FB</th>
<th>FS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building A</td>
<td>Ventilation on</td>
<td>0.92</td>
<td>-356</td>
<td>0.92</td>
<td>0.04</td>
<td>-0.14</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Ventilation off</td>
<td>0.94</td>
<td>59</td>
<td>0.99</td>
<td>0.01</td>
<td>0.00</td>
<td>0.09</td>
</tr>
<tr>
<td>Building B</td>
<td>Ventilation on</td>
<td>0.84</td>
<td>37</td>
<td>0.78</td>
<td>0.10</td>
<td>-0.23</td>
<td>-0.15</td>
</tr>
<tr>
<td></td>
<td>Ventilation off</td>
<td>0.93</td>
<td>-167</td>
<td>1.04</td>
<td>0.00</td>
<td>-0.02</td>
<td>0.23</td>
</tr>
<tr>
<td>Building C</td>
<td>Ventilation on</td>
<td>0.88</td>
<td>1124</td>
<td>0.50</td>
<td>0.36</td>
<td>-0.34</td>
<td>-1.04</td>
</tr>
<tr>
<td></td>
<td>Ventilation off</td>
<td>0.91</td>
<td>47</td>
<td>1.02</td>
<td>0.05</td>
<td>0.05</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Figure 4.7. PN concentrations for Building A (Modeled versus Measured).
Figure 4.8. PN concentrations for Building B (Modeled versus Measured).

Figure 4.9. PN concentrations for Building C (Modeled versus Measured).
4.3.6.3 Evaluation of the influence of ventilation/filtration on indoor PN concentration

Indoor PN concentrations were also predicted using the model, for situations where concentrations were only influenced by outdoor sources, named “only outdoor”, and when they were influenced by both outdoor sources and printer emissions, named “outdoor and printing”. Ratios of predicted indoor PN concentrations, together with measured indoor PN concentrations during the working-hours for each building were calculated and are presented in Table 8. The average ratio of “only outdoor” sources for Building A was significantly higher than for the other two buildings, while the average ratio for Building C was significantly lower ($p < 0.01$). This indicates that indoor PN concentrations for Building A were more strongly influenced by outdoor particles, while Building C was less strongly influenced by outdoor particles, as a result of the use of ES filters for cleaning outdoor air. Comparing “only outdoor” ratios and “outdoor and printing” ratios for the three buildings, we found that the contribution of printing and other indoor sources was significantly higher for Building C, but significantly lower for Building A compared to the other buildings. In addition, these ratios can be used to estimate the contribution of different sources to indoor PN concentration levels. For instance, the percentage contribution of outdoor sources, printing, and other indoor sources to indoor particle concentration in Building A and C were approximately 85%, 2%, 13%, and 66%, 11%, 23%, respectively.

To further evaluate the influence of filtration on indoor particle concentrations, the existing filters at Building A were assumed to operate under three different scenarios: (1) filtration of mixing air only (which is currently used), (2) filtration of outdoor air only, and (3) filtration both mixing air and outdoor air. The indoor PN concentrations for these different filtration scenarios are illustrated in Figure 4.10. The predicted concentrations were close to the measured values when the filter was applied to the mixing air flow. However, they are predicted to increase by 77% and decrease by 43% if the filter is applied to the outdoor air flow only, or both outdoor air and mixing air flows, respectively. These results indicate that,
not only the efficiency of a filter, but also the air streams which pass through it, has a significant influence on indoor particle levels, and using filters for both mixing and outdoor air flows can dramatically reduce indoor particle levels in mechanically ventilated buildings. Also, the effects of changes in filter type, efficiency and position in the air stream on indoor particle concentrations can be predicted relatively simply using the approach outlined here, which is often a more practical option compared to the more time and cost-intensive alternative of measurements.

Table 4.8. Ratios (Mean ± SD) of predicted and measured indoor PN concentrations during working hours

<table>
<thead>
<tr>
<th>Site</th>
<th>Only outdoor</th>
<th>Outdoor and printing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building A</td>
<td>0.85 ± 0.13</td>
<td>0.87 ± 0.12</td>
</tr>
<tr>
<td>Building B</td>
<td>0.72 ± 0.17</td>
<td>0.80 ± 0.15</td>
</tr>
<tr>
<td>Building C</td>
<td>0.66 ± 0.24</td>
<td>0.77 ± 0.19</td>
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</table>

Figure 4.10. PN concentrations at Building A at different scenarios.
4.4 Conclusions

We investigated the influence of ventilation and filtration on indoor particle concentrations within office buildings located close to busy traffic areas based on both experimental measurements and modelling. The findings of this study and their implications are summarised below.

The average indoor PN and PM$_{2.5}$ concentrations were $(2.46 - 5.71) \times 10^3$ p cm$^{-3}$ and $5.2 - 6.81$ µg m$^{-3}$, respectively, and the average outdoor PN and PM$_{2.5}$ concentrations were $(8.94 - 17.4) \times 10^3$ p cm$^{-3}$ and $9.25 - 13.9$ µg m$^{-3}$, respectively, for the three buildings. The significantly higher indoor and outdoor particle concentrations for Building A compared to Buildings B and C were due to the proximity of this building’s air intakes to a strong outdoor particle source (i.e. busway). This suggests that the physical position of the HVAC system’s outdoor air intakes can significantly reduce the impact of outdoor particles on indoor air, and this should always feature highly in considerations at the design phase.

The in-situ efficiency of deep bag filters ranged from 26.3 to 46.9% for the three buildings, while the efficiency of the electrostatic filter in Building C was 60.2% and the efficiency of the FCU filter in Building A was 21%. The results show that the efficiency of the DB filters was strongly affected by particle characteristics, in particular particle size and particle upstream concentration. The efficiency of the ES filter was lower than those tested in the laboratory, which could be due to the different operating conditions and upstream particle characteristics between the real-world and laboratory environments. However, this work only measured one ES filter in one office building and therefore, further investigations into in-situ ES filter efficiency under different conditions are required prior to any conclusive recommendations regarding their relative advantages and disadvantages compared to DB filters. Additionally, the overall filtration efficiency of the FCU filter was significantly lower than in the central plant rooms. This result strongly suggests that FCUs should be assessed for
in order their capacity to clean outdoor air to the same extent as the central HVAC system, such that changes can be made accordingly.

The I/O particle concentration ratios showed that mixing air filters not only prevent outdoor particles penetrating indoors but they also reduce the impact of indoor particle sources on indoor particle concentrations. Also, the utilisation of both outdoor and mixing air filters can significantly reduce and keep indoor particle concentration lower when compared to mixing air filters alone.

Based on the comparison of I/O particle concentration ratios and their I/O correlation during rush-hours, nucleation events and overall working-hours, the results indicate that indoor PN concentration was strongly influenced by outdoor PN concentration during rush-hours and nucleation events. Many studies have investigated outdoor particle formation and its effect on regional environments or climate change, but they are yet to focus on their effects on indoor environments, especially office buildings where many people spend an appreciable proportion of their day. This work highlights the potentially under-appreciated role of nucleation in generating particles that can penetrate inside buildings and contribute to exposures incurred by large numbers of people.

A previously developed dynamic model for indoor PN concentration was modified, evaluated and applied to assess the influence of filtration and ventilation on indoor particle levels under different indoor and outdoor particle source conditions. The results of 24 h modelling for all buildings indicated that the model generally performed very well against evaluation criteria under most scenarios, and offered serviceable performance even when for criteria were not met.

These findings provide scientific grounds for the selection and location of appropriate filters and air intakes in building HVAC systems, in order to minimise occupant exposure to high outdoor particle concentrations from both combustion products and new particle formation.
typical of urban areas. The modelling approach reported here can be used either prior to
construction to determine optimum filtration media and operating characteristics or post-
occupancy to determine the likely effects of changes to these. The results also provide
information to improve understanding of indoor particle dynamics and behaviours in office
buildings under different ventilation scenarios.

Acknowledgement

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building managers and the security staff at each of the buildings we investigated and Ms
Rachael Appleby from the International Laboratory for Air Quality and Health, for assisting
us during the project implementation.

4.5 References

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### 4.6 Supplementary Information

Table 4.9-S1. Descriptive statistics for indoor and outdoor particle concentrations

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<tr>
<th>Site</th>
<th>Statistic description</th>
<th>PN ($\times 10^3$ p cm$^{-3}$)</th>
<th>I/O</th>
<th>PM$_{2.5}$ ($\mu$g m$^{-3}$)</th>
<th>I/O</th>
</tr>
</thead>
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<td></td>
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<td></td>
<td>Outdoor</td>
<td></td>
</tr>
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Table 4.10-S2. I/O ratios of PN and PM$_{2.5}$ concentrations at Buildings A, B and C

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<th>Daily PM$_{2.5}$</th>
<th>Cleaning PN</th>
<th>Cleaning PM$_{2.5}$</th>
<th>Off/absence PN</th>
<th>Off/absence PM$_{2.5}$</th>
<th>On/absence PN</th>
<th>On/absence PM$_{2.5}$</th>
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Figure 4.11-S1. Schematic diagram of the HVAC systems at Buildings A, B and C.
Optimisation of Indoor Environmental Quality and Energy Consumption within Urban Office Buildings

Tran Ngoc Quang\textsuperscript{1,3}, Congrong He\textsuperscript{1}, Luke D. Knibbs\textsuperscript{1,4}, Richard de Dear\textsuperscript{2} and Lidia Morawska\textsuperscript{1}

\textsuperscript{1}International Laboratory for Air Quality and Health, Queensland University of Technology, Brisbane, QLD 4001, Australia
\textsuperscript{2}Faculty of Architecture, Design and Planning, The University of Sydney, NSW 2006, Australia
\textsuperscript{3}Institute of Environmental Science and Engineering, National University of Civil Engineering, Hanoi, Vietnam
\textsuperscript{4}School of Population Health, The University of Queensland, Herston, QLD4006, Australia

Re-submitting for Publication to the \textit{Building and Environment} Journal
STATEMENT OF JOINT AUTHORSHIP

Title: Optimisation of indoor environmental quality and energy consumption within urban office buildings

Authors: Tran Ngoc Quang, Congrong He, Luke D. Knibbs, Richard de Dear and Lidia Morawska

Tran Ngoc Quang (Candidate)
Conducted the thermal comfort survey and measurements; collected, analysed and interpreted the thermal comfort data; developed, assessed and applied the models to analyse indoor environmental quality and energy usage in office buildings; and wrote the manuscript.

Congrong He
Conducted the thermal comfort survey and measurements; commented on the development of the models, the interpretation of the data and the writing of the manuscript.

Luke D. Knibbs
Designed and conducted the thermal comfort survey and measurements; and contributed to the writing of the manuscript.

Richard de Dear
Assisted in the experimental design of the thermal comfort survey and measurements; assisted in the interpretation of the thermal comfort data; and proof reading.

Lidia Morawska
Commented on the development of the models, the interpretation of the data and the writing of the manuscript; and proof reading.
5 Optimisation of Indoor Environmental Quality and Energy Consumption within Urban Office Buildings

Abstract

Many studies have shown that indoor air quality is strongly influenced by outdoor pollution and especially high outdoor particle levels from vehicle emissions and new particle formation in urban areas. However, indoor particle concentrations are not considered in most cases when designing and optimising building HVAC (Heating, Ventilation and Air Conditioning) systems. This study aimed to develop a multi-component model that can be applied to maximise indoor environmental quality, which includes indoor particle number (PN) and CO₂ concentrations, and indoor thermal comfort while minimising energy usage inside mechanically ventilated office buildings. The integrated model, which was fed with experimental data, was employed to assess the potential improvement of indoor air quality and energy saving under different ventilation conditions in air-conditioned office buildings in Brisbane, Australia. When operating the ventilation system under predicted optimal conditions of indoor environmental quality and energy conservation and using outdoor air filtration, average indoor PN concentration decreased by up to 4 times, while indoor CO₂ concentration and energy consumption were not significantly different compared to the normal operating conditions used during the summer time. However, the benefits of operating the system according to this configuration were most pronounced during the winter time. In terms of indoor air quality, average indoor PN and CO₂ concentrations decreased by 42% and 23%, respectively, while potential energy savings due to free cooling could reach as high as 96% of the normal operating conditions used during winter. Application of such a model for the operation of HVAC systems can help to significantly improve indoor air quality and energy conservation in air-conditioned office buildings strongly influenced by outdoor pollution sources. These findings also provide practical information to assist the placement and operation of filters and outdoor air intakes in mechanically ventilated buildings.
Keywords: particle number, CO₂, indoor temperature, outdoor air flow rate, multi-component model, optimum

5.1 Introduction

Numerous studies have demonstrated that an increase in outdoor ventilation rate can improve occupant health and productivity (Park and Yoon, 2011; Sekhar et al., 2003; Seppänen et al., 2006; Tham, 2004; Wargocki et al., 2004; Wargocki et al., 2000), and reduce the energy consumption of the HVAC (Heating, Ventilation and Air Conditioning) system inside office buildings, due to the free cooling during mild weather (i.e. when the outdoor temperature is equal to or lower than the desired indoor temperature) (Fisk et al., 2004; Wang, 2009).

However, increasing the outdoor ventilation rate can also increase indoor particle levels, especially in buildings located in areas with high outdoor particle concentrations from vehicle emissions (K. Koponen et al., 2001; Morawska et al., 2009; Quang et al., 2013; Viana et al., 2011; Weschler et al., 1996) and particle formation (nucleation) events (Quang et al., 2013). Epidemiological studies have consistently shown the relation between fine and ultrafine particle concentrations and increases in respiratory and cardiovascular morbidity and mortality (Davidson et al., 2005; Franck et al., 2011; Oberdorster, 2000; Oberdörster et al., 2005; Pope, 2000; Schwartz and Neas, 2000).

Other studies of the indoor environment have sought to optimise indoor thermal comfort and energy consumption (e.g. Al-Sanea and Zedan (2008), Chowdhury et al. (2008), Freire et al. (2008), Taylor et al. (2008), Conceição et al. (2009)). However, only a few investigated the impact on indoor air quality, and those that did used CO₂ concentration as the sole indicator (Atthajariyakul and Leephakpreeda, 2004; Congradac and Kulic, 2009; Kavgic et al., 2008; Mathews et al., 2001; Nassif et al., 2008; Wong et al., 2008a; Wong et al., 2008b). To-date, no research has considered particle concentration as an indicator when optimising HVAC system operation. Thermal comfort studies have shown that a person's thermal sensation is dependent on their geographic location (Busch, 1990) and the time of year (i.e. seasons).
A summer neutral (optimal) temperature has been quantified for indoor environments in Brisbane, Australia (de Dear and Auliciems, 1985), however, the same is not true of winter.

In order to provide a robust tool for optimising the operation of building HVAC systems, this work aimed to develop a multi-component model, to guide the maximisation of indoor environmental quality and the minimisation of energy consumption inside mechanically ventilated office buildings. More specifically, the objectives of the work were to: (i) develop indoor air quality models, including particle number (PN) and CO2 concentrations, (ii) build an HVAC energy consumption model based on optimal indoor temperature and outdoor ventilation rates; (iii) quantify optimal temperature inside office buildings in Brisbane during the winter time to determine appropriate parameters for objective (ii); and (iv) apply a multi-component model to evaluate indoor air quality and energy usage under different ventilation scenarios during winter and summer, in urban office buildings located in area with high outdoor PN concentrations.

5.2 Experimental methods

5.2.1 Development of indoor air quality model

5.2.1.1 Indoor PN concentration model

For buildings located in areas with high outdoor PN concentrations, where outdoor particles were a main source of indoor concentrations, a dynamic model of indoor particle number concentration was developed by Quang et al. (2013):

$$ C_{in}^{t_t} = C_{in}^{t_{t-1}}e^{-\alpha_{in} \Delta t} + C_{out}^{t_t} \beta_{in} \Delta t \quad (p \text{ cm}^{-3}) $$

(5.1)

Where:

\[ C_{in}^{t_t} : \text{indoor PN concentration at time } t_t (p \text{ cm}^{-3}) \]

\[ C_{in}^{t_{t-1}} : \text{indoor PN concentration at time } t_{t-1} (p \text{ cm}^{-3}) \]

\[ C_{out}^{t_t} : \text{outdoor PN concentration at time } t_t (p \text{ cm}^{-3}) \]
Δt : time step (h)

α_{ti} : total removal rate of the indoor PN concentrations at time \( t_i \)

\[ \alpha_{ti} = \frac{3.6 \times 10^3 k}{V} \left( Q_{RA}^{ti} F_{E_{AHS}} + Q_{exc}^{ti} + Q_{Exf}^{ti} + V \lambda_{ti} \right) \text{ (h}^{-1}) \] (5.2)

β_{ti} : total penetration rate of outdoor particle indoor at time \( t_i \)

\[ \beta_{ti} = \frac{3.6 \times 10^3}{V} \left[ Q_{OA}^{ti} (1 - F_{O_{OA}}) (1 - F_{E_{AHS}}) + Q_{Inf}^{ti} P_{Inf}^{ti} \right] \text{ (h}^{-1}) \] (5.3)

k: mixing factor (unitless) \((k = 1 \text{ if perfect air mixing conditions are assumed})\)

λ_{ti} : particle deposition rate at time \( t_i \) (s\(^{-1}\))

P_{Inf}^{ti} : penetration factor via the building envelope at time \( t_i \) (unitless)

Q_{OA}^{ti} : outdoor air flow rate at time \( t_i \) (m\(^3\) s\(^{-1}\))

Q_{RA}^{ti} : return air flow rate at time \( t_i \) (m\(^3\) s\(^{-1}\))

Q_{exc}^{ti} : general exhaust flow rate at time \( t_i \) (m\(^3\) s\(^{-1}\))

Q_{Exf}^{ti} : exfiltration flow rate at time \( t_i \) (m\(^3\) s\(^{-1}\))

Q_{Inf}^{ti} : infiltration flow rate at time \( t_i \) (m\(^3\) s\(^{-1}\))

F_{E_{OA}} : the overall efficiency of the outdoor air filter

F_{E_{AHS}} : the overall efficiency of the air handing system filter

5.2.1.2 Indoor CO\(_2\) concentration model

A CO\(_2\) mass-balance model was developed based on the balance of CO\(_2\) generated inside a building, mainly from the building occupants, and also that transported from outside the building via ventilation and penetration. However, during the operation of a buildings ventilation system, the inside air pressure usually remains positive and therefore, in this case, infiltration was considered negligible compared to the contribution from outdoor air brought in by ventilation. Hence, the model was formulated based on the following equations:

\[ M_{p_{ti}}^{CO_{2}} + M_{vent_{ti}}^{CO_{2}} = 0 \] (5.4)

Where:
\[ M_{p_{t_{l}}}^{CO_2} = N_{p_{t_{l}}} \times G_{p_{t_{l}}}^{CO_2} \quad (5.5) \]

\[ M_{vent_{t_{l}}}^{CO_2} = Q_{OA}^{t_{l}} (C_{out_{t_{l}}}^{CO_2} - C_{int_{t_{l}}}^{CO_2}) \quad (5.6) \]

\( N_{p_{t_{l}}} \): number of occupants presenting inside the building at time \( t_{l} \) (person)

\( G_{p_{t_{l}}}^{CO_2} \): volume of \( CO_2 \) generated by an individual occupant at time \( t_{l} \), \( G_{p_{t_{l}}}^{CO_2} = 0.0052 \ \text{l s}^{-1} \) (or equals to 10.21 mg s\(^{-1}\)) for an average adult at a normal activity in the office, such as sitting and reading and writing (Persily, 1997).

\( Q_{OA}^{t_{l}} \): outdoor air flow rate at time \( t_{l} \) (m\(^3\) s\(^{-1}\))

\( C_{out_{t_{l}}}^{CO_2} \): concentration of outdoor \( CO_2 \) at time \( t_{l} \) (ppm)

\( C_{int_{t_{l}}}^{CO_2} \): concentration of indoor \( CO_2 \) at time \( t_{l} \) (ppm)

From Equations (4), (5) and (6), the final indoor \( CO_2 \) concentration model can be written as:

\[ C_{int_{t_{l}}}^{CO_2} = \frac{N_{p_{t_{l}}} \times G_{p_{t_{l}}}^{CO_2}}{1.8 \times Q_{OA}^{t_{l}}} + C_{out_{t_{l}}}^{CO_2} \quad (ppm) \quad (5.7) \]

**5.2.1.3 Quantification of optimal outdoor ventilation rates by integrating PN and \( CO_2 \) concentration models**

From Equation 5.1 and Equation 5.7, it can be seen that both indoor PN and \( CO_2 \) concentrations are dependent on outdoor air flow rates, \( Q_{OA} \). If other parameters are assumed invariant during each time step, then Equation 5.1 and Equation 5.7 can be written as:

\[ C_{int_{t_{l}}}^{PN} = f(Q_{OA}^{t_{l}}) \text{ and } C_{int_{t_{l}}}^{CO_2} = f(Q_{OA}^{t_{l}}) \]

Since the units of indoor PN and \( CO_2 \) concentrations are different, to make their values comparable, their concentration values were normalised by dividing them by their indoor standard or guideline. The standardised indoor concentrations for PN and \( CO_2 \) in office buildings were \( STD_{PN} \) and \( STD_{CO_2} \), respectively. In this case, outdoor air flow rate was defined as an optimal when:
If assigning outdoor air flow rate \( Q_{OA}^{t_i} \) as the variable in Equation 5.8, the solution to this equation would be an optimal outdoor air flow rate, which balanced indoor PN and CO\(_2\) concentrations at time \( t_i \).

### 5.2.2 Development of HVAC energy consumption model

When outdoor air ventilation is increased, potential energy savings can occur during more mild or cool weather conditions (i.e. when the enthalpy of outdoor air is lower than for indoor air) due to free cooling. However, the opposite is true during the summer time, when additional energy consumption is requested to cool the extra outdoor that is brought in by the increased air flow rate. If outdoor air filters are used, further energy consumption is required during both mild and hot weather conditions. Based on these energy components, a total energy usage equation was formulated.

#### 5.2.2.1 During mild weather

The total energy saving at time \( t_i \) can be expressed as follows:

\[
E_{t_i} = E_{t_i}^{free\_cooling} - E_{t_i}^{filtration} \tag{5.9}
\]

Where:

\[
E_{t_i}^{free\_cooling} = \rho Q_{OA}^{t_i} \Delta H^{t_i} \text{ (W)} \tag{5.10}
\]

\( \rho \): density of moisture air (kg m\(^{-3}\))

\( Q_{OA}^{t_i} \): outdoor air flow rate at time \( t_i \) (m\(^3\) s\(^{-1}\))

\( \Delta H^{t_i} \): difference between indoor and outdoor air enthalpy (KJ kg\(^{-1}\))

\[
\Delta H^{t_i} = H_{in}^{t_i} - H_{out}^{t_i} \tag{5.11}
\]

\[
H_{in}^{t_i} = f(T_{in}^{t_i}, RH_{in}^{t_i}) \tag{5.12}
\]

\( T_{in}^{t_i} \): indoor temperature at time \( t_i \) (°C)

\( RH_{in}^{t_i} \): indoor relative humidity at time \( t_i \) (decimal)
Due to their high efficiency, low air pressure-drop and the small space required for installation, electrostatic filters are widely used for cleaning outdoor air in large building HVAC systems. In this case, the energy consumption due to filtration was:

$$E_{\text{filtration}}^{t_i} = P_{\text{corona}} Q_{OA}^{t_i} \text{ (kW)} \quad (5.14)$$

In which, $P_{\text{corona}}$ is the coronal power of electrostatic filter(s) (kW/1000 m$^3$ h$^{-1}$).

### 5.2.2.2 During hot weather

The total energy consumption at time $t_i$ can be expressed as follows:

$$E_{t_i} = E_{t_i}^{\text{cooling}} + E_{t_i}^{\text{filtration}} \quad (5.15)$$

Where:

$$E_{t_i}^{\text{cooling}} = \rho Q_{OA}^{t_i} \Delta H_{t_i} \text{ (W)} \quad (5.16)$$

$\rho$ : density of moisture air (kg m$^{-3}$)

$q_{OA}^{t_i}$ : outdoor air flow rate at time $t_i$ (m$^3$ s$^{-1}$)

$\Delta H_{t_i}$ : difference between outdoor and indoor air enthalpy (KJ kg$^{-1}$)

$$\Delta H_{t_i} = H_{out}^{t_i} - H_{in}^{t_i} \quad (5.17)$$

$$H_{in}^{t_i} = f(T_{in}^{t_i}, RH_{in}^{t_i}) \quad (5.18)$$

$T_{in}^{t_i}$: indoor temperature at time $t_i$ (°C)

$RH_{in}^{t_i}$ : indoor relative humidity at time $t_i$ (decimal)

$$H_{out}^{t_i} = f(T_{out}^{t_i}, RH_{out}^{t_i}) \quad (5.19)$$

$T_{out}^{t_i}$ : outdoor temperature at time $t_i$ (°C)

$RH_{out}^{t_i}$ : outdoor relative humidity at time $t_i$ (decimal)

And the energy consumption of ES filters is:
\( E_{\text{filtration}} = P_{\text{corona}} Q_{OA}^t (\text{kW}) \) \hspace{1cm} (5.14)

### 5.2.3 Optimisation of indoor environmental quality and energy usage

#### 5.2.3.1 During mild weather

From Equations (9), (10) and (14), total potential energy savings can be calculated as follows:

\[
E_t = \rho Q_{OA}^t \Delta H_t - P_{\text{corona}} Q_{OA}^t
\]  
\hspace{1cm} (5.20)

Substituting \( Q_{OA,\text{optimal}}^t \) for \( Q_{OA}^t \) and \( \Delta H_{t_i}^{\text{optimal}} \) for \( \Delta H_t \), we have:

\[
E_{t_i}^{\text{optimal}} = \rho Q_{OA,\text{optimal}}^t \Delta H_{t_i}^{\text{optimal}} - P_{\text{corona}} Q_{OA,\text{optimal}}^t
\]  
\hspace{1cm} (5.21)

Where:

\[
\Delta H_{t_i}^{\text{optimal}} = H_{\text{in}}^{\text{optimal}} - H_{\text{out}}^{t_i}
\]

\[
H_{\text{in}}^{\text{optimal}} = f(T_{\text{in}}^{\text{optimal}}, RH_{\text{in}}^{\text{optimal}})
\]

During mild weather \((H_{\text{out}}^{t_i} \leq H_{\text{in}}^{\text{optimal}})\), the outdoor air brought inside can cool down indoor air. Therefore, in this case, increasing the outdoor air ventilation rate can not only save energy for cooling indoor air (free-cooling), but it can also serve to decrease indoor CO\(_2\) concentrations. However, indoor PN concentration will increase if outdoor PN levels are higher than indoor levels. To keep indoor PN concentration at an acceptable level, a standardised indoor PN concentration (STD\(_{PN}\)) was applied to limit outdoor air flow rate. Alternatively, the use of outdoor air filter(s) might be required to clean outdoor particles, if their concentrations are high.

#### 5.2.3.2 During hot weather

From Equation 5.15, Equation 5.16 and Equation 5.14, the total energy consumption for cooling and filtering outdoor air flow can be given by:

\[
E_t = \rho Q_{OA}^t \Delta H_t + P_{\text{corona}} Q_{OA}^t
\]  
\hspace{1cm} (5.22)

Substituting \( Q_{OA,\text{optimal}}^t \) for \( Q_{OA}^t \) and \( \Delta H_{t_i}^{\text{optimal}} \) for \( \Delta H_t \), we have:

\[
E_{t_i}^{\text{optimal}} = \rho Q_{OA,\text{optimal}}^t \Delta H_{t_i}^{\text{optimal}} + P_{\text{corona}} Q_{OA,\text{optimal}}^t
\]  
\hspace{1cm} (5.23)

Where:
\[ \Delta H_{t_i}^{optimal} = H_{out}^{t_i} - H_{in}^{optimal} \]

\[ H_{in}^{optimal} = f(T_{in}^{optimal}, RH_{in}^{optimal}) \]

During hot weather \((H_{out}^{t_i} > H_{in}^{optimal})\), it is clear that when the outdoor air ventilation rate is reduced, the energy consumption required for both cooling and filtering outdoor air will also be reduced. At the same time, the number of outdoor particles brought inside will decrease, while indoor CO\(_2\) concentration will increase. Therefore, an indoor CO\(_2\) limitation (STD\(_{CO2}\)) is applied to keep the indoor CO\(_2\) concentrations at an acceptable level during this period.

### 5.2.4 Quantification of a winter optimal temperature

Brisbane is the capital city of Queensland State, Australia, and is located at 27.4\(^o\) S 153.1 E. Brisbane weather is characterised by warm, humid summers with average temperature in hottest month ranges from 21.3 to 30.3 \(^o\)C, and mild winter with average temperature in coldest month ranges from 10 to 21.8 \(^o\)C (Guan, 2009; Meteorology, 2013).

Thermal comfort parameters were surveyed and measured during winter in Building C, an office building which was studied in our previous works (Quang et al., 2013; Quang et al., 2012). Building C has one central plant room that is located centrally, from where outdoor and recirculating air were mixed and treated before being supplied to each office space via a horizontal duct system. A flexible instrument holder was used to concurrently measure physical parameters of air temperature, globe temperature, relative humidity and air velocity at the height of 0.85 m above floor level and within a 1 m radius of the seated subject. Specifically, an HOBO sensor was used to measure air temperature, global temperature and relative humidity. The stated accuracy of the instrument was ±0.35 \(^o\)C and ±2.5% for temperature and relative humidity, respectively. Mean radian temperature was assessed using a 32-mm-diameter global thermometer. Indoor air velocities were measured by a TSI Model 9535 VelociCal hot-wire anemometer.
A questionnaire form, approved by the Human Research Ethics Committee at the Queensland University of Technology (approval #0900001434), was distributed to occupants to collect information on clothing and metabolic activities and the physical parameters described above were measured simultaneously to the questionnaire being completed. A subjective indication of thermal sensation was also included in the questionnaire, with the results given the term 'Actual Mean Vote' (AMV). The thermal sensation scale was based on the ASHRAE seven-point scale from cold (-3) to hot (+3), with neutral at 0. A copy of the questionnaire form is provided in the supporting information section. Values of Predicted Mean Vote (PMV) were calculated for each subject by a Matlab program. Then PMV and AMV values were binned into 0.25 °C intervals according to operative temperatures that were the paired average of air temperatures and mean radiant temperatures, and a probit regression technique was employed to identify the neutral (optimal) temperature.

5.2.5 Evaluated office buildings and methods to collect model input data

In order to assess the performance of the integrated model, office buildings in which indoor PN concentration was strongly influenced by high outdoor particle concentrations originating from vehicle emissions and/or nucleation events were required. Based on these criteria, Buildings A and B described in our previous works (Quang et al., 2013; Quang et al., 2012), were chosen.

Building A is a 4 story building, ~17 m in height, and located close to a busy bus-only roadway (busway). Building A had two central ventilation plants, which were located towards the middle of each floor. Outdoor air was taken from air intakes located at the front of each plant room, which were close to the nearby busway. Outdoor air intakes were digitally controlled and therefore, outdoor flow rate could be easily changed if required. Deep bag filters were located in the air stream of mixed outdoor air and return air. Indoor particle concentrations were more strongly influenced by outdoor air in this building compared to the other buildings investigated (Quang et al., 2013).
Building B is a 18 story building, ~77 m in height, and located in the centre of the Brisbane’s CBD. Building B has a sole central plant room located at the rooftop level, where outdoor air was taken in via air intakes and mixed with return air from all levels, before it was filtered by deep bag filters and conditioned in air handling units. Measurements at this building were performed in summer, and more frequent and stronger nucleation events were observed at Building B compared to the other buildings used in the study (Quang et al., 2012).

Model input parameters collected at each building were as follows: indoor and outdoor PN were measured by TSI CPCs; indoor and outdoor CO₂ concentration, temperature and relative humidity were measured by TSI QTraks; and the velocities of outdoor, return and mixing airs were measured by a TSI Model 8705 anemometer and a 9535 VelociCalc. Further details on the measurement approach for these parameters are provided in Quang et al. (2013; 2012). In addition, the number of occupants inside the tested offices was determined based on hourly counts conducted by the investigators.

5.2.6 Data analysis

All statistical analyses (correlation, regression, t-test and One-Way ANOVA) were conducted using SPSS for Windows version 18 (SPSS Inc.). The 5% level was used to indicate statistical significance in all cases.

5.3 Results and discussion

5.3.1 Quantification of optimal indoor temperature in an air-conditioned office building

Summary statistics of indoor climatic measurements during the winter months, together with the results of the questionnaire for the 87 respondents in Building C are given on Table 5.1 and Table 5.2, respectively. Mean radiant and air temperatures were not significantly different, and generally similar to those previously measured in Brisbane office buildings during the summer months by de Dear and Auliciems (1985). Mean relative humidity ranged
between 34 and 56 %, while mean air velocity was 0.08 m s\(^{-1}\), both of which were comparable to the levels observed in other mechanically ventilated office buildings in Australia (de Dear and Auliciems, 1985). Our mean activity level of 1.25 met was also comparable to this earlier work, however as expected, the winter clothing insulation values in our survey were significantly higher than those surveyed in Brisbane during the summer.

A summary of the AMV and PMV values are given in Table 5.3 and these were plotted versus operative temperatures \(T_o\) in Figure 5.1. The linear regression equations that best fit the AMV and PMV data are given below:

\[
\text{AMV} = 0.543T_o - 12.93 \quad (R^2 = 0.92) \quad (5.24)
\]

\[
\text{PMV} = 0.419T_o - 9.722 \quad (R^2 = 0.58) \quad (5.25)
\]

From Equations (5.24) and (5.25), the optimal temperature, where PMV and AMV values were equal to zero (i.e. when most of the occupants felt most comfortable), were found to be 23.8\(^\circ\)C and 23.2 \(^\circ\)C, respectively, in a Brisbane office building during winter time. Compared to the neutral temperatures in the summer in Brisbane reported by de Dear and Auliciems (1985), the winter observed temperature is identical (23.8 \(^\circ\)C vs. 23.8 \(^\circ\)C), while the predicted temperature in the winter is lower (23.2 \(^\circ\)C vs. 25.1 \(^\circ\)C). In this study, thermal comfort surveys and measurements were conducted for 87 subjects in one office building. The small sample size is appropriate as the aim of the exercise was to determine a realistic input value for the integrated model. However, in order to confirm the optimal temperature and gain a better understanding of indoor thermal comfort in office buildings during winter in Brisbane (subtropical), a larger sample in more buildings would be required.
Table 5.1. Summary of the indoor micro-climatic data

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature (°C)</td>
<td>23.8</td>
<td>0.5</td>
<td>24.7</td>
<td>22.1</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>44.1</td>
<td>7.2</td>
<td>55.8</td>
<td>33.6</td>
</tr>
<tr>
<td>Mean radiant temperature (°C)</td>
<td>23.9</td>
<td>0.6</td>
<td>25.1</td>
<td>22.2</td>
</tr>
<tr>
<td>Operative temperature $t_o$ (°C)</td>
<td>23.8</td>
<td>0.5</td>
<td>24.8</td>
<td>22.4</td>
</tr>
<tr>
<td>Air velocity (m/s)</td>
<td>0.08</td>
<td>0.06</td>
<td>0.28</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 5.2. Summary of metabolic and clothing data

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clothing insulation (clo)</td>
<td>0.78</td>
<td>0.18</td>
<td>1.40</td>
<td>0.40</td>
</tr>
<tr>
<td>Metabolism heat (met)</td>
<td>1.25</td>
<td>0.10</td>
<td>1.60</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Table 5.3. Summary of thermal comfort votes

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted mean vote PMV</td>
<td>0.20</td>
<td>0.32</td>
<td>1.04</td>
<td>-0.54</td>
</tr>
<tr>
<td>Observed mean vote AMV</td>
<td>-0.13</td>
<td>1.08</td>
<td>3.00</td>
<td>-2.00</td>
</tr>
</tbody>
</table>

Figure 5.1. Mean binned thermal sensation ASHRAE votes and PMV calculations related to operative temperature.
5.3.2 Model input parameters

The model input parameters were based on both measured data and that reported in the literature. For example, optimal indoor temperatures, based on the findings of this research and also from the literature (de Dear and Auliciems, 1985), and optimal indoor relative humidities (RH) gathered from Parlour (2000) were used to calculate optimal indoor thermal enthalpy for the winter and summer time, respectively. To optimise indoor environmental quality, which includes indoor air quality and thermal comfort, together with the minimisation of energy usage, acceptable or recommended indoor concentrations for PN and CO$_2$ were applied. The recommended concentration for indoor CO$_2$ was considered to be lower than 1000 ppm, as that suggested by the ASHRAE standard 62.1-2010 (ASHRAE, 2010) for office buildings. Since there are currently no standards for indoor PN concentration, a concentration of 3000 p cm$^{-3}$ was recommended as a proxy “standard” for indoor PN levels. This figure was based on the low levels of indoor PN observed in recent studies in office buildings (Koponen et al., 2001; Quang et al., 2013; Wang et al., 2010; Wu et al., 2012). The corona power of electrostatic filter was obtained from Neundorfer (2013). The mixing factor, mixing and outdoor air filter efficiencies, particle penetration factor and indoor particle deposition rate were based on the findings of our previous experimental work in buildings A, B and C (Quang et al., 2013). The remaining parameters were directly measured inside the buildings. The input data used in the component models and integrated model are summarised in Table 5.4.

Table 5.4. Summary of model input parameters

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Sym.</th>
<th>Building A</th>
<th>Building B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room effective volume (m$^3$)</td>
<td>$V_{room}$</td>
<td>$7.94 \times 10^3$</td>
<td>$4.38 \times 10^3$</td>
</tr>
<tr>
<td>Mixing factor</td>
<td>$k$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Filter efficiency (mixing air)</td>
<td>$FE_{AIS}$</td>
<td>0.47</td>
<td>0.26</td>
</tr>
<tr>
<td>Filter efficiency (outdoor air)</td>
<td>$FE_{OA}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Penetration factor</td>
<td>$P_{bd}$</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Deposition rate (h$^{-1}$)</td>
<td>$\lambda$</td>
<td>$4.51 \times 10^{-5}$</td>
<td>$4.51 \times 10^{-5}$</td>
</tr>
<tr>
<td>CO$_2$ emission rate (mg s$^{-1}$ person$^{-1}$)</td>
<td></td>
<td>10.21</td>
<td>10.21</td>
</tr>
<tr>
<td>Input parameter</td>
<td>Sym.</td>
<td>Building A</td>
<td>Building B</td>
</tr>
<tr>
<td>-----------------------------------------------------------</td>
<td>------</td>
<td>----------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Number of occupants (person)</td>
<td>Sym.</td>
<td>20-110</td>
<td>13-46</td>
</tr>
<tr>
<td>Corona power of ES filter (KW/1000 m$^3$ h$^{-1}$)</td>
<td>$P_{corona}$</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Air quality parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outdoor PN concentration ($\times 10^3$ p cm$^{-3}$)</td>
<td>$PN_{out}$</td>
<td>8.83-39.3</td>
<td>6.85-53.9</td>
</tr>
<tr>
<td>Outdoor CO$_2$ concentration (ppm)</td>
<td>$CO_{2out}$</td>
<td>371-483</td>
<td>397-424</td>
</tr>
<tr>
<td>Indoor CO$_2$ concentration (ppm)</td>
<td>$CO_{2in}$</td>
<td>554-790</td>
<td>675-967</td>
</tr>
<tr>
<td>Climate parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outdoor temperature ($^\circ$C)</td>
<td>$T_{out}$</td>
<td>11-24</td>
<td>26-34</td>
</tr>
<tr>
<td>Outdoor humidity (decimal)</td>
<td>$RH_{out}$</td>
<td>40-86</td>
<td>37-67</td>
</tr>
<tr>
<td>Optimal indoor temperature ($^\circ$C)</td>
<td>$T_{in}^{optimal}$</td>
<td>23.8</td>
<td>23.8</td>
</tr>
<tr>
<td>Optimal indoor humidity (decimal)</td>
<td>$RH_{in}^{optimal}$</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Air flow rate (m$^3$ s$^{-1}$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outdoor</td>
<td>$Q_{oa}$</td>
<td>1.45-3.25</td>
<td>0.45</td>
</tr>
<tr>
<td>Return</td>
<td>$Q_{ra}$</td>
<td>13.8</td>
<td>7.25</td>
</tr>
<tr>
<td>Supply</td>
<td>$Q_{sa}$</td>
<td>15.8</td>
<td>7.7</td>
</tr>
<tr>
<td>Exceed</td>
<td>$Q_{exc}$</td>
<td>1.45-3.25</td>
<td>0.45</td>
</tr>
</tbody>
</table>

5.3.3 Assessment the performance of IAQ model components

Predicted and measured indoor PN and CO$_2$ concentrations at Building A and Building B are presented in Figure 5.2 and Figure 5.3, respectively. The statistical indicators from ASTM D5157 (ASTM-1997, 2008) were applied to evaluate the performance of the indoor PN and CO$_2$ models. The statistical tools used for evaluating the accuracy of the model predictions included: (i) the correlation coefficient of predictions compared to measurements ($r$), for which the value should be 0.9 or greater; (ii) the line of regression between the predictions and measurements, which should have a slope ($b$) between 0.75 and 1.25, and an intercept ($a$) less than 25% of the average measured concentration; and (iii) the normalised mean square error (NMSE), for which the value should be less than 0.25. At the same time, the bias of the model was measured based on: (i) the normalised fractional bias of the mean concentration (FB), for which the value should be 0.25 or lower; and (ii) the fractional bias based on the variance (FS), for which the value should be 0.5 or lower. These indicators for indoor PN and CO$_2$ concentration models were calculated and given in Table 5.5. Compared to the criteria outlined in the ASTM D5157, all evaluation indicators satisfied the criteria for both PN and
CO₂ models in the two buildings. This indicates that these models can perform well, even when some parameters were not taken into account in the models, such as the influence of indoor particle sources and penetration of CO₂ via building envelopes on indoor PN and CO₂ concentrations, respectively. The evaluation indicators for the PN models were also in good agreement with those of the previous model that included the effect of indoor particle sources (Quang et al., 2013).

Table 5.5. Summary of indicators for the assessment of indoor PN and CO₂ concentration models

<table>
<thead>
<tr>
<th>Site</th>
<th>Model</th>
<th>r</th>
<th>a</th>
<th>b</th>
<th>NMSE</th>
<th>FB</th>
<th>FS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building A</td>
<td>Indoor PN</td>
<td>0.91</td>
<td>-732</td>
<td>0.95</td>
<td>0.05</td>
<td>-0.17</td>
<td>0.09</td>
</tr>
<tr>
<td>Building A</td>
<td>Indoor CO₂</td>
<td>0.94</td>
<td>-115</td>
<td>1.15</td>
<td>0.00</td>
<td>-0.02</td>
<td>0.39</td>
</tr>
<tr>
<td>Building B</td>
<td>Indoor PN</td>
<td>0.97</td>
<td>-36</td>
<td>0.90</td>
<td>0.04</td>
<td>-0.11</td>
<td>-0.14</td>
</tr>
<tr>
<td>Building B</td>
<td>Indoor CO₂</td>
<td>0.92</td>
<td>-177</td>
<td>1.21</td>
<td>0.00</td>
<td>0.02</td>
<td>0.48</td>
</tr>
</tbody>
</table>
Figure 5.2. Indoor PN and CO₂ concentrations – predicted versus measured in Building A.
5.3.4 Optimisation of indoor environmental quality and energy usage in office buildings located in high outdoor PN concentration areas using the integrated model

Two typical data sets were selected to validate the integrated model for mild and hot weather conditions. One set was measured in a winter day in Building A, where high outdoor PN concentrations mainly originated from vehicle emissions (Quang et al., 2012). The other was measured in Building B in a summer day, when outdoor particle levels were strongly affected.
by new particle formation – a frequent occurrence in Brisbane during summer (Quang et al., 2012). The integrated model was applied to predict indoor air quality (indoor PN and CO₂ concentrations) and relevant energy usage for different ventilation operation modes, including (i) normal operation or non-optimisation, (ii) optimisation mode without outdoor air filtration, (iii) optimisation mode with full outdoor air filtration (i.e. outdoor air filters were always running when the ventilation system was turn on), and (iv) optimisation with partial operation of outdoor air filtration (i.e. outdoor air filters only ran when indoor PN levels were higher than the standard concentration (3000 p cm⁻³)).

5.3.4.1 During mild weather

The integrated model was applied to predict indoor PN and CO₂ concentrations, and potential energy savings due to free cooling in Building A during mild weather conditions (winter), the results of which are presented in Table 5.6 and Figure 5.4. In general, optimised indoor PN concentrations were significantly lower and decreased by up to 42% compared to normal (non-optimisation) operation of the ventilation system (p < 0.01). However, when the system was in optimisation mode without outdoor air filtration, indoor PN and CO₂ concentrations were at time higher than their respective ‘standards’ during the morning rush-hours. While indoor CO₂ concentration was significantly lower under optimisation mode with full outdoor air filtration than other modes (p < 0.01), there was no significant difference between the remaining operation modes (p = 0.38). Similarly, potential energy savings were not significantly different for normal and optimised operation modes, without and with partial outdoor air filtration (p = 0.43), however they were significantly higher (up to 50%) under optimisation mode with full outdoor air filtration than the other three modes (p < 0.01). These findings clearly show that the application of the integrated model for determining optimal ventilation mode can markedly decrease indoor PN concentration. In particular, the optimisation mode with full outdoor air filtration not only helped to improve indoor PN and CO₂ concentration, but it also increased potential energy savings due to free cooling.
Table 5.6. Summary of IEQ and potential energy saving at Building A during mild weather

<table>
<thead>
<tr>
<th></th>
<th>Measured</th>
<th>Modelled</th>
<th>Optimisation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>w/o OAF*</td>
<td>full OAF*</td>
</tr>
<tr>
<td>Indoor PN concentration ($\times 10^3$ p cm$^{-3}$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>6.36</td>
<td>5.72</td>
<td>3.01</td>
</tr>
<tr>
<td>SD</td>
<td>1.71</td>
<td>1.79</td>
<td>0.04</td>
</tr>
<tr>
<td>Max</td>
<td>10.1</td>
<td>9.37</td>
<td>3.25</td>
</tr>
<tr>
<td>Median</td>
<td>5.99</td>
<td>5.42</td>
<td>3.00</td>
</tr>
<tr>
<td>Min</td>
<td>3.81</td>
<td>2.65</td>
<td>2.99</td>
</tr>
<tr>
<td>Indoor CO$_2$ concentration (ppm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>696</td>
<td>683</td>
<td>711</td>
</tr>
<tr>
<td>SD</td>
<td>70</td>
<td>86</td>
<td>176</td>
</tr>
<tr>
<td>Max</td>
<td>790</td>
<td>776</td>
<td>1083</td>
</tr>
<tr>
<td>Median</td>
<td>728</td>
<td>729</td>
<td>691</td>
</tr>
<tr>
<td>Min</td>
<td>554</td>
<td>498</td>
<td>392</td>
</tr>
<tr>
<td>Potential energy saving (kW)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>14.2</td>
<td>13.2</td>
<td>30.1</td>
</tr>
<tr>
<td>SD</td>
<td>10.1</td>
<td>6.5</td>
<td>17.2</td>
</tr>
<tr>
<td>Max</td>
<td>35.8</td>
<td>27.2</td>
<td>65.1</td>
</tr>
<tr>
<td>Median</td>
<td>9.2</td>
<td>12.1</td>
<td>26.7</td>
</tr>
<tr>
<td>Min</td>
<td>0.4</td>
<td>0.6</td>
<td>-5.5</td>
</tr>
</tbody>
</table>

*OAF: outdoor air filters
Figure 5.4. Optimisation of indoor environmental quality and potential energy savings at Building A during the mild weather*.

*Note: “normal”: normal operation or no optimisation; “w/o OAF”: optimisation without outdoor air filtration; “full OAF”: optimisation with full operation of outdoor air filters; “partial OAF”: optimisation with partial operation of outdoor air filters
5.3.4.2 During hot weather

Indoor PN and CO₂ concentrations, and energy consumption in Building B during the hot weather day, when outdoor particles were strongly influenced by new particle formation, were predicted and are presented in Table 5.7 and Figure 5.5. Overall, indoor PN concentrations under optimisation modes were significantly lower than under normal operation mode ($p < 0.01$). Energy consumption was not significantly different between all operation modes ($p = 0.28$). However during the nucleation event, many values for indoor PN and CO₂ concentration under optimisation mode without outdoor air filtration exceeded the allowable limits. Indoor CO₂ concentrations under optimisation mode with full and partial outdoor air filtration were comparable and significantly lower than the standard ($p < 0.05$). However indoor PN concentration with full outdoor air filtration was significantly lower than for partial outdoor air filtration and the standard ($p < 0.01$). Based on these findings, optimisation mode with full outdoor air filtration is highly beneficial for in terms of indoor air quality in office buildings where indoor particles are strongly affected by high concentrations of newly-formed outdoor particles.

In summary, the results from running the integrated model showed that the optimisation mode with full outdoor air filtration can improve indoor air quality and energy conservation during both mild and hot weather in the mechanically ventilated office buildings which are strongly affected by outdoor particle levels.
Table 5.7. Summary of IEQ and energy consumption in Building B during hot weather

<table>
<thead>
<tr>
<th></th>
<th>Measured</th>
<th>Modelled</th>
<th>Optimisation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>Optimisation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>w/o OAF*</td>
<td>full OAF*</td>
<td>partial OAF*</td>
</tr>
<tr>
<td>Indoor PN concentration (×10^3 p cm^-3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>4.25</td>
<td>3.76</td>
<td>1.68</td>
</tr>
<tr>
<td>SD</td>
<td>2.78</td>
<td>2.59</td>
<td>1.09</td>
</tr>
<tr>
<td>Max</td>
<td>10.2</td>
<td>10.7</td>
<td>3.77</td>
</tr>
<tr>
<td>Median</td>
<td>3.27</td>
<td>2.50</td>
<td>1.17</td>
</tr>
<tr>
<td>Min</td>
<td>1.47</td>
<td>1.38</td>
<td>0.38</td>
</tr>
<tr>
<td>Indoor CO₂ concentration (ppm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>894</td>
<td>902</td>
<td>925</td>
</tr>
<tr>
<td>SD</td>
<td>87</td>
<td>118</td>
<td>60</td>
</tr>
<tr>
<td>Max</td>
<td>967</td>
<td>995</td>
<td>1142</td>
</tr>
<tr>
<td>Median</td>
<td>934</td>
<td>945</td>
<td>894</td>
</tr>
<tr>
<td>Min</td>
<td>675</td>
<td>575</td>
<td>894</td>
</tr>
<tr>
<td>Energy consumption (kW)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>13.4</td>
<td>13.0</td>
<td>13.4</td>
</tr>
<tr>
<td>SD</td>
<td>2.3</td>
<td>4.2</td>
<td>4.5</td>
</tr>
<tr>
<td>Max</td>
<td>17.1</td>
<td>18.6</td>
<td>18.3</td>
</tr>
<tr>
<td>Median</td>
<td>14.4</td>
<td>14.2</td>
<td>14.0</td>
</tr>
<tr>
<td>Min</td>
<td>9.0</td>
<td>3.3</td>
<td>3.2</td>
</tr>
</tbody>
</table>

*OAF: outdoor air filters
Figure 5.5. Optimisation of indoor environmental quality and energy consumption during hot weather at Building B*.

*Note: “normal”: normal operation or no optimisation; “w/o OAF”: optimisation without outdoor air filtration; “full OAF”: optimisation with full operation of outdoor air filters; “partial OAF”: optimisation with partial operation of outdoor air filters
5.4 Conclusions

An integrated model based on previously validated sub-models was developed to help optimise indoor environmental quality and energy consumption in mechanically ventilated office buildings in Brisbane, Australia, located in urban areas with generally high outdoor particle concentrations. Model parameters were mostly determined from experimental work performed at the locations modelled. These spanned indoor air quality, filter efficiency, thermal comfort and energy consumption.

Results from running the model to evaluate indoor PN and CO₂ concentrations, and energy usage under optimisation mode with full outdoor air filtration during mild and hot weather conditions were very positive in terms of the improvement of both indoor air quality and energy conservation. Combined with our previous work (Quang et al., 2013; Quang et al., 2012), these findings highlight a practical approach to locating and operating HVAC systems in urban office buildings in order to balance the best possible indoor air quality for occupants against the logistics of energy consumption. This approach is timely given the contribution of commercial building energy consumption to greenhouse gas emissions in Australia and overseas.

If other building thermal load components are added to this model, it will make it the most comprehensive model available to-date and if input with relevant local data, would be highly useful for simulating and guiding the operation of HVAC systems in any climatic region.

Acknowledgement

This project was funded by the Queensland Department of Public Works, and the Australian Research Council, through ARC Linkage Grant LP0776542. We would also like to thank the building managers and the security staff at each of the buildings we investigated and Ms Rachael Appleby from the International Laboratory for Air Quality and Health, for assisting us during the project implementation.
5.5 References


Morawska L, Jamriska M, Guo H, Jayaratne ER, Cao M, Summerville S. Variation in indoor particle number and PM2.5 concentrations in a radio station surrounded by busy roads before and after an upgrade of the HVAC system. Building and Environment 2009; 44; 76-84.


Wargocki P, Wyon DP, Fanger PO. The performance and subjective responses of call-center operators with new and used supply air filters at two outdoor air supply rates. Indoor Air 2004; 14: 7-16.


5.6 Supporting information

Thermal comfort survey form

Queensland University of Technology

W____ SUB______ Building________________________Brisbane, Queensland

Thermal Comfort Study

Please note: All survey responses will remain confidential. Participants will remain anonymous and will only be identified as an assigned ID code. You are under no obligation to complete this questionnaire.

1. Location________________________________________ 2. Date:________________________

3. Time:________

In this part of the survey we would like to know how you feel RIGHT NOW, at this moment.

4a. (Thermal environment) Please tick the scale below at the place that best represents how you feel at this moment. You may tick in an appropriate place between two categories, if you wish.

<table>
<thead>
<tr>
<th>Cold</th>
<th>Cool</th>
<th>Slightly Cool</th>
<th>Neutral</th>
<th>Slightly Warm</th>
<th>Warm</th>
<th>Hot</th>
</tr>
</thead>
</table>

4b. Is the thermal environment acceptable to you? 1 o unacceptable 2 o acceptable

4c. Please select the box below that best represents how you feel at this moment.

I would like to be:

3 o warmer
2 o no change
1 o cooler

5. Please select the boxes that best represent how you feel at the moment about the AIR MOVEMENT in your office.

6 o very acceptable
5 o moderately acceptable
4 o slightly acceptable
3 o slightly unacceptable
2 o moderately unacceptable
1 o very unacceptable

I would like:

3 o more air movement
2 o no change
1 o less air movement
6. **(General Comfort)** How comfortable is your office right now?

   6 o very comfortable
   5 o moderately comfortable
   4 o slightly comfortable
   3 o slightly uncomfortable
   2 o moderately uncomfortable
   1 u very uncomfortable

7. **(Temperature)** What would you estimate the temperature to be right now? ________________

8. **(Activity)** What activities have you been engaged in during the preceding hour?

<table>
<thead>
<tr>
<th>sitting quietly</th>
<th>sitting typing</th>
<th>standing still</th>
<th>on your feet</th>
<th>working</th>
<th>driving a car</th>
<th>walking around</th>
</tr>
</thead>
<tbody>
<tr>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
</tbody>
</table>

   Last 10 minutes?
   The 10 minutes preceding?
   The 10 minutes before that?
   The half hour before that?
   o o o o o o o

9. **(Clothing)** Please indicate whether you are wearing any of the items listed below by circulating the appropriate number. 0 = not wearing item. 1 = light weight item. 2 = medium weight item. 3 = heavy weight item

   **FEMALES:**

   **Underlayer:**
   0 1 2 3 top
   0 1 2 3 bottom
   0 1 2 3 slip

   **Footwear:**
   0 1 2 3 socks
   0 1 2 3 pantyhose
   0 1 2 3 shoes

   **Midlayer**
   0 1 2 3 short sleeved shirt
   0 1 2 3 long sleeved shirt
   0 1 2 3 dress
   0 1 2 3 skirt
   0 1 2 3 pants or slacks
   0 1 2 3 shorts

   **Outerlayers**
   0 1 2 3 sweater
   0 1 2 3 vest
   0 1 2 3 jacket

   **MALES:**

   **Underlayer:**
   0 1 2 3 top
   0 1 2 3 bottom

   **Footwear:**
   0 1 2 3 socks
   0 1 2 3 shoes

   **Midlayer**
   0 1 2 3 short sleeved shirt
   0 1 2 3 long sleeved shirt
   0 1 2 3 pants
   0 1 2 3 shorts

   **Outerlayers**
   0 1 2 3 sweater
   0 1 2 3 vest
   0 1 2 3 jacket
6 Overall Conclusions

6.1 Motivation of the Study

Due to urbanisation and urban transit oriented planning, more buildings are located close to busy traffic corridors. In areas with high outdoor particle concentrations, a large number of particles can penetrate inside a building via its ventilation system, as well as the building envelope. HVAC systems are commonly used to control indoor air quality and thermal comfort in office buildings, however they require a large amount of energy to operate. The three studies described in this thesis were combined to fulfil the aims of the work. One such aim was to improve scientific understanding of the characteristics and dynamics of particles in and around office buildings. Based on the findings of this work, a comprehensive model was developed to facilitate the optimisation of building HVAC systems. While this work was undertaken in Brisbane, Australia, it is believed that the outcomes reported in this thesis are applicable for other similar office buildings, both in Australia and overseas.

6.2 Principal Significance of Findings

In the first paper, the vertical profiles of particle concentrations around three office buildings in Brisbane were quantified and the influence of vehicle emissions and new particle formation were determined. The major findings of this work are summarised below.

As expected, vehicle emissions strongly influenced both PN and PM$_{2.5}$ concentrations at both street and roof levels, especially during rush-hours at all three buildings. Similarly, building topography, distance from the emission sources, and wind speed and direction also had an observed effect on particle concentrations at the three buildings.

On the other hand, new particle formation events were found to influence and contribute to increases in PN concentrations at both rooftop and street levels at all three buildings. However, the factors that contributed to the observed phenomena were different between buildings. For those buildings close to busy roads, the new particles were mainly formed from
local vehicle emissions and therefore, the formation process was expected to depend mainly on local conditions, such as high condensable gas concentrations and solar radiation intensity, together with low pre-existing particle concentrations. Meanwhile, for buildings where the newly formed particles were blown in from the direction of a nearby industrial zone, new particle production was not the result of local sources but was strongly influenced by wind speed, wind direction and the origin of incoming air masses. Therefore, all of these factors need to be undertaken into consideration prior to modelling urban canyon particle profiles and concentrations, and a ‘one-size-fits-all’ approach is unlikely to be able to account for the specific determinants at each individual building. In addition, nucleation events are often studied in the context of their role as physical phenomena, and typically within the context of producing natural and anthropogenic aerosols that may affect climate change. This study has shown that the typically under-valued role of nucleation can produce particles that can affect large numbers of people, due to the high density and occupancy of urban office buildings and the fact that the vast majority of people’s time is spent indoors.

The vertical profiles of PM$_{2.5}$ concentrations around building envelopes were found of decreasing concentrations with increasing height. However, vertical profiles of PNSD were building-specific and the rate of change with height was different at all three buildings. The results indicate that it is not only vehicle emissions that influence particle vertical profiles, but new particle formation as well, with both increases in particle number and a reduction in particle mass observed during nucleation events. These results serve to further define the specific effect of roadway proximity and nucleation formation on the vertical profiles of PN and PM$_{2.5}$ concentrations around building envelopes. Moreover, the highly building-specific nature of these profiles and factors affecting them, indicate that measurements should form the basis of any modelling or planning exercise prior to or after the construction of a new building. Such an approach, which is currently lacking for the most part, will ensure the greatest reliability. This has important implications for selecting appropriate sites for the air
intakes of building HVAC systems, in order to minimise occupant exposure to combustion products and also to investigate how street-level exposures may be mitigated via improved design practices.

Correlations between PNSD and PM$_{2.5}$ were characterised by a significant variability and dependence on particle size fraction, measured height and particle emission sources. The linear correlations for the building envelopes, especially during rush-hours and nucleation events, varied fluctuated significantly. This indicates that it is not appropriate to use particle mass concentrations to infer PN concentrations when modelling vertical concentrations around the building envelope and at a street level. This finding, while not a novel observation, adds weight to the existing case for considering particle mass and number separately during any urban modelling or exposure assessment exercise.

In summary, vertical profiles of PM$_{2.5}$ concentration around building envelopes showed a consistent decrease in concentration with increasing distance from nearby streets. However, vertical profiles of PN size fraction concentrations were building-specific and its rate of change was inconsistent with height. These results were not unexpected, in view of the complex flow patterns around the building envelopes, as well as in the busway and street canyons that were proximate to some of the buildings. The results of simultaneous measurements indicated that it was not only vehicle emissions, but also new particle formation that influenced the vertical profiles of particle concentrations. Time series ratios of PN and PM$_{2.5}$ concentrations at street and rooftop levels showed clear diurnal variation, which suggests that it is impossible to generalise vertical profiles of particle concentrations for all buildings, and that there is a need to conduct measurements or model these vertical profiles for a specific case when planning building morphology and air intake locations. Furthermore, newly formed particles and building-scale variability should also be taken into account when modelling particle concentrations around the building envelope, and also for urban environments and the exposures that occur within them.
The results of this work serve to provide better insight into the impact of nucleation and local scale variability on particle concentrations, and will also help to better define particle behaviour and variability around building envelopes, which has implications for studies of both human exposure and particle dynamics.

The influence of ventilation and filtration on indoor particle concentration within office buildings located close to busy traffic areas was reported in the second paper. The findings and their implications can be summarised accordingly.

The average indoor PN and PM$_{2.5}$ concentrations were $(2.46 - 5.71) \times 10^3$ p cm$^{-3}$ and 5.2 – 6.81 µg m$^{-3}$, respectively, and the average outdoor PN and PM$_{2.5}$ concentrations were $(8.94 - 17.4) \times 10^3$ p cm$^{-3}$ and 9.25 – 13.9 µg m$^{-3}$, respectively, for the three buildings. The significantly higher indoor and outdoor particle concentrations for Building A compared to Buildings B and C were due to the proximity of this building’s air intakes to a strong outdoor particle source (i.e. busway). This suggests that the location of the HVAC system’s outdoor air intakes can significantly reduce the impact of outdoor particles on indoor air.

The in-situ efficiency of deep bag (DB) filters ranged from 26.3 to 46.9% for the three buildings, while the efficiency of the electrostatic (ES) filter in Building C was 60.2% and the efficiency of the fan coil unit (FCU) filter in Building A was 21%. The results show that the efficiency of the DB filters was strongly affected by particle characteristics, in particular particle size and particle upstream concentration. The efficiency of the ES filter was lower than those tested in the laboratory, which could be due to the different operating conditions and upstream particle characteristics between the real-world and laboratory environments. However, this work only measured one ES filter in one office building and therefore, further investigations into in-situ ES filter efficiency under different conditions is recommended. Additionally, the overall filtration efficiency of the FCU filter was significantly lower than those applied in the central plant rooms. This result strongly suggests that a better filter needs
to be used for the FCU, in order to clean outdoor air, if it contains high particle concentrations.

The I/O particle concentration ratios showed that mixing air filters not only prevent outdoor particles penetrating indoors, but they also reduce the impact of indoor particle sources on indoor particle concentrations. On the other hand, the utilisation of both outdoor and mixing air filters can significantly reduce and keep indoor particle concentration lower when compared to the use of only mixing air filters.

Based on the comparison of I/O particle concentration ratios and their I/O correlation during rush-hours, nucleation events and overall working-hours, the results indicate that indoor PN concentration was strongly influenced by outdoor PN concentration during rush-hours and nucleation events. Many studies have investigated new particle formation and its effect on regional environments or climate change, but they are yet to focus on indoor environments, especially office buildings. Once again, this work draws attention to the under-valued role of nucleation in generating particles that can penetrate inside buildings and affect large numbers of people, due to the high density and occupancy of urban office buildings.

A previously reported dynamic model for indoor PN concentration was modified, evaluated and applied to assess the influence of the filtration/ventilation systems on indoor particle levels under different indoor and outdoor particle source conditions. The results of the 24 h modeling indicated that the model performed very well when outdoor air was the main source of indoor particles, with less uncertainty for indoor source emissions, or when the ventilation system was turned off. These results also highlighted the fact that the filtration of both mixing air and outdoor air can significantly reduce indoor particle levels.

These findings provide scientific grounds for the selection and location of appropriate filters and air intakes in building HVAC systems, in order to minimise occupant exposure to high outdoor particle concentrations from combustion products and new particle formation. The
results also serve to provide a better understanding of indoor particle dynamics and behaviours in office buildings, under different ventilation scenarios.

Based on the findings of the first and second papers, a multi-component model was developed, in order to optimise indoor environmental quality and energy consumption in mechanically ventilated office buildings located close to high outdoor PN concentrations originating from vehicle emissions and/or new particle formation. Indoor PN and CO₂ concentrations, and energy usage were evaluated under different operation modes, for optimal indoor temperature settings (according to a survey of building occupant preferences) during summer and winter. It was found that indoor air quality and potential energy savings increased significantly when the ventilation system as operated according to optimal operation modes compared to the normal modes used during the summer and winter months. If combined with other building thermal load components, the model will become more comprehensive and highly effective for the simulation and operation of HVAC systems to maximise indoor air quality and minimise energy consumption within office buildings located close to busy traffic areas.

In conclusion, this is the first time that the influence of new particle formation on the particle concentrations around the building envelopes and inside the office buildings has been identified and quantified. This thesis developed the first multi-component model consisting of indoor PN and CO₂ concentrations, thermal comfort and energy usage, and it can be applied to optimise building HVAC systems. Overall, this study not only improves scientific understanding and knowledge regarding the characteristics and dynamics of particles around and inside office buildings, but also provides scientific and practical information for the design, upgrading and operation of HVAC systems in mechanically ventilated office buildings.
6.3 Future Directions

This study has identified the presence of nucleation events and assessed the influence of vehicle emissions and new particle formation, in terms of when and how these sources affected the vertical profiles of particle concentrations around buildings. However, further investigation, including the simultaneous measurements of particle characteristics, chemicals, such as gas-phase primary pollutants (CO, NO and SO2), and secondary pollutants (O3 and SO4²⁻), and local meteorological parameters at different heights around buildings envelopes is highly suggested in order to get better understanding of the dynamics and behavior of these newly formed particles.

Based on the findings of this study, indoor particle concentrations are strongly influenced by indoor and outdoor particle sources, as well as the type and operation of ventilation/filtration systems. Therefore, indoor particle concentrations at different levels in these building are expected to be different. It would be interesting to quantify the vertical profile of indoor particle concentrations to further understand their characteristics and behaviour.
To improve the accuracy of predicted indoor concentrations of both PN and CO₂, the comprehensive investigation of indoor sources and their emission rates in the office building need to be improved. For instance, the working period and frequency of all laser printers, and the number of occupants present in the building could be monitored automatically using internet server software and entry door cameras, respectively.

The levels of measured and perceived indoor air quality are not always the same, especially from the perspective of employers and employees who work in the buildings. Therefore, it would be interesting to compare objective measurements with perceived indoor air quality, to find out if there is any association between the two. This could help to improve the planning and design of mechanically ventilated office buildings.

In this study, thermal comfort surveys and measurements were conducted for 87 subjects in one office building. In order to confirm the optimal temperature and gain a better understanding of indoor thermal comfort in office buildings in cities of similar climate to Brisbane (subtropical), a larger sample size in more buildings is suggested for the next study.

The multi-component model currently focuses on indoor air quality and outdoor air ventilation, one of the thermal loads of a building’s HVAC system. If other models that can predict particle concentration around building envelopes and other building thermal load components are added to this model, it will make it the most comprehensive model available to-date. When relevant local data are used, the model is a highly useful for simulating and guiding the design, upgrading and operation of building HVAC system in any climatic region.