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Characteristics of ultrafine particle sources and deposition rates in primary school classrooms

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HIGHLIGHTS

- Indoor PNC up to 10 times higher than outdoor during school hours.
- Indoor sources emission and deposition rates are quantified.
- Particle deposition rates approximately 100 times larger than air exchange rate.

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ABSTRACT

The aim of this work was to investigate changes in particle number concentration (PNC) within naturally ventilated primary school classrooms arising from local sources either within or adjacent to the classrooms. We quantify the rate at which ultrafine particles were emitted either from printing, grilling, heating or cleaning activities and the rate at which the particles were removed by both deposition and air exchange processes. At each of 25 schools in Brisbane, Australia, two weeks of measurements of PNC and CO_2 were taken both outdoors and in the two classrooms. Bayesian regression modelling was employed in order to estimate the relevant rates and analyse the relationship between air exchange rate (AER), particle infiltration and the deposition rates of particle generated from indoor activities in the classrooms. During schooling hours, grilling events at the school tuckshop as well as heating and printing in the classrooms led to indoor PNCs being elevated by a factor of more than four, with emission rates of $(2.51 \pm 0.25) \times 10^{11}$ p min^{-1}, $(8.99 \pm 6.70) \times 10^{11}$ p min^{-1} and $(5.17 \pm 2.00) \times 10^{11}$ p min^{-1}, respectively. During non-school hours, cleaning events elevated indoor PNC by a factor of above five, with an average emission rate of $(2.09 \pm 6.30) \times 10^{11}$ p min^{-1}. Particles were removed by both air exchange and deposition; chiefly by ventilation when AER > 0.7 h^{-1} and by deposition when AER < 0.7 h^{-1}.

1. Introduction

Numerous toxicological studies reported the association of ultrafine particles (UFP- particle with a diameter < 0.1 μm), with respiratory and cardiovascular morbidity (Oberdorster et al., 2005; WHO, 2005). Children are more vulnerable to air pollution health effects because their bodies are still developing, and they breathe at a higher volumetric rate per body mass than adults. Since children spend about 25% of their time at school and most of the time indoors, understanding the levels of UFPs and the factors that control them in indoor environments is an important step in characterizing children's exposure.

Particles in indoor air may originate from indoor sources and/or infiltrate from outdoor air (Diapouli et al., 2007; Ho et al., 2004; Kingham et al., 2000; Lazaridis et al., 2008). In the absence of indoor sources, indoor concentrations show similar temporal variations to those observed outdoors. Generally, indoor sources are classified according to the activities of the building occupants. A number of indoor pollutant sources have been found to produce a substantially high particle number concentrations (PNCs) in the classroom microenvironment, including gas heaters, burning candles, the use of an electric griddle for food related activities and a variety of cleaning activities (Mullen et al., 2011; Zhang and Zhu, 2012). Art activities, such as painting, gluing and drawing, are

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other important sources of particles in the classroom microenvironment (Morawska et al., 2009a). The use of vacuum cleaners during cleaning activities can also produce a substantial amount of aerosol particles (Knibbs et al., 2011; Lioy et al., 1999), as well as laser printers (He et al., 2007, 2010; McGarry et al., 2011; Morawska et al., 2009b; Schripp et al., 2008).

The quantitative assessment of indoor particle emissions is a complex task and is very important for the assessment of the total human exposure to particles. Although several studies have identified indoor sources and quantified particle levels during classroom activities to date, only qualitative information on the contribution of indoor particle sources to concentration levels is currently available. A quantitative assessment of particle emissions has only been reported for residential houses (Fan and Zhang, 2001; He et al., 2004; Hussein et al., 2006), however, the activities conducted, and the potential indoor sources in a classroom microenvironment, differ from those found in homes.

An understanding of particle deposition is important for the overall quantification of exposure to indoor particles, originating from both indoor and outdoor sources. A number of studies have been published on particle emission and deposition rates, which mainly focused on residential houses (Abt et al., 2000; He et al., 2005; Long et al., 2001; Thatcher et al., 2002; Thatcher and Layton, 1995) or office buildings (Jamriska et al., 2003; Smolik et al., 2005). However, these findings may not be directly applicable to classroom microenvironments due to differences in the surface area to volume ratio within the room, turbulent diffusion, surface roughness and the number of occupants differing between classroom and home environments, influencing particle losses in this particular microenvironment.

This paper incorporates the collected air quality and room characteristics data for two naturally ventilated teaching classrooms in each of 25 urban schools to quantify: 1) air exchange rates (AERs) in classrooms; 2) the effect of particle infiltration and particle sources on indoor PNC levels; and 3) indoor particle deposition rates and the associated impact of AER on particle deposition.

2. Methodology

2.1. Study design

This study was part of a large multidisciplinary epidemiological study, titled "Ultrafine Particles from Traffic Emissions and Children's Health (UPTECH)" (http://www.qut.edu.au/research/research-projects/uptech). Twenty-five randomly selected primary schools within the Brisbane Metropolitan Area (a subtropical city with approximately 2 million residents) took part in this study, from October 2010 to August 2012. The selection of schools was based on there being no major air pollution sources or infrastructure projects in close proximity to the school grounds other than vehicular traffic. At each school, two classrooms (ventilated naturally with open windows) were selected for the study.

Classroom characteristics, such as type of floor, size and volume of the classroom, building materials and number of the classrooms' occupants (students and teachers) were recorded. A classroom activity survey was developed for this study and teachers were requested to record every classroom activity that could potentially generate indoor air pollution, such as printers, heater, paint etc on a daily basis during the measurement period. Additionally, the cleaners were requested to fill out the developed survey whenever they undertook cleaning in the classrooms. Cleaning of the classrooms occurred twice a day, always outside school hours (between 5 and 8 am in the morning and 3 and 6 pm in the afternoon). It should be noted that there were some limitations in relation to observing the activities inside the classroom, since no researchers or cameras were allowed to be in the classroom during school teaching hours.

Air quality measurements were conducted at one school at a time. At each school, PNC and CO_2 measurements were conducted 24 h a day for two weeks at three outdoor sites (OA, OB and OC) within the school grounds as well as at two indoor sites (teaching classrooms: IA and IB). The indoor sampling location in each classroom was located at the rear or front of the room, 2 m away from the doors and windows, and at the same height at which the pupils would breathe when seated. Further details of the study design along with measurement dates are available in the Supplementary Information (SI) file.

2.2. Instrumentation

PNC measurements were conducted using water-based Condensation Particle Counters (WCPC, TSI Model 3781 or TSI Model 3787). CO_2 concentration and temperature were measured using a portable CO_2 metre (pSense, Model AZ 0018). Outdoor meteorological conditions, including wind direction, wind speed, temperature, solar radiation and relative humidity, were continuously measured at the centrally located outdoor site (OB) by a weather station (Monitor Sensor μSmart Series). The weather station, CPCs and CO_2 metres were programmed to collect the data in 30 s sampling intervals. Traffic counts with 5 min interval were measured on the busiest road adjacent to the schools, using a "MetroCount 5600". Traffic densities (vehicles per hour) for each school are provided in the SI file. Detailed information on the outdoor sampling sites, instrumentation and selection criteria have already been published in our other UPTECH paper (Salimi et al., 2013) and a general summary is available in the SI file.

2.3. Data analysis

Bayesian statistical modelling is used here to develop regression models for recorded events (identified peaks in PNC with associated activities recorded in the classroom diary) that are able to jointly estimate the AER and particle deposition rate. By calculating the deposition rate at the same time as the AER, uncertainty in AER can be taken into account when estimating the deposition rates. Further to this, by developing a hierarchical model for the rate parameters, the data are partially pooled and information about deposition and AER during one event informs estimates of the parameters for the other events. This approach recognises that while deposition and air exchange may be similar across classrooms they are not necessarily independent, identically distributed events. Events where no activity was recorded in the activity diary, explaining the source of the particles, were listed as "unspecified".

Statistical modelling was performed with Just Another Gibbs Sampler (JAGS) 3.3.0 using the rjags library in R 3.0.2 (Plummer, 2012). The Markov Chains were checked for convergence and at least 5000 samples were drawn for posterior inference.

2.3.1. Quantification of air exchange and particle deposition rates

The air exchange rates (AERs), α, in each classroom were estimated based on an exponential decay model for the CO_2 concentration after some elapsed time in hours, t, from a peak concentration of CO_{20} (He et al., 2005; Weichenthal et al., 2008). Because students are a source of CO_2 during lesson times (through their exhalation), the time period used for calculating the AER from the CO_2 measurements started at the time that the students left the classroom for a lunch break. The estimation of quantification of average AERs during school hours, over the two week measurement period were based on the decay of CO_2 in the classroom once the students had left the classroom for break. For the non-school