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Variation in indoor particle number and $PM_{2.5}$ concentrations in a radio station surrounded by busy roads before and after an upgrade of the HVAC system

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Abstract

Indoor particle number and $PM_{2.5}$ concentrations were investigated in a radio station surrounded by busy roads. Two extensive field measurement campaigns were conducted to determine the critical parameters affecting indoor air quality. The results indicated that indoor particle number and $PM_{2.5}$ concentrations were governed by outdoor air, and significantly affected by the location of air intake and design of HVAC system. Prior to the upgrade of the HVAC system and relocation of the air intake, the indoor median particle number concentration was 7.4 $\times 10^3$ particle/cm^3 and the median $PM_{2.5}$ concentration was 7μg/m^3. After the relocation of air intake and the redesign of the HVAC system, the indoor particle number concentration was between 2.3×10^3 and 3.4×10^3 particle/cm^3, with a median value of 2.7×10^3 particle/cm^3; and the indoor $PM_{2.5}$ concentration was in the range of 3 - 5μg/m^3, with a median value of 4μg/m^3. By relocating the air intake of the HVAC, the outdoor particle number and $PM_{2.5}$ concentrations near the air intake were reduced by 35% and 55%, respectively. In addition, with the relocation of air intake and the redesign of the HVAC system, the particle number penetration rate was reduced from 42% to 14%, and the overall filtration efficiency of the HVAC system (relocation of air intake, pre-filter, AHU and particle losses in the air duct) increased from 58% to 86%. For $PM_{2.5}$, the penetration rate after the upgrade was approximately 18% and the overall filtration efficiency was 82%. This study demonstrates that by using a comprehensive approach, including the assessment of outdoor conditions and characterisation of ventilation and filtration parameters, satisfactory indoor air quality can be achieved, even for those indoor environments facing challenging outdoor air conditions.

Key words: particle number concentration; $PM_{2.5}$; HVAC; AHU; penetration rate; filtration efficiency

1. Introduction

In most urban environments, motor vehicle emissions comprising of a myriad of gaseous and solid or liquid particles constitute the most significant contribution to the urban air pollution. Health effects of this pollution have been known for decades, with a more recent focus on the impacts of particles in the ultrafine size range (< 0.1μm). However, the detrimental impacts of airborne particles are associated not only with health effects, but also with adverse effect on materials and instrumentation as a result of surface contamination. The problem may become particularly serious in buildings housing sensitive electronic equipment, such as in the telecommunication and broadcasting industries, and also in office buildings, where computers, servers and other hardware is located. Deposition of particles on the surface of electronic equipment and exposed circuits may lead to a failure of the electronic systems, resulting in a substantial economical cost. For example, in the USA, the cost associated with equipment failure due to particle pollution indoors has been estimated to be of the order of hundreds of million dollars annually (Litvak et al. 2000). Commercial buildings in an urban environment are often located near busy roads or traffic intersections, which compromises the indoor air quality (IAQ) in the buildings, and in turn, not only health of its occupants, but also the integrity of the equipment.

There are currently no IAQ standards in Australia, in relation to particulate pollution indoors (similar situation exists also in other countries), and only limited information is available on the parameters governing particle pollution levels indoors particularly, in mechanically ventilated buildings, including the magnitude of the impact of the outdoor air, the effect of air intakes' location, heating, ventilation and air conditioning (HVAC) effect on particle transport and removal, and indoor/outdoor relationship.

The study reported in this paper investigated the factors affecting IAQ in a building surrounded by busy roads and housing several broadcasting radio stations, in the Central Business District (CBD) of an Australian capital city. The study was motivated by complaints

about black soot contamination of indoor surfaces and a higher than usual failure rate of the electronic equipment in the radio stations. Two consecutive monitoring campaigns, measuring particle characteristics including particle number concentration and $PM_{2.5}$, were conducted outside and inside the building with the following objectives: (i) identification of airborne contaminants' sources and pathways of contamination; (ii) characterization of the HVAC system performance in relation to its filtration efficiency; and (iii) assessment of the HVAC systems performance in improving IAQ after an upgrade.

2. Experimental

2.1. Building location, traffic and HVAC parameters

The radio station building is located in the centre of the city and is surrounded by several busy roads carrying outbound, inbound and local traffic. There are several traffic lights within approximately 50m of the building. The HVAC air intake was located on the north side of the building at the 1st level, approximately 10m above, and 3m away from a busy road. In the process of the upgrade, the air intake was relocated to the roof of the building, at a distance of approximately 70m from the nearest busy road. The traffic flow rate during the daytime is moderate to heavy, with a significant increase during the peak hours, between 07:00-09:00 in the morning, and 16:00-18:00 in the afternoon. Detailed traffic flow rate and speciation patterns for the roads near the sampling location were reported in another study (Holmes et al., 2005). The building is equipped with a HVAC system which operated at constant airflow rate during the day and night. In the plant room, 10% outdoor air (OA), which is ducted directly into the plant room using an inline fan, is mixed with 90% return air (RA), which is delivered from indoors through an open plenum (ceiling space) and passed through an Air Handling Unit (AHU), consisting of a battery of dry media filters, cooling coils and an air fan. RA mixes with OA in the plant room, creating mixed air (MA), which is then drawn into the AHU by a fan. Once the air has passed through the AHU filters, it becomes supply air (SA). The SA is delivered through a ducting system into rooms 1, 2, 3 and once inside these rooms, the air is then termed Indoor Air (IA).

Room 1 housed the OA air intake, room 2 was a storage room, room 3 was media control room housing electronic equipment and room 4 was an office. Before the upgrade, the HVAC system in the building did not have a pre-filter located at the outdoor air intake and the AHU located in the plant room contained a low efficiency air filter (class G4 Australian Standard). After the upgrade, the air intake was equipped with both air pre-filters (G4 class) and secondary medium efficiency air filters (class F8). Figure 1 presents a schematic diagram of the rooms and the HVAC system prior to the upgrade.

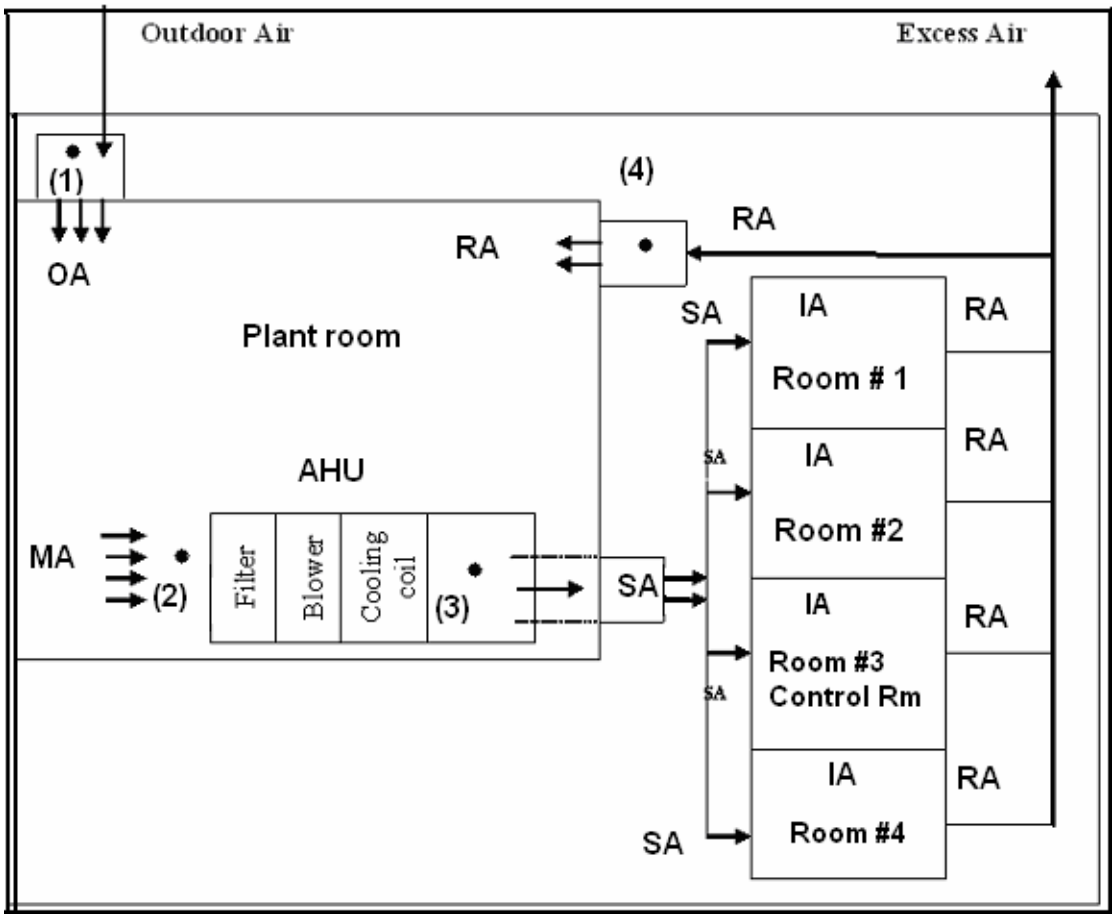

Figure 1 Schematic diagram of the plant room with the HVAC system and the sampling points (supplying air to Rooms 1-4. Room 3 is the Control room). Legend: (1) OA sampling point; (2) MA sampling point; (3) SA sampling point; (4) RA sampling point. IA – Indoor Air. AHU – Air Handling Unit.

2.2. Instrumentation and parameters measured

Particle number concentration and size distribution in the range of 0.017 – 0.600μm was measured by a Scanning Mobility Particle Sizer (SMPS; TSI model 3071A with Condensation Particle Counters, CPC, TSI models 3010 and 3022). SMPS operates on a principle of particle classification by an electrostatic classifier, according to their electrical mobility, which is a function of their size, followed by particle counting by the CPC, which utilizes laser light scattering. The whole process is automated and software controlled. The size distribution scanning time was set to 2 minutes.

Total particle number concentration in the size range from to 0.02μm to1μm was measured by a TSI Model 8525 P-Trak Ultrafine Particle Counter (TSI Incorporated, St. Paul, MN, USA) and an Aerodynamic Particle Sizer (APS) (TSI Model 3320) was used for the measurement of particle number concentrations and size distributions in the size range 0.7 – 20μm.

Approximation of $PM_{2.5}$ (mass concentration of particles with aerodynamic diameters smaller than 2.5μm) was measured by a laser photometer (DustTrak TSI Model 8520). The time resolution was set to one second. DustTrak is an optical photometer measuring the amount of scattered light, which is proportional to the volume concentration of the aerosol. In order to obtain results closer to gravimetric $PM_{2.5}$ values, an experiment was conducted under laboratory conditions to compare the DustTrak readings with the readings of a TEOM (50ºC R&P 1400a with a URG $PM_{2.5}$ cyclone inlet) (Morawska et al. (2003) and He et al. (2005)). The calibration equation obtained was: $PM_{2.5(TEOM)} = 0.394\ PM_{2.5(DustTrak)} + 4.450$ ($R^2 = 0.83$), and this equation was used in this work. All the instruments were calibrated in the laboratory and compared before the measurements.

2.3. Air sampling

Two field sampling runs were conducted at the site during weekdays that had similar meteorological conditions, traffic volumes and indoor activities. The first one run was from

07:00 on 18 November to 19:00 of 19 November 2003, and the second run was from 13:00-17:00 on 2 December 2004, after the upgrade of the HVAC system in the building. While the durations of the runs were relatively short, they were adequate in relation to the aims of the project. The key information required was the ratio of particle concentrations at different locations, measured within a period of time when the outdoor concentrations were as stable as possible. In an environment affected by traffic, where the conditions change all the time, periods of relative stability are relatively short. The ratios of the concentrations were calculated for individual measurement periods, not from any long term average. Therefore, since the project did not aim at establishing the baseline of absolute particle concentrations at the sites, a sufficient number of data points, used to calculate the ratios, were obtained within hours (rather than days or weeks, if the absolute concentrations were of the main interest).

Two sets of instruments were used: (i) stationary, for monitoring outdoor air characteristics near the air intake location, including SMPS, DustTrak and APS; and (ii) mobile, including SMPS and DustTrak, with the instruments mounted on a trolley, allowing for sampling at various indoor locations. During run 1, the stationary system was situated in room 1 and was sampling from outdoor air, with its sampling intake located 1 m away from the building HVAC intake and taking readings every 2 minutes, whilst the portable system was used to take at least triplicate measurements at each of the investigated locations within the building. The sampling interval was 2 minutes for the DustTrak and the SMPS, and 20 seconds for the APS. To compare the concentrations between different locations, the measurements at each location were conducted several times. For example, the SA vs. OA assessment was conducted by measuring particle characteristics of SA (3 readings), followed by 3 OA measurements (6 minutes), and then repeating the same procedure 4 times.

Run 2 was conducted shortly after completion of the HVAC system's upgrade and at the time of the round 2 measurements, the filters had been used approximately for 8 weeks. During run 2, the stationary system was situated on outside balcony on the 2nd level of the building. The site was approximately 20m away from the relocated HVAC air intake. The stationary system (CPC 3010 and DustTrak) operated continuously, taking readings every 30

seconds, whilst the portable system, consisting of P-Trak and Dustrak, was applied to conduct several sets (at least 5) of triplicate measurements (each requiring 30 seconds). Outdoor sampling during run 2 was in a more open space (compared to run 1). This resulted in more rapid changes in the measured concentration. Therefore, in order to obtain better data resolution, a 30 second sampling interval was selected. As such, the CPC was used in run 2 for particle number concentration measurements, as the instrument allows a much faster time resolution than the SMPS.

Particle characteristic of OA, SA, IA, RA and MA were measured in various locations of: (i) the ducting of the HVAC system; (ii) the plant room; and (iii) indoors. The sampling points for each location are presented in the Figure 1. OA, MA, SA and RA in the plant room were measured by sampling the air from different locations within the plant room by the mobile system. The RA was measured in front of and inside the duct, delivering the RA into the plant room, while the OA was measured inside the duct delivering the OA into the plant room. The MA was measured in front of the AHU air filters, just before the air entered the AHU and the filtered and air-conditioned SA was monitored in the AHU duct. The IA was investigated in room 3 (server control room) and particle characteristics were measured at various points to assess their spatial variation, as well as to identify the presence of indoor sources (if any) and particle losses within the HVAC ducts.

SA for all four rooms was measured only in room 3 (which is approximately 5m away from the AHU) by directly inserting L-shaped air sampling probe into the centre of the straight part of the duct, facing opposite to the airflow. The sampled air was then delivered to the measuring instruments via conductive plastic 2 m long tubes of inner diameter 8 mm. The diffusion loss in the tube was less than 10% for particles > 0.03μm. During the measurements, the probes and sampling lines used were identical. Since the focus of the study was mainly on the ratios of indoor to outdoor air particles, particle losses in the tubes did not affect the outcomes. An air splitter was applied for the cases where several instruments sampled the air from the same location.

2.4. Meteorological conditions

The meteorological conditions outside the building were not monitored. However, based on Bureau of Meteorology data, the weather was mostly fine during the measurements, with air temperature and relative humidity in the range of 18-29°C, and 55-65%, respectively. The meteorological conditions were stable, with only light to moderate winds.

2.5. Data analysis

SPSS statistical software was used to conduct a statistical analysis of the data set (e.g. correlation, regression, t-test, one-way ANOVA). Source characterisation and interpretation were achieved by particle size distribution analysis and available source identification data in the International Laboratory for Air Quality and Health (ILAQH) of Queensland University of Technology.

3. Results and Discussion

The descriptive statistics of the particle number (PN) and $PM_{2.5}$ concentrations in outdoor and indoor air over the two sampling periods are presented in Table 1, to give a general idea of the concentration ranges and their variation at the site. The mean and median PN and $PM_{2.5}$ values were calculated using the data collected every 2 minutes and every 30 seconds, respectively. It can be seen that the mean values were associated with very large standard deviations and were higher than the median values. This means that the values were affected by very high temporary concentrations, which were a result of the buildings close proximity to the road. Under these circumstances, median is a better representation of particle concentration.

Figure 2 shows the time series of PN measured simultaneously, outdoors and indoors (room 3), during run 1. For comparison, the time series of indoor $PM_{2.5}$ is also plotted in the figure (however, outdoor $PM_{2.5}$ was not measured during this period).

Table 1 Statistics for particle number (PN) and $PM_{2.5}$ concentrations measured outdoors (OA, near the air intake) and indoors (IA, Room 3) over the two sampling periods.

	PN (run 1)		**PN (run 2)**	
	OA [1)]	**IA [1)]**	**OA [2)]**	**IA [2)]**
STATISTICS	**(particle/cm^3)**	**(particle/cm^3)**	**(particle/cm^3)**	**(particle/cm^3)**
Mean	3.4E+04	8.8E+03	2.1E+04	2.7E+03
Standard Deviation	3.6E+04	5.0E+03	5.0E+03	2.4E+03
Median	2.0E+04	7.4E+03	2.0E+04	2.7E+03
25% percentile	1.0E+04	4.7E+03	1.8E+04	2.6E+03
75% percentile	4.3E+04	1.2E+04	2.4E+04	2.8E+03
Minimum	3.7E+03	2.3E+03	1.1E+04	2.3E+03
Maximum	2.3E+05	2.6E+04	4.1E+04	3.4E+03
Number of samples	398	398	91	91
CMD	47 ± 18 nm	56 ± 9 nm	N/A	N/A
	$PM_{2.5}$ (run 1)		**$PM_{2.5}$ (run 2)**	
	OA [1)]	**IA [1)]**	**OA [2)]**	**IA [2)]**
STATISTICS	**(µg/m^3)**	**(µg/m^3)**	**(µg/m^3)**	**(µg/m^3)**
Mean	N/A	8	24	4
Standard Deviation	N/A	3	4	0.6
Median	N/A	7	24	4
25% percentile	N/A	6	21	4
75% percentile	N/A	9	25	5
Minimum	N/A	4	19	3
Maximum	N/A	21	48	5
Number of samples	N/A	1592	364	364

[1)] Sampling interval: 18/11/2003 20:16 - 19/11/2003 09:31

[2)] Sampling interval: 2/12/2004 13:10–16:10

N/A: not available

OA - outdoor air; IA – indoor air; CMD (Count Median Diameter).

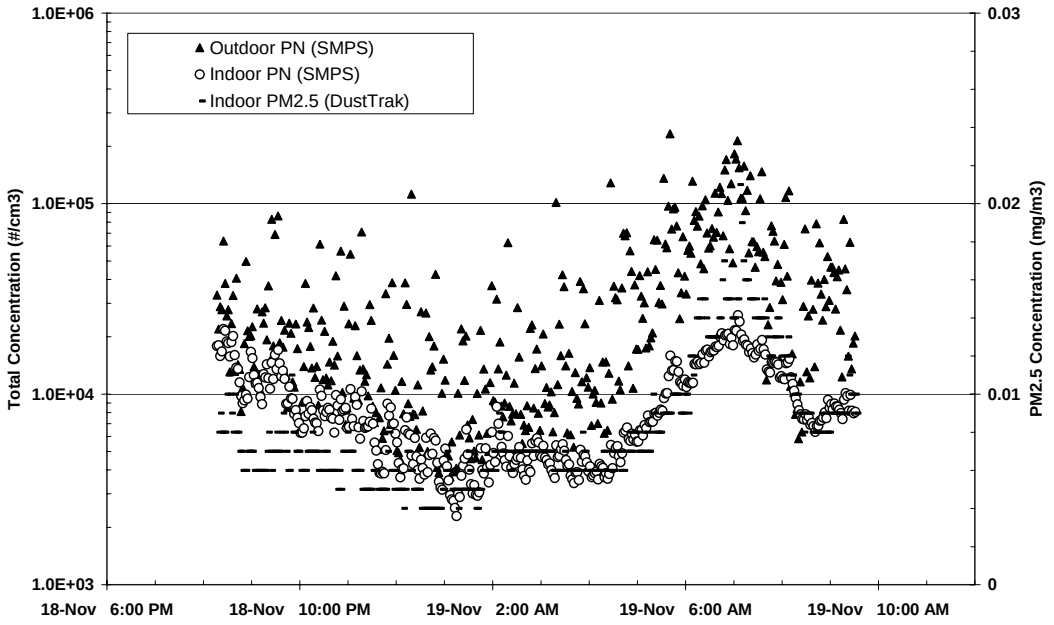

Figure 2 Time series of outdoor (at air intake) and indoor (room 3) particle number concentration and indoor $PM_{2.5}$ during run 1.

3.1 Outdoor Air

Outdoor PN concentration fluctuated between approximately 3.7×10^3 and 2.3×10^5 particles/cm^3, with the mean value of 3.4×10^4 particles/cm^3 during run 1 (Table 1). The median value for this location, of 2.0×10^4 particles/cm^3, was the same during both runs, and is twice as high as the urban air background for the city, which is approximately 1.0×10^4 particles/cm^3 (Morawska et al 2002). The PN concentration showed higher levels between 07:00-09:00, which is during the traffic peak hours (Figure 2), indicating that the main source of outdoor particles is related to exhaust emissions originating from the local traffic. During the traffic peak hours, the median PN concentration level was approximately ten times higher than the urban background.

To further understand outdoor particle characteristics, the average particle size distribution (PSD) measured over several time intervals is plotted in Figure 3. It can be seen that most particles are in the ultrafine size range, and that the PSD is uni or bi modal and varying depending on the selected averaging time interval. For the traffic peak hours between 07:00-

09:00 and 16:00-18:00 the PSD showed higher particle number concentrations and more distinct modes, when compared with PSD measured at other time intervals. The locations of the morning peak (27nm) and the afternoon peak (36nm) indicated the contribution of petrol fuelled vehicles, while the location of the second morning peak (98nm) is characteristic of contributions from diesel vehicles. This could be confirmed by checking the composition of the traffic on the roads, which showed that the fleet was dominated by light vehicles, with diesel buses accounting for 18% of the total vehicle number (Holmes et al., 2005). Measurements conducted in the city over the years showed that particles produced by petrol and diesel vehicles have a CMD of 20-60nm and 20-130nm, respectively (Morawska et al., 1998, 1999; Holmes et al., 2005).

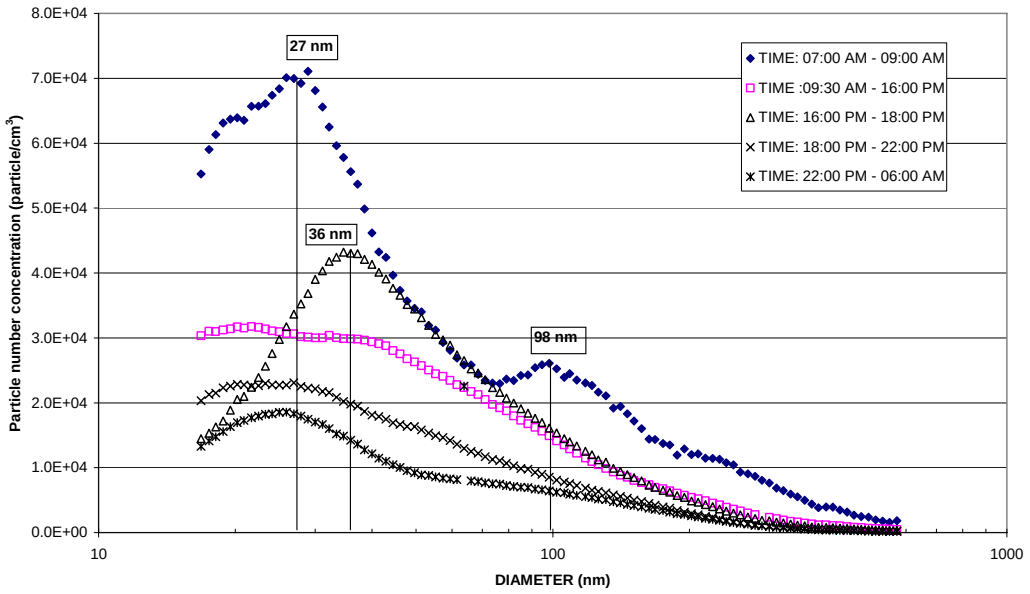

Figure 3 Particle Size distribution of OA measured by a stationary SMPS

Therefore, based on the analyses of measured PSD, in terms of general shape, concentration levels, modality and CMD, and comparison with the results of the previous studies on the particle source in the area (Morawska et al., 1998, 1999; Holmes et al., 2005), it can be concluded that the main source of outdoor particle number near the radio station building is related to traffic emissions.

In summary, the above results indicate that for such high outdoor air pollution levels, the IAQ is likely to be compromised, resulting in a high indoor concentration, contamination of the ductwork, other parts of the HVAC system and indoor surfaces, including exposed electronic equipment.

3.2 Indoor air

As can be seen from Figure 2, the indoor PN and $PM_{2.5}$ concentrations followed the trends of outdoor PN concentrations, with both outdoor and indoor concentrations showing minima between 01:00-04:00 and maxima between 07:00-09:00 during run 1. The indoor concentrations displayed less variations and smaller standard deviations compared to the outdoors. The indoor PN concentrations observed in room 3 (Table 1) were lower than the outdoor concentrations during both run 1 and run 2. The indoor median value was 7.4×10^3 particle/cm^3 for run 1 and 2.7×10^3 particle/cm^3 for run 2, whereas the outdoor median value was 2.0×10^4 particle/cm^3. Indoor $PM_{2.5}$ concentrations were between 4-21μg/m^3 during run 1 and between 3-5μg/m^3 during run 2, with median values of 7μg/m^3 and 4μg/m^3 respectively.

Measurements of spatial distribution of PN concentration in indoor air (room 3) showed a uniform distribution, with variation less than 5% between different locations within the room.

3.3 Ratios of particle concentrations in the plant room

Particle concentrations measured within the plant room as a part of run 1 were used to determine: 1) the presence of indoor sources by computing the RA/SA ratio; 2) the filtration efficiency of air filters (including the effect of heating/cooling coil) from the SA/MA ratio; and 3) the overall relationship between indoor and outdoor concentrations from the RA/OA ratio.

The ratios of particle number concentrations measured in different sections of the HVAC system in the plant room are presented in Table 2. In general, five readings of OA, SA, MA and RA were averaged for different ratios.

It can be seen that the mean RA/SA ratio for both PN and $PM_{2.5}$ were very close to one, implying the absence of indoor sources. Also, the mean SA/MA ratios were close to one, which means that the AHU containing the air filters and cooling/heating coil did not have any effect on filtering the particles during run 1 (filtration efficiency zero). The RA/OA ratios were less than one, indicating the dominance of outdoor sources. Under these conditions the ratios of MA/OA and SA/OA are, very similar to the RA/OA ratios, as expected.

Table 2 Ratio of particle concentration measured at different sections of the HVAC system in the plant room, during run 1. Filters were installed and the cooling coil was operational (ON) in the HVAC system.

	Ratio of particle concentration MEAN ± SD				
	RA/OA	**MA/OA**	**SA/OA**	**RA/SA**	**SA/MA**
PN	0.32±0.13	0.30±0.14	0.31±0.11	1.01±0.11	1.11±0.19
$PM_{2.5}$	0.47±0.12	0.49±0.14	0.49±0.14	0.98±0.06	1.00±0.01

OA - outdoor air; RA – return air; MA – mixed air; SA – supply air.

The filtration efficiency of the AHU on different sizes of particles was further assessed. Figure 4 presents the experimentally determined size dependent penetration rates of the installed filters and the heating/cooling coil of the tested AHU in run 1. It can be seen that the penetration rate (SA/MA ratio) for different size channels was almost the same, around one, regardless of the size of particles, suggesting inefficiency of the AHU system in filtering particles of any size. The relatively large uncertainties were caused by the changes and variation in the measured PN levels over the measuring time intervals (6 minutes for each RA, SA and MA sampling).

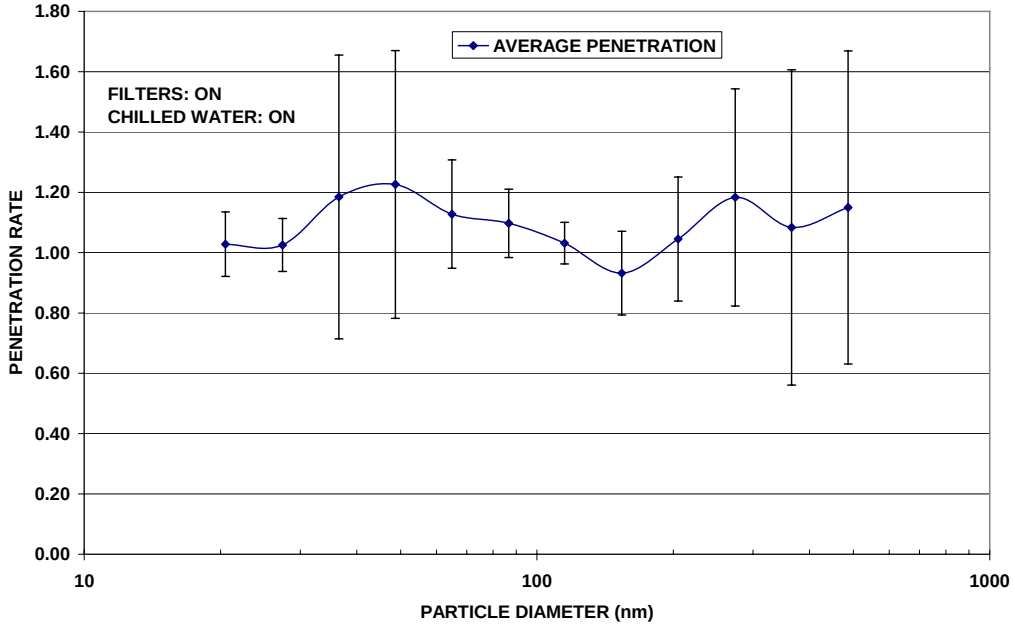

Figure 4 Size dependent penetration efficiency of Air Handling Unit (SA/MA).

In summary, the AHU, containing a battery of low efficiency, dry media air filters and the cooling/heating section during run 1, had no effect on particle reduction in the supply air delivered indoors. As discussed previously, this resulted in high levels of particulate pollution indoors, particularly of submicrometer particles penetrating from outside.

The above assessment of indoor and outdoor pollution levels led to a conclusion that the surface contamination indoors was likely caused by the combination of two factors: (i) extremely high OA pollution levels; and (ii) application of an HVAC system which was not adequate for the environmental conditions. Consequently, a set of recommendations was made, including the relocation of the air intakes and redesign of the HVAC system.

3.4 I/O ratios

Since the concentrations measured in the indoor air of the building (rather than in the AHU) was the main focus of the study, analysis of I/O PN and $PM_{2.5}$ concentration ratios were conducted (for indoor concentrations measured in room 3) to evaluate the effect of outdoor air on the indoor air and to determine presence of indoor sources. In general the I/O

PN ratio observed for time interval 20:00-09:30 (i.e. including night time with limited traffic flowrate and early morning traffic peak hours) was much less than one, indicating the dominant effect of outdoor concentrations and absence of any indoor sources of significance. From Figure 2, the average I/O ratio for PN was 0.42 ± 0.23 (mean ± standard deviation), however the ratio for $PM_{2.5}$ and PM_{10} is unavailable. These results indicate that approximately 58% of outdoor particles were removed via deposition in the duct and HVAC systems, as well as on indoor surfaces. Over an extended period of time with high outdoor concentrations, it is likely that the surface deposition of particulate matter could become a problem, resulting in visible contamination of the interior, equipment and other material surfaces, as was observed.

3.5 The effect of redesign of the HVAC system

The redesign of the HVAC system included the installation of a pre-filter section (on the roof of the building) and an upgrade of the air filter section of the AHU. The overall removal efficiency of the redesigned HVAC system was assessed during run 2. Table 3 shows the I/O ratios for PN and $PM_{2.5}$ measured after the upgrade of HVAC system in the building.

Table 3 The I/O ratios (indoor measured in room 3), during run 2 (after the upgrade of the HVAC system).

I/O	Mean	SD	Median	25% percentile	75% percentile	Min	Max	N
PN	0.14	0.03	0.13	0.12	0.16	0.08	0.23	100
$PM_{2.5}$	0.18	0.03	0.18	0.16	0.19	0.10	0.23	100

SD: Standard Deviation

N: number of measurements

Comparison of the pre- and post-upgrade results shows that I/O ratio for PN was reduced by about three times (14% vs. 42%). In other words, the overall efficiency of the system in removing particles form indoor air increased from approximately 58% to 86% after the upgrade of HVAC system.

Since the I/O ratios for $PM_{2.5}$ for the pre-upgraded HVAC system were unavailable, a comparison of the system's performance before and after the upgrade cannot be made for $PM_{2.5}$. However, the post-upgrade I/O ratio for $PM_{2.5}$ was similar to the post-upgrade I/O for PN, and thus a similar overall efficiency of the system for $PM_{2.5}$ can be inferred.

3.6 Effect of relocation of the HVAC air intake

In addition to the redesign of the HVAC system, the air intake of the HVAC system was also relocated. The air intake was moved from the immediate vicinity of the road (as described previously) to a new location on the building's roof (about 20 m above the ground and 70 m away from the nearest road). Monitoring of PN and $PM_{2.5}$ of OA near the relocated air intake on a balcony (15m away) was conducted when the upgrade of HVAC was completed.

The results of OA levels measured before and after the relocation of air intake are presented in Table 4. The data was collected under similar environmental conditions, including the day, traffic count, sampling time interval and outdoor meteorological conditions for both runs.

It can be seen there was quite a significant reduction of particle concentration measured during run 2, in the order of 50%, for both PN and $PM_{2.5}$. Since traffic and meteorological conditions remained stable and similar throughout both sampling periods, it can be concluded that the reduction in particle concentration measured resulted mainly from the relocation of the air intake. While theses results should be treated with caution, and only as indicators (since the measurements were conducted at different times and for relatively short periods of time), they point out to the fact that the location of the air intake is a critical factor, which could reduce the indoor air pollution level significantly, with an effect comparable that of the installation of a low-to-medium efficiency air filter.

Table 4 Particle number and mass concentrations of outdoor air measured near a HVAC air intake location, where $OA^{2)}/OA^{1)}$ ratios are based on the ratios for individually measured (paired) concentration data (not on the values listed in the table).

	$OA^{1)}$ $PM_{2.5}$ ($\mu g/m^3$)	**$OA^{2)}$ $PM_{2.5}$ ($\mu g/cm^3$)**	**$OA^{1)}$ PN ($\#/cm^3$)**	**$OA^{2)}$ PN ($\#/cm^3$)**	**$OA^{2)}/OA^{1)}$ $PM_{2.5}$ (-)**	**$OA^{2)}/OA^{1)}$ PN (-)**
Mean	58	24	4.2 E+04	2.1E+04	0.45	0.65
Std Dev.	26	4	2.5E+04	5.0E+04	0.13	0.35
Median	49	24	3.7E+04	2.0E+04	0.46	0.59
N*	360	360	92	92	360	92

[1)] Measured on 19 Nov 2003 at 13:10-16:10

[2)] Measured on 2 Dec 2004 at 13:10-16:10

* Number of measurements

4. Conclusion and Implications

Indoor air pollution in the radio station was significantly affected by the levels of outdoor air pollution. Before the upgrade of the HVAC system, the mean indoor particle number concentration was 8.8×10^3 particle/cm^3, while particle mass concentration ($PM_{2.5}$) was 8$\mu g/m^3$. These values were much higher than those measured in office buildings with similar surroundings. Analysis of the relationship between outdoor air and supply air indicated that there were no obvious indoor sources in the investigated areas.

The performance of the HVAC system in the studied building was assessed before and after the upgrade. The results showed that by relocating the air intake of the HVAC, the PN and $PM_{2.5}$ levels near the intake were reduced by 35% and 55%, respectively. It was found that the particle penetration rate for PN was reduced from 42% to 14%, and the overall filtration efficiency of the HVAC system (relocation of air intake, pre-filter, AHU and particle losses in the air duct) increased from approximately 58% to 86% after the upgrade of HVAC system. For $PM_{2.5}$, the penetration rate after upgrade was approximately 18% and the overall

removal efficiency was about 82%. The upgraded HVAC system could effectively reduce indoor airborne particulate pollution in the building.

Outdoor air pollution levels can be extremely high around commercial buildings located in close proximity to dense traffic routes in developed cities. This affects indoor air quality in those buildings, posing a risk to the occupants, interior and electronic equipment. Whilst this study was site specific, it provides data and information valuable to the operators, owners and occupants of buildings facing similar challenges. The presented results may assist in setting relevant benchmarks and parameters affecting air quality in buildings located in an urban, high traffic environment.

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