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Impact of ventilation scenario on air exchange rates and on indoor particle number concentrations in an air-conditioned classroom

H. Guo[1*], L. Morawska[1], C. He[1], D. Gilbert[2]

1. International Laboratory for Air Quality and Health, Queensland University of Technology, 2 George Street, Qld 4001, Australia
2. Built Environment Research Unit, Department of Public Works, Queensland Government, Australia

* Now at the Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hong Kong

ABSTRACT

A two-week intensive measurement campaign of indoor and outdoor air pollution was carried out in September 2006, in a primary school to investigate indoor-outdoor correlations of particle number concentrations (PN), and the impact of air exchange rate (ACH) on the indoor PN concentration. The ACHs in the classroom for different conditions associated with window opening and the operational status of air conditioners (A/C) and fans were tested. As expected, the lowest ACH (0.12 h^{-1}) was found when the windows were closed and A/C and fans were off. In contrast, the highest ACH (7.92 h^{-1}) was observed when the windows were opened and A/C and fans were all on. The analysis of the PN I/O ratios at different ACHs in the absence of indoor sources indicates that the mean I/O ratio was 0.621 ± 0.007 (mean ± 95% confidence interval) when the windows were closed, and A/C and fans were off; 0.524 ± 0.023 when windows were closed, fans were off and A/C was on; and 0.502 ± 0.029 when windows were closed, A/C was off and fans were on. To further understand the relationship between indoor and outdoor PN concentrations, the impact of outdoor PN concentration on I/O ratios at different ACHs was investigated. It was found that the relationship between outdoor PN concentration and the I/O ratio at different ACHs followed a power trendline with an equation of I/O ratio = A*PN_{out}^{-b} (A and b are coefficients, PN_{out} is outdoor PN concentration), suggesting that the penetration efficiency decreased with increasing outdoor PN concentration. It is the first time we found that when the outdoor PN concentration increased there was an associated increase in the concentration of nano-particles, which have been demonstrated to have higher deposition rates and lower penetration efficiencies. Based on the above equation, the study also showed a significant effect of ACH on indoor PN concentrations under stable outdoor PN concentrations. In general, the higher the ACH was, the lower the indoor PN concentration was.

Key words: indoor to outdoor ratios; Particle number concentration; Air exchange rate; Air conditioned classroom; nano-particles

Introduction

School indoor air quality (IAQ) has become a global concern as children spend the second highest percentage of their time in schools and are especially susceptible to air pollution (Leickly, 2003; USEPA, 2003). In the past several decades, exposure to indoor air pollutants has increased due to a variety of factors, including the construction of more tightly sealed buildings, reduced ventilation rates to save energy, and the use of synthetic building materials and furnishings (ALA, 2000). In addition, human activities and decisions, such as delaying maintenance to "save" money, can lead to problems from indoor sources and ventilation systems. Basically, four factors affect IAQ: sources of indoor air pollutants; the heating, ventilation, and air-conditioning (HVAC) system; pollutant pathways and occupants.

Particulate matter has been recognized as a significant cause of health problems in outdoor and indoor environments, including schools (Ransom and Pope III, 1992). Studies were conducted to understand the relationship between indoor and outdoor particulate matter concentrations in various indoor environments such as residences, offices and schools, providing an indication of how well the building envelope protects against outdoor particulate matter; or how well the building ventilation system disperses the indoor-generated particles (e.g. Lee et al., 2002; Chao et al., 2003; Li and Chen, 2003; Morawska et al., 2001, 2003; Blondeau et al., 2005; Poupard et al., 2005). Most of these studies, however, were related to the IAQ under naturally ventilated conditions.

Air exchange rate (ACH) is the rate at which outdoor air replaces indoor air in a given space. Air exchange is one of several crucial, ancillary variables in understanding indoor-outdoor relationships and therefore, as such, can have an important influence on pollution levels in classrooms. If outdoor air is cleaner than indoor air, the IAQ will be improved by opening windows, turning on ceiling fans, or otherwise increasing the ACH. On the other hand, during times of high outdoor air pollution, closing the windows or otherwise reducing the ACH can have a protective effect (Anderson et al., 1999). This is particularly true for particles coming from outdoors, which deposit on walls and thus are removed from indoor air: the lower the ACH, the more particles will be removed from the air. For airborne pollutants, including particulate matter originating from both indoors and outdoors, the benefits of increasing air exchange depend on the relative intensity of pollution between indoor and outdoor air (Li and Chen, 2003). Outdoor air enters and leaves a room by infiltration, natural ventilation, and mechanical ventilation, where air movement associated with infiltration and natural ventilation is caused by air temperature differences between indoors and outdoors and by wind. In addition, there are a number of mechanical ventilation systems, ranging from outdoor-vented fans that intermittently remove air from a single room, to air handling systems that use fans and duct work to continuously remove indoor air and distribute filtered and conditioned outdoor air to strategic points throughout the room.

This study aimed to investigate the impact of ventilation scenario on ACHs and indoor particle number concentrations (PN) in an air-conditioned classroom; and to compare the IAQ in a classroom for conditions where air conditioning is the sole source of outside air or where the air conditioning is supplemented with open windows in order to increase the rate at which outdoor air is brought into the classroom. The ACHs and indoor-outdoor particle number concentrations (PN) were measured in a classroom and at an oval under various scenarios of natural ventilation, mechanical ventilation and infiltration.

Material and Methods

Sampling sites

The subject school is located in a small village surrounded by local residences and roads carrying a low level of local traffic (Figure 1). The outdoor sampling site was located at the school's oval; while the indoor sampling site was in an air conditioned classroom. The size of the classroom is about 9.60 × 7.25 × 2.70 m (length × width × height). The classroom is usually occupied by students during school hours on weekdays.

Figure 1 Sampling sites and surrounding area

Instruments and parameters measured

Particle number concentration and size distribution in the size range from 0.014 to 0.800 µm were simultaneously measured indoors and outdoors using two Scanning Mobility Particle Sizers (SMPS), each comprising of an Electrostatic Classifier (EC) (TSI, Model 3071A) and Condensation Particle Counter (CPC) (TSI Models 3010 and 3025). The SMPS operates on the principle of particle classification by the EC 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. A scan time of 3 minutes was selected as the operating parameter for both instruments in this study.

In addition, wind direction, wind speed, temperature and relative humidity were measured by a portable weather station (Davis Instruments Weather Monitor II).

Monitoring design

Measurements of outdoor PN concentrations together with meteorological conditions were conducted in a fixed location for a period of two weeks at the school oval (4th September to 20th September, 2006) (Figure 1). The instrumentation was installed and operated in an air-conditioned trailer. Outdoor air was drawn into the instrumentation via conductive, plastic, 1.5 m long tubes of inner diameter 8 mm, from an inlet on the roof of the trailer. Since the measured particle size range in this study was from 0.014 to 0.800 µm, it was assessed that the diffusion loss in the tube was about 8% for particles equal to 0.014 µm, ~5% for particles of 0.020 µm, <2% for particles of 0.050µm and no loss for particles larger than 0.100 µm (Baron and Willeke, 2001). Therefore, the outdoor PN concentrations measured by SMPS needed to be corrected. Indoor PN concentration measurements were conducted in an air conditioned classroom, simultaneously with the outdoor measurement. The instrumentation was placed on a desk, 1.5 m above the ground, in the middle of the classroom. The exhaust air of the instruments was discharged to the outside of the classroom via a tube.

Air conditioning and ventilation system

The air conditioner (A/C) in the classroom was installed on the wall. The outdoor air intake of the air conditioner was 133 liters per second when the A/C was on. The mixture of outdoor and return air was filtered before passing through the cooling coil. The filter was 45 mm thick, with an efficiency of 20% with number 1 test dust (F4). There was no exhaust air system in the classroom and only ceiling fans and the supply-air fan of the A/C unit served as exhaust ventilation of the classroom.

Measurement of air exchange rate

The tracer gas technique employed to calculate the ACH involves injecting a tracer gas and mixing it through the classroom, then measuring its decay rate with an appropriate instrument. If exfiltration rates of the tracer gas are constant, mixing is uniform, the chemical reaction between the gas and other chemicals is negligible and no indoor source of the gas is operating, the ACH can be calculated from the following equation:

$$ACH = \frac{1}{t} \ln \frac{C_0}{C_t}$$

Where t is time, and C_t and C_0 are concentrations of the gas at time t and 0, respectively.

The above equation can be rearranged to give the following:

$$\ln C_t = \ln C_0 - ACH * t$$

Thus, $\ln C_t$ has a linear relationship with t, and the slope of the scatter plot of $\ln C_t$ versus t is the ACH value.

In this study, ACHs in the classroom were measured by a sable CO_2 analyzer (Model CA-10a, Sable Systems International, NV) using CO_2 as a tracer gas. The sable CO_2 analyzer can resolve down to 1 ppm at CO_2 concentrations from zero to above atmospheric levels, and yet it is also capable of accurate measurements at percent-range CO_2 levels that saturate conventional CO_2 analyzers with more limited range. The response time of the analyzer is under one second. In general, both SF_6 and CO_2 tracer gases will provide adequate results for ACH using the ASTM method (ASTM, 2000). However, CO_2 gas is easy to procure, inexpensive, and more environmentally friendly than SF_6. In order to reduce indoor sources of CO_2 and interference from students, the measurements of ACHs under different ventilation scenarios were completed either on weekends or after-school hours when there were no people in the classroom. For each ventilation scenario, two–three measurements of ACHs were conducted. Each measurement was rather time-consuming and it took three whole days of the two-week sampling period to complete all the scenarios presented in the paper.

To measure the ACHs under different ventilation scenarios, all the windows and doors of the classroom were closed and the ceiling fans were turned on to mix indoor air thoroughly. The CO_2 gas was released into the classroom by a CO_2 cylinder. The amount of CO_2 released was controlled by the valve of the cylinder. A Sable CO_2 analyzer was placed 1.5 m above the ground in the middle of the classroom to monitor the CO_2 levels. When the indoor CO_2 level was more than 50% higher than the background level and a relatively stable concentration condition was established, the cylinder was closed. A ventilation scenario was then simulated and the decay of CO_2 gas under the scenario was measured.

Data analysis and interpretation

SPSS statistical software and Microsoft Excel were used to conduct descriptive statistical analysis, Analysis of Variance (ANOVA) with *post-hoc* multiple comparisons, regression analyses to determine the relationship between indoor and outdoor air pollution and the statistical difference between two parameters. A level of $p = 0.05$ was used for all statistical procedures.

Questionnaires

During the sampling period, every activity in the classroom that could cause indoor air pollution was recorded each day, as was the operation hours of the air conditioner and the presence of outdoor sources of particulate matter.

Results and discussion

Indoor and outdoor particle number concentrations (PN)

Table 1 presents descriptive statistical analysis of the data for PN concentrations measured in the classroom and at the oval. The overall indoor to outdoor PN ratio (I/O ratio) was recorded between 0.01 and 30.40 with a mean value of 1.28, reflecting the impact from indoor sources, meteorological conditions and the airtightness of the classroom. Detailed analysis is presented below.

Table 1 Descriptive statistics of data set obtained from the classroom and at the oval (Effective sampling period: 6/9/06 17:10 – 20/9/06 16:47)

Outdoor PN (particle/cm^3)		**Indoor PN (particle/cm^3)**		**I/O ratio**	
Mean	2.93×10^3	Mean	2.11×10^3	Mean	1.28
Standard Deviation	5.33×10^3	Standard Deviation	1.89×10^3	Standard Deviation	1.99
Median	1.82×10^3	Median	1.54×10^3	Median	0.80
Minimum	9.80×10^1	Minimum	1.88×10^2	Minimum	0.01
Maximum	1.23×10^5	Maximum	1.43×10^4	Maximum	30.40
95% CI*	1.30×10^2	95% CI	4.6×10^1	95% CI	0.05

* 95% CI: 95% confidence interval

Figure 2 illustrates the time series of I/O ratio for PN for the duration of the sampling period. It can be seen that the I/O ratio varied day-to-day and over time and was frequently greater than one. Detailed inspection of the sampling data indicated that this occurrence was caused by the following factors:

1) **Indoor sources**: there were two routine classroom cleaning activities scheduled each weekday before and after school hours. Elevated indoor PN levels were observed during these regular periods of classroom cleaning. During school hours, high I/O ratios were sometimes found as well and were due to candle burning (e.g. 7/9/06), and match burning/kerosene burning (e.g. 19/9/06).

2) **Meteorological impact**: the meteorological conditions had significant influence on the I/O ratios for PN. When it was raining, the outdoor PN decreased significantly due to wash-out effects. Consequently, the I/O ratios increased temporarily until equilibrium was achieved. For instance, on the 10th of September (Sunday), there were no indoor sources operating in the classroom; however the I/O ratios were higher than would be typically expected on that day. Our weather station data showed that there were several showers occurring on this day accounting for this result.

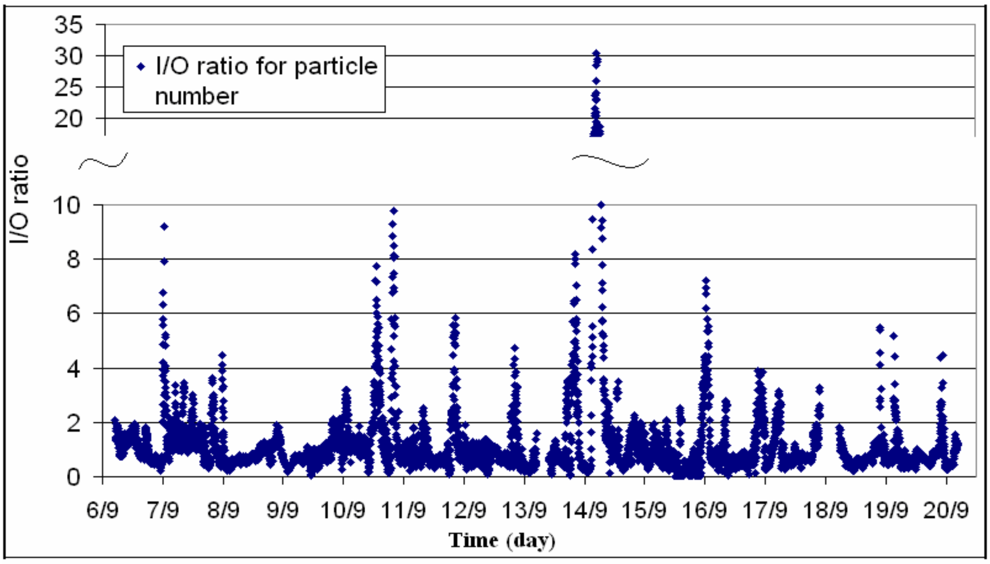


Figure 2 Time series of I/O ratio for particle number concentration. Marks on horizontal axis indicate 12 noon.

3) **Combination of indoor sources and meteorological condition**: under the combined impact of these two parameters the I/O ratios often increased significantly, reaching a maximum of 30. This was observed on the 14th of September during cleaning hours. On this day it was raining so that the effect of the cleaning activity in increasing the indoor PN level was compounded by the outdoor PN decrease associated with the rain. Thus, the I/O ratios increased significantly.

4) **Airtightness of the classroom**: the airtightness of the classroom could also contribute to an I/O ratio higher than one. For example, this was observed on Saturday the 16th of September, 2006. In the early morning of this day, there was a fire near the outdoor sampling site and the classroom. The maximum outdoor PN reached 1.23×10^5 particle/cm^3. The highly-polluted outdoor plume infiltrated the classroom, elevating the indoor PN level. Later it started to rain and consequently, the outdoor PN level rapidly decreased. The elevated indoor PN decreased much more slowly due to the low ACH of the tightly-sealed classroom. This situation was

reflected by the high I/O ratios measured on the 16th of September. Detailed discussion about the impact of ACH on I/O ratios is presented later.

Regression statistics analysis conducted on the entire data set showed that indoor PN did not correlate with outdoor PN (R^2 = 0.04). Figure 3 shows a scatter plot correlation of indoor and outdoor PN. The data set was categorized into two groups: one with very high outdoor PN concentrations and another with more typical indoor and outdoor PN concentrations. The group with very high outdoor PN was dominated by strong outdoor sources, i.e. biomass burning, while the other group showed a significant correlation between indoor and outdoor PN (R^2 = 0.31). The result showed clear impact of typical outdoor sources over the indoor PN concentrations once the strong outdoor PN sources i.e. data points with I/O ratio < 0.10, were removed.

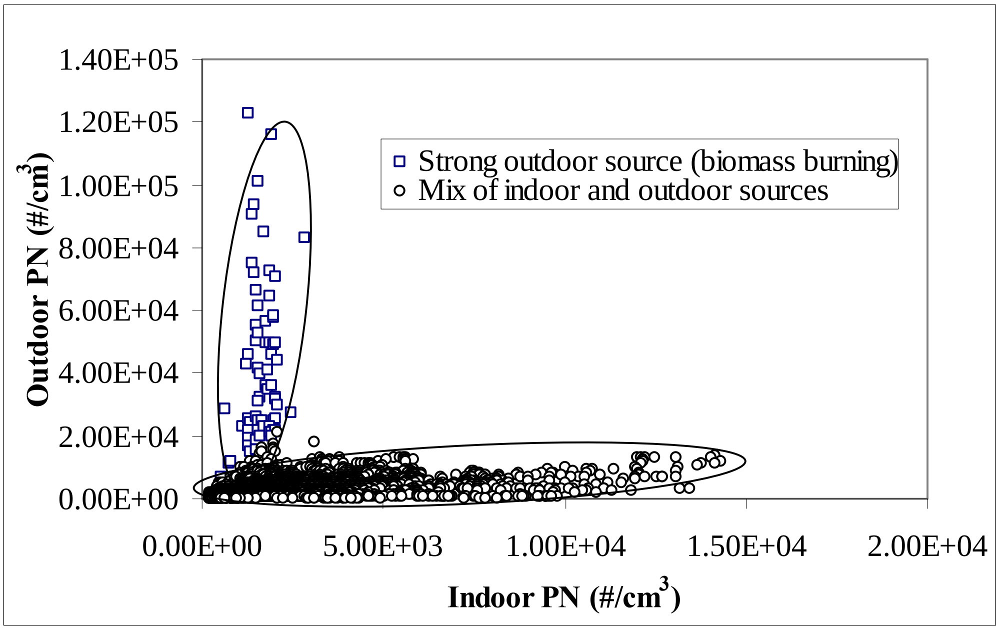


Figure 3 Scatter plot of indoor PN vs. outdoor PN

Calculation of air exchange rates under different scenarios

Figure 4 shows the ACH under different conditions in the air conditioned classroom. As expected, the ACH was the lowest (0.120 ± 0.004 h^{-1}) when the windows were closed, air conditioner (A/C) was off and fans were off. Such conditions were often observed between 3 pm and 8am on weekdays and for the whole day on weekends. The highest ACH (7.92 ± 0.25 h^{-1}) was observed when the windows were open, and A/C and fans were on; indicating the significant contribution of the combination of natural and mechanical ventilation to ACH. The result also showed that when the windows were opened and fans were on, the ACH with A/C on (7.92 h^{-1}) was much higher than that with A/C off (2.16 ± 0.51 h^{-1}).

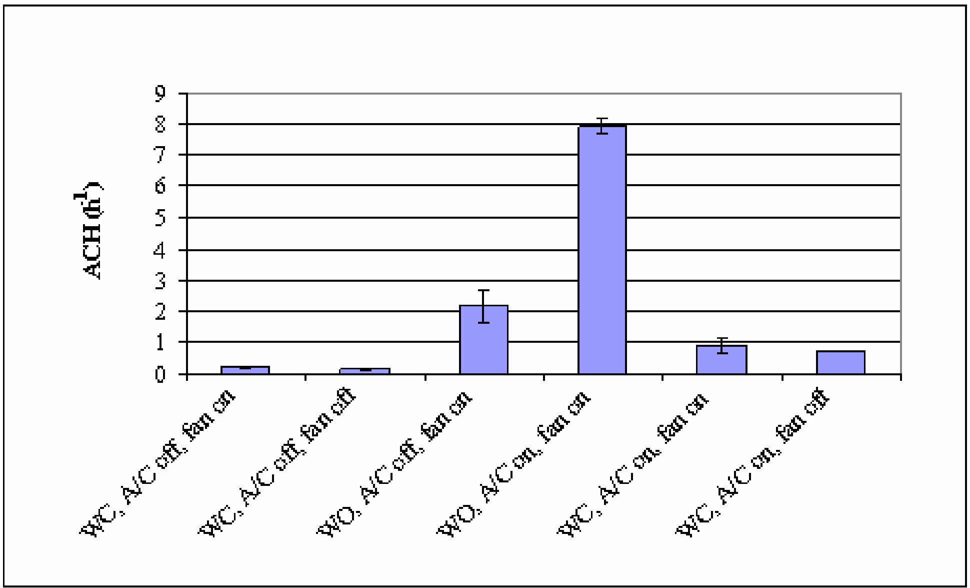


Figure 4 ACH in the air conditioned classroom under different scenarios: WC – window closed, WO – window open and A/C – air conditioner

It was found that the ACH was 0.90 ± 0.25 h^{-1} when the windows were closed, A/C was on and fans were on, which was higher than that when the windows were closed, fans were on but A/C was off (0.230 ± 0.025 h^{-1}). This indicates the impact of A/C on the ACH, which consequently affects the IAQ in the air-conditioned classroom. Similarly, when the windows were closed and fans were off, turning on the A/C increased the ACH (0.72 ± 0.00 h^{-1}) compared to that when the A/C was off (0.120 ± 0.004 h^{-1}).

In addition to the air conditioner, the ceiling fans were found to affect the ACH in the classroom. In particular, when the windows were closed and A/C was off, turning on the fans would increase the ACH in the classroom (0.230 h^{-1} fans on, versus 0.120 h^{-1} fans off). Similarly, turning on the fans increased the ACH from 0.72 h^{-1} to 0.90 h^{-1} when windows were open and the A/C was on.

Impact of air exchange rate on I/O ratio

To avoid the interference of indoor sources, only the data collected during the periods with no indoor sources operating were considered. Furthermore, since the indoor and outdoor concentrations varied temporally, rather than investigating the relationship between ACH and IAQ by using absolute concentrations, the I/O ratio of PN concentration is used instead.

Table 2 presents the descriptive statistics for I/O ratios under different scenarios. It can be seen that the mean I/O ratio of PN ranged from 0.502 ± 0.029 (mean ± 95% confidence interval) at an ACH of 0.23 h^{-1}, to 0.621 ± 0.007 with an ACH of 0.12 h^{-1}. The mean I/O ratio at the ACH of 0.12 h^{-1} was significantly higher than at other scenarios; while the other scenarios had similar I/O ratios.

The results revealed that the mean I/O ratio with windows closed, A/C on and fans off (0.524) was significantly lower than that with windows closed, A/C off and fans off (0.621) (*p*

<0.001); indicating that the IAQ in the classroom could be improved when the A/C is on and in the absence of indoor sources. In fact, the mean indoor PN when A/C was on ((1.57 ± 0.16) × 10^3 particle/cm^3) was statistically lower than that when A/C was off ((1.84 ± 0.04) × 10^3), even though the mean outdoor PN was similar for both situations.

Table 2 Descriptive statistics for indoor to outdoor PN concentration ratios (I/O) under different scenarios

Scenario*	**Mean**	**S.D.**[1)]	**95% C.I.** [2)]	**Sample size**	**ΔT (˚C)** [3)]	**WS (m/s)** [4)]
Windows closed, A/C off and fans off (ACH: 0.12 h^{-1})	0.621	0.203	0.007	3098	+1.2	1.1 (0.8)
Windows closed, A/C on and fans off (ACH: 0.72 h^{-1})	0.524	0.199	0.023	297	+1.0	2.4 (0.8)
Windows closed, A/C off and fans on (ACH: 0.23 h^{-1})	0.502	0.168	0.029	129	+0.6	5.5 (2.6)
Windows open, A/C off and fans off (ACH not measured)	0.559	0.267	0.026	398	+3.0	2.6 (0.4)
Windows open, A/C off and fans on (ACH: 2.16 h^{-1})	0.531	0.189	0.081	21	+1.4	1.0 (0.9)

* The calculation was based on the 3-min average sampling data for the period from 6 to 20 September, 2006.
1) Standard deviation; 2) 95% confidence interval; 3) Indoor-outdoor temperature difference; 4) Average wind speed (standard deviation).

For the scenario where windows were closed, A/C was off and fans were on, the mean I/O ratio (0.502) was much lower than that with fans off (0.621) (p<0.001). This implies that fans could also play a role in improving the IAQ.

It is interesting that the mean I/O ratio under the conditions of windows closed, A/C off and fans on (0.502) was consistent with that of windows closed, A/C on, but fans off (0.524); implying similar penetration efficiency under the conditions of either A/C or fans on. Here, the penetration efficiency is assumed to equal to the I/O ratio, as the deposition rate of particles is generally much smaller than the air change rate. The low penetration efficiency for the former condition was caused by the lower ACH, which made it difficult to bring polluted outdoor air into the classroom. Indeed, during the measurement under the condition where windows were closed, A/C was off and fans were on, coincidently, there was a biomass burning event near the site in the southwest direction. The measured outdoor PN concentration increased significantly from ~5.0 × 10^3 up to over 9.0 × 10^3 particle/cm^3 within 30 minutes and then decreased slowly. Simultaneously, the indoor PN concentration increased very slowly from ~1.6 × 10^3 to ~1.9 × 10^3 particle/cm^3 within 30 minutes and up to ~2.4 × 10^3 particle/cm^3 after 2 hours. This verified that the lower ACH protected the classroom from the infiltration of polluted outdoor air. On the other hand, the low penetration efficiency for the latter situation was mainly due to the filtration of the A/C system.

During the measurements, the conditions where windows were open, A/C was off and fans were off were sometimes observed during school hours on weekdays. In particular, between the 11^{th} and the 15^{th} of September, the A/C was off for most of the day, therefore the classroom was naturally ventilated. Under the natural ventilation, the mean I/O ratio was 0.559 ± 0.026, which was lower than that observed in naturally ventilated Australian residences and high-rise apartments in Hong Kong (Morawska et al., 2001, 2003; Chao et al., 2003). Detailed comparison is given below in the section of "Comparison with other studies".

Comparing the conditions with windows closed to that of windows open while the A/C was off and fans were off, it was found that window opening had a significant impact on the mean I/O ratio (0.621 versus 0.559, $p<0.001$). Contrary to the expectation, the I/O ratio was lower for windows open condition (0.559 ± 0.026) than that for windows closed condition (0.621 ± 0.007). This was probably due to the fact that it was not easy to dilute indoor air once the windows were closed whereas the outdoor air could be significantly diluted at such a relatively clean rural site. Consequently, the mean I/O ratio would be higher for the conditions of windows closed.

On the other hand, if the A/C was off but the fans were on, window opening did not affect the mean I/O ratio significantly (0.502 versus 0.531, $p = 0.511$). The ACH with windows open was as high as 2.16 h^{-1} (Table 2), which is favorable to the exchange of indoor and outdoor air. If the outdoor air was clean, high ACH would dilute indoor air and result in relatively low I/O ratio. In contrast, the ACH with windows closed was only 0.23 h^{-1}. Under such condition, closing the windows would protect the indoor air from polluted outdoor air pollution. Indeed, the lower the ACH, the more particles will be removed from the air. Therefore, it is not unusual that the I/O ratio would be small at low ACH.

However, conclusions should be drawn with caution because the penetration efficiency is affected by several factors, such as outdoor PN concentrations and meteorological conditions at the time when the measurements are conducted. For the conditions where windows were closed, A/C was off and fans were on, during the measurement there was a biomass burning plume transported to the sites that significantly increased the outdoor PN levels but had less impact on indoor PN concentrations because of closed windows. Consequently, the I/O ratio decreased. In contrast, if there were no obvious outdoor sources or the wind speed was high, the mean outdoor PN level would not normally reach the levels recorded in this study (4.45×10^3 particle/ cm^3). In this case, the I/O ratio would be higher, indicating that the penetration efficiency would be higher.

Similarly, the I/O ratio could also be affected by outdoor PN concentrations for the condition where the windows were open, A/C was off and fans were on. For instance, if the outdoor PN concentration increased from 2.0×10^3 to 3.0×10^3 particle/cm^3, the I/O ratio would decrease from 0.41 to 0.27 based on the relationship between outdoor PN and I/O ratio. This will be further discussed later.

Comparison with other studies

The above results showed that the I/O ratio for particle number concentration ranged from 0.502 to 0.621 at different ACHs when there were no indoor sources. These findings are comparable with previous observations in Australian residences (Morawska et al., 2001, 2003), where the mean I/O ratio for submicrometer particles (particles with diameter less than 1 µm) was 0.890 when all the doors and windows of the tested houses were open and no indoor sources were in operation (Morawska et al., 2001). In the study presented here, under a similar condition (windows open, A/C and fans off), the mean I/O ratio for the tested particle size-range was 0.559 ± 0.026 (mean ± 95% confidence interval). Morawska et al. (2001) also found that the I/O ratio was 0.780 when all the doors and windows of the houses were closed. In comparison, this study found that the I/O ratio was 0.621 ± 0.007 under a similar condition. Obtained from the same study, Morawska et al. (2003) reported that the average ratio of daytime, non-activity, indoor to outdoor concentrations in Australian residences was 0.930.

Previous studies also investigated particle penetration efficiency in naturally or mechanically ventilated venues (Chao et al., 2003; Thornburg et al., 2001). Under the condition that the deposition rate is much smaller than the air change rate, the penetration efficiency is equivalent to the I/O ratio. Chao et al. (2003) reported that the penetration efficiency in six non-smoking naturally ventilated residences of high-rise apartment buildings was particle-size dependent: the penetration efficiency was 0.79 in the size range of 0.853 to 1.382 µm, and 0.48 in the range of 4.698 to 9.647 µm. Based on a chamber test result, Mosley et al. (2001) found a size-resolved profile for the penetration efficiency, where the maximum penetration was in the range of 0.01 to 1.00 µm. Wahlin et al. (2002) reported a more detailed size-resolved penetration efficiency in a naturally ventilated residence in Denmark. It was found that the penetration efficiency fluctuated around 40 to 60 % for particles from 0.01 to 0.40 µm.

In this study, the mean I/O ratio observed for different scenarios in the absence of indoor sources was generally lower than in other studies. The lower I/O ratios found in this study were likely due to the impact of the following factors as discussed above: 1) A/C operation in the classroom; 2) fans on in the classroom; 3) the airtightness of the classroom; 4) the lower level of outdoor PN at the rural site; and 5) the combination of the above factors.

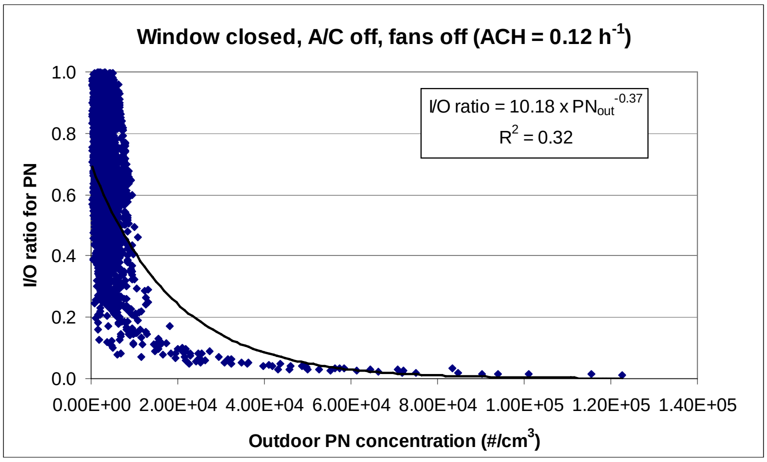
Impact of outdoor PN concentration on I/O ratio

Figure 5 shows the scatter plots of I/O ratio versus outdoor PN concentration for different scenarios. It was found that the relationship between the I/O ratio and outdoor PN concentration followed a power trendline for each scenario. The I/O ratio decreased with increasing outdoor PN concentrations. That is,

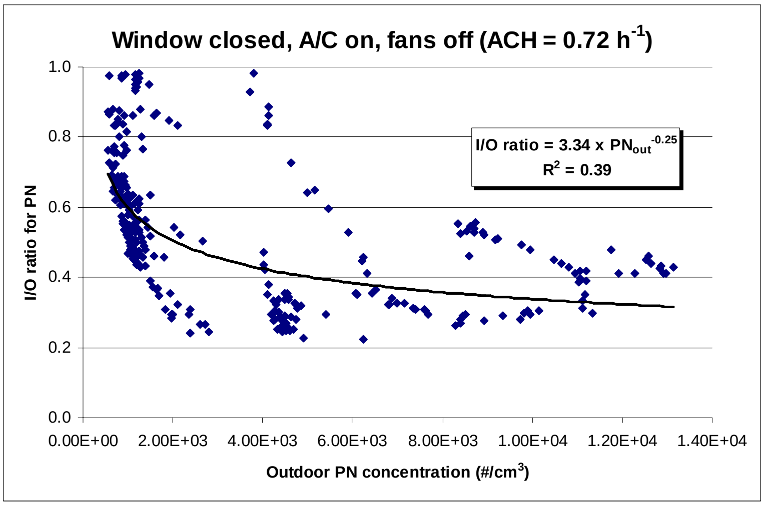
$$\frac{I}{O} ratio = A * C_o^{-b}$$

Where, *A* and *b* are coefficients, and C_0 is the outdoor PN concentration.

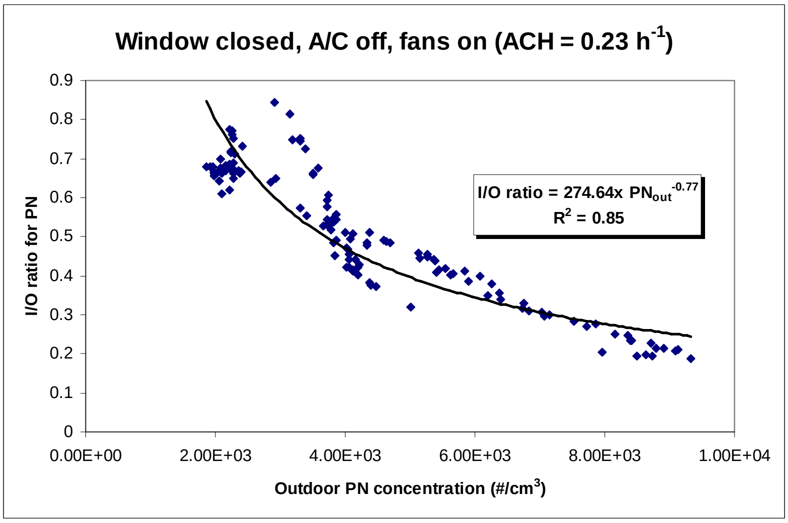
It was also found that the goodness of fit was not great in *A* and *b* values below, in particular for the conditions in Figures 5(a) and 5(b). This may reflect the fact that the I/O ratio was also affected by other factors i.e. classroom occupancy and operation of A/C, in addition to the outdoor PN concentration. Further study on this matter is required for detailed explanation.


Window closed, A/C off, fans off (ACH = 0.12 h^{-1})
I/O ratio = 10.18 x PN$_{out}^{-0.37}$
R^2 = 0.32
I/O ratio for PN
1.0
0.8
0.6
0.4
0.2
0.0
0.00E+00 2.00E+04 4.00E+04 6.00E+04 8.00E+04 1.00E+05 1.20E+05 1.40E+05
Outdoor PN concentration (#/cm^3)

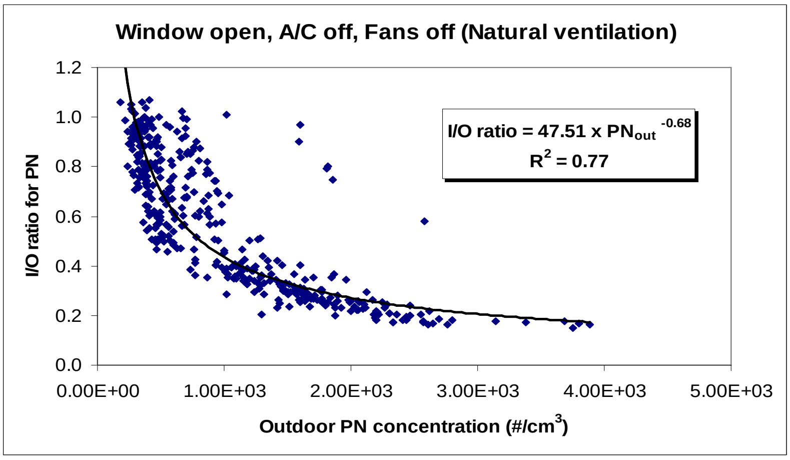
(a)


Window closed, A/C on, fans off (ACH = 0.72 h^{-1})
I/O ratio = 3.34 x PN$_{out}^{-0.25}$
R^2 = 0.39
I/O ratio for PN
1.0
0.8
0.6
0.4
0.2
0.0
0.00E+00 2.00E+03 4.00E+03 6.00E+03 8.00E+03 1.00E+04 1.20E+04 1.40E+04
Outdoor PN concentration (#/cm^3)

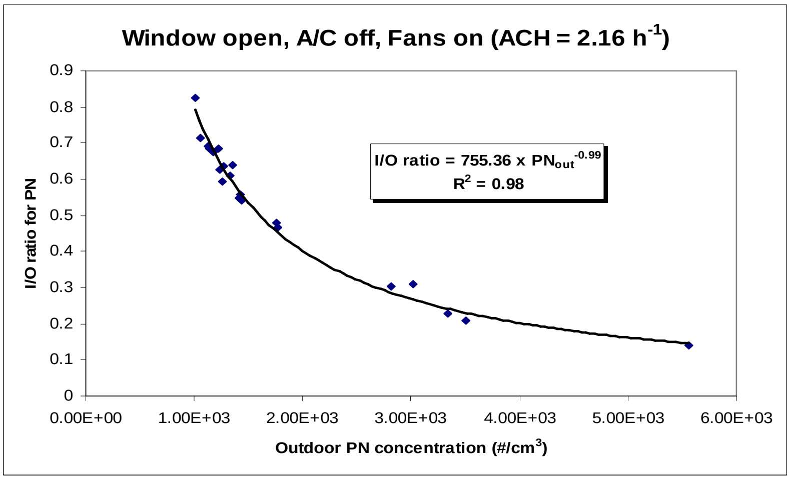
(b)


Window closed, A/C off, fans on (ACH = 0.23 h^{-1})
I/O ratio = 274.64x PN$_{out}^{-0.77}$
R^2 = 0.85
I/O ratio for PN
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.00E+00 2.00E+03 4.00E+03 6.00E+03 8.00E+03 1.00E+04
Outdoor PN concentration (#/cm^3)

(c)



(d)



(e)

Figure 5 Scatter plots of I/O ratio versus outdoor PN for different scenarios. (a) windows closed, A/C off and fans off; (b) windows closed, A/C on and fans off; (c) windows closed, A/C off and fans on; (d) windows open, A/C off and fans off; (e) windows open, A/C off and fans on

To better understand the reason why the I/O ratio decreased with the increase of the outdoor PN concentration, the relationship between outdoor PN and the count median diameter (CMD) under normal meteorological conditions (i.e. fine weather with wind speed < 1.5 m/s and no rain) is plotted in Figure 6. It can be seen that the data points fell into two groups. The CMD in one group decreased from ~70 nm to ~30 nm with the increase of outdoor PN concentration on both a weekday (8 September, 06) and weekend day (9 September, 06), when the outdoor PN was less than 3.0 x 10^3 and 4.0 x 10^3 particle/cm^3, respectively. The CMD in the other group fell in the range of 25 to 40 nm, with size corresponding to increase in the outdoor PN.

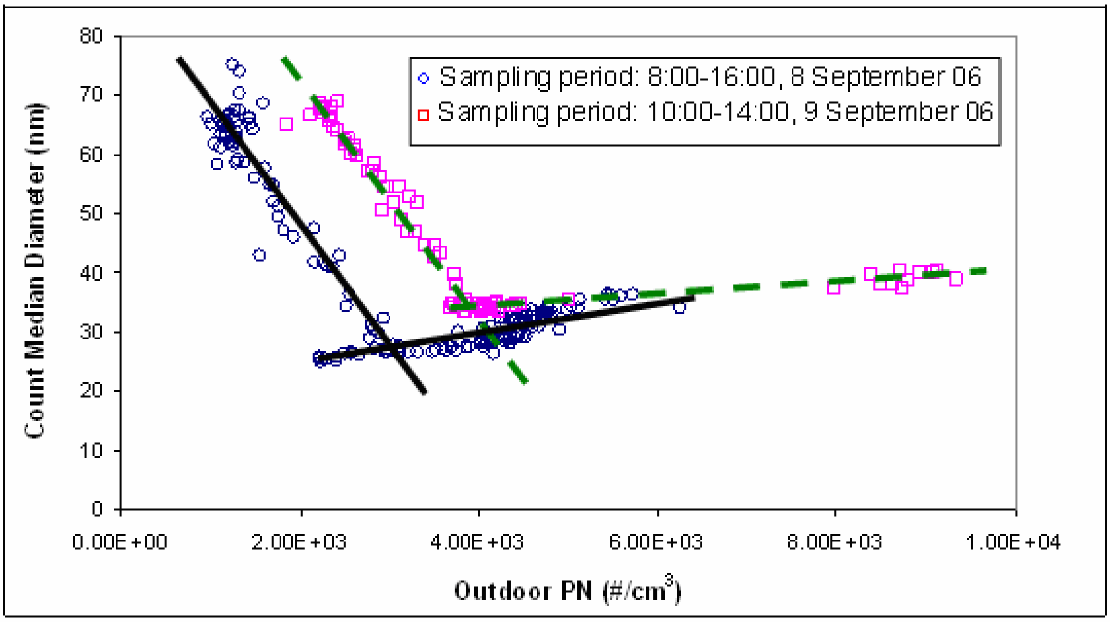


Figure 6 Relationship between outdoor PN and Count Median Diameter (CMD)

The above results show that when the outdoor PN concentration increased, it actually increased the concentration of particles with diameter less than 50 nm (nano-particles), which most likely were fresh combustion aerosols. In previous studies, it was found that nano-particles had the highest deposition rate among submicrometer particles (particles with diameter less than 1 µm) (He et al., 2005). In addition, in a recent study, it was found that nano-particles had lower I/O ratios than particles with diameters between 50 and 350 nm (Guo et al., 2007). Based on these facts, it is concluded that the I/O ratio decreased while the outdoor PN increased under this condition.

Relationship between ACH and calculated indoor PN concentration

To determine the impact of ACH on indoor PN concentrations, the relationship between ACH and calculated indoor PN concentration was plotted (Figure 7). This figure was obtained by first identifying constant outdoor PN concentrations; then obtaining I/O ratios for each individual ACH condition based on the *power* equations for each. Following this, the indoor PN concentration was calculated by multiplying modeled I/O ratio by outdoor PN concentration. Finally, the ACH versus indoor PN was plotted.

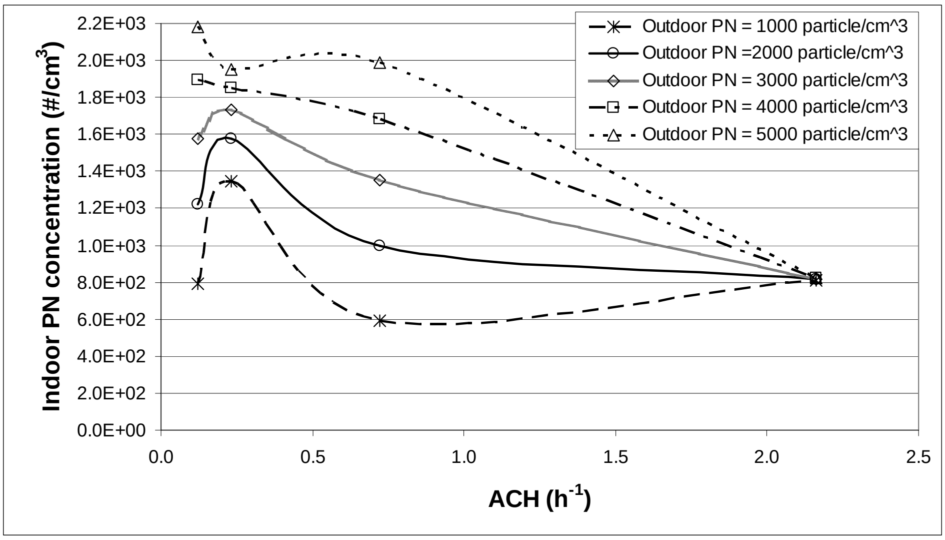


Figure 7 Relationship between ACH and calculated indoor PN

The relationship between indoor PN concentration and ACH when the outdoor PN concentration ranged from 1.0×10^3 to 5.0×10^3 particle/cm^3 showed that the indoor PN concentration generally decreased with increasing ACH; except in the extreme case where windows were closed, A/C was off and fans were off. It appeared that when the ACH was high enough (natural ventilation: windows open, A/C off and fans on, ACH = 2.16 h^{-1}), the indoor PN concentration would decrease to a similar level regardless of the outdoor PN levels. The modeling result also showed that the airtightness of the building had a significant effect on the decrease of indoor PN concentration. For instance, the indoor PN concentration was lower for the condition of windows closed, A/C off and fans off (ACH = 0.12 h^{-1}) than that for the condition of window closed, A/C off and fans on (ACH = 0.23 h^{-1}), due to a less impact of polluted outdoor air. The scenarios involving mechanical ventilation (windows closed, A/C on, fans off - ACH = 0.72 h^{-1} and windows closed, A/C off, fans on - ACH = 0.23 h^{-1}) were in between the above two extremes (0.12 h^{-1} and 2.16 h^{-1}). In addition, the ACH under the condition of natural plus mechanical ventilation (windows open, A/C on and fans on) was also measured and in this case reached as high as 7.92 h^{-1}. Unfortunately, the indoor and outdoor PN concentrations were not simultaneously measured during this period of high ACH (7.92 h^{-1}) because of the temporary unavailability of the equipment. However, it could be speculated from the trendlines in Figure 7 that the high ACH would dilute the indoor PN concentration significantly.

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