Topic B9: IAQ in rapidly urbanizing cities

Reduction in $PM_{2.5}$ Levels at the International School of Beijing Due to Positive Building Pressurization and Air Filtration Upgrades

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SUMMARY

While recent attention has been focused on outdoor $PM_{2.5}$ levels in Beijing, many people spend much of their time indoors where concentrations are unstudied. Some firms and individuals have made significant efforts to reduce their indoor exposure to $PM_{2.5}$, but the efficacy of these efforts is not documented. This study investigated the impact of extensive upgrades to the air handling system at the International School of Beijing (ISB) on indoor concentrations of $PM_{2.5}$. School personnel conducted $PM_{2.5}$ monitoring before and after upgrades. Students conducted $PM_{2.5}$ monitoring after upgrades. Indoor $PM_{2.5}$ concentrations were significantly lower after the upgrades, dropping from an average of 17 µg/m3 to 3 µg/m3 and maintained reduced average indoor levels even when outdoor $PM_{2.5}$ values exceeded 200 µg/m3. Thus, buildings in rapidly urbanizing and highly polluted cities like Beijing can significantly improve indoor air quality through targeted facilities improvements that create positive building pressurization and enhanced air filtration.

INTRODUCTION

$PM_{2.5}$ presents a public health problem in many areas worldwide, especially large rapidly urbanizing cities in rapidly developing countries such as Beijing, China ("Database", 2010). One specific type of substance causing poor air quality is particulate matter. Particulate matter is a major air pollutant that is composed of mixtures of extremely small particles and liquid droplets. Particle pollution is made up of a number of components, including certain products of combustion, acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles ("Particulate Matter", 2013).

Particulate matter is categorized based on the size of the particles with $PM_{2.5}$ particles (also known as fine particles) being those smaller than 2.5 µm. Coarse particles are classified as particles from 2.5 µm to 10 µm (PM_{10}). Coarse particles are elevated near roadways and other sources of dust such as construction sites, mining and some factories. These particles are capable of being inhaled through normal bodies and may reach the lungs. Fine particles, on the other hand, are smaller than 2.5 µm ($PM_{2.5}$), and are mainly formed as a product of combustion. In and around Beijing, this combustion is primarily associated with emissions from coal power plants, certain types of industries factories, and automobiles. Since Beijing and the region around it relies heavily on the use of coal for power generation and for heat production and has seen a rapid growth in automobile and truck traffic in the last decade, annual average $PM_{2.5}$ concentrations are currently some of the highest in the world. $PM_{2.5}$ also can reduce visibility. It can also cause environmental damage as particles may enter bodies of water, including rivers, streams, and lakes, making them acidic. Lastly, $PM_{2.5}$ pollutants can stain or damage stone or other materials, including important objects such as statues and monuments. In this study, we will be focusing on $PM_{2.5}$, a type of particulate matter that is commonly found in the location of study, Beijing, China.

The air quality issue has gained recent attention in Beijing due to widening public awareness of and access to hourly average values for $PM_{2.5}$ from multiple monitoring sites run by the Chinese Ministry of Environmental Protection and at the US Embassy. Poor air quality events in Beijing are quite frequent and depending on weather conditions, can last up to a week with “Hazardous” PM 2.5 levels in excess of 300 µg/m3 and on several occasions have exceeded 500 µg/m3 (Mintz, 2009). These exceptionally high $PM_{2.5}$ levels have on these occasions resulted in the Air Quality Index (AQI), on both the Chinese and the US scales, going above the AQI scale maximum of 500, and this has recently gained significant media attention and has resulted in a higher level of public concern regarding air quality (“Air Quality Index”, 2013).

During the winter of 2013, students at the International School of Beijing (ISB) surveyed indoor air quality as part of a science class using hand-held TSI AM510 Aerosol Monitors, and found that concentrations of $PM_{2.5}$ were relatively high inside the building, at times in excess of 150 µg/m3 in classrooms, hallways and other large spaces on days with exceptionally high outdoor $PM_{2.5}$ concentrations. These periods of poor indoor air quality were of growing concern to the students, parents, faculty and staff. It was thought that poor indoor air quality was likely a result of inadequate filtration of fresh air intakes by existing air handling units and periods of negative building pressurization resulting in a significant infiltration of polluted air into the building through operable windows and exterior doors.

Following an appraisal of the results of student testing of indoor $PM_{2.5}$ concentrations during 2012-2013 school year and increasing awareness of air quality issues, ISB Administrators were motivated to find a long-term solution to the problems that were resulting in poor indoor air quality in order to adequately protect students, staff and faculty from the harmful health effects of high $PM_{2.5}$ concentrations.

In response to these observations and after an appraisal of the HVAC system it was determined that the existing air handlers, which employed two-stage filtration using F6 and F8 filters were inadequate in reducing the indoor $PM_{2.5}$ concentrations. Rather than continuing to use these on days with exceptionally high outdoor $PM_{2.5}$ levels, which resulted in pushing relatively more polluted air into the building than existed in the building, the air handling units with fresh air intakes were temporarily shut down, which created negative pressure in the school, as was evident by a significant wind rushing in when the doors were opened. This caused even more infiltration of highly polluted air through doorways and gaps around operable windows.

HVAC and Building Upgrades

The first phase (completed during June and July of 2013) of the upgrades included the installation of 35 new Air Handling Units (AHUs), which handle all of the fresh air intakes for the 51,000m^2 school. The air handling system upgrades at the International School of Beijing consisted of replacing 35 aging Sinko brand fresh air AHUs that had 2-stage filtration (F6 and F8) with new Dunham-Bush CS3 Series Modular Central Station AHUs with a 3-stage filtration system. The new 3-stage filtration included a F6, F8 and a High-Efficiency Particulate Absorption (HEPA) H-14 air filters as the 3rd stage. HEPA is a collective group of air filters that meet the HEPA standard. The HEPA class H-14 filter implies that the filter separates > 99.995% of particles with the size as small as 0.3 μm.

These upgrades allowed for both higher levels of filtration at fresh air intakes, and also enabled adequate building-wide pressurization through 30% higher airflow rates to the classrooms and open spaces. In addition, 8 existing and newly constructed high-traffic double-door entrances and all stairwells were pressurized to an even higher level to further reduce infiltration of unfiltered air into the school from outside when these doors were used and to limit the penetration of more polluted air on the first floor to higher floors within the 3-story building. In addition, all operable windows were removed to limit another possible sources of infiltration into the building.

The approximate cost of all of the upgrades described was 10,737,055 RMB, or approximately 1,771,528 USD. Regular filter management has the following replacement schedule and costs:

Stage	Filter	Replacement	Cost
1st	F6 or G3	Weekly or Monthly	RMB 75-135 ($12-22 USD) /piece RMB 60-90 ($10-15 USD) /piece
2nd	F8	Monthly	RMB 96-180 ($16-30 USD) /piece
3rd	H14	Every 6-8 months	≈RMB 800 ($132 USD) /piece

All new air handler units are controlled by variable frequency drives for maximum energy conservation. Given the increase in the air volume that these units are capable of, ISB has noted a positive pressure within the building. Together, the upgraded AHUs have required roughly a 10 percent increase in the amount of energy use to support the increased air volume handled and greater air-filtration. Replacement of the remaining 24 AHUs that handle and recondition return air is planned for the summer of 2014.

During the spring of 2013, a systematic plan was developed to monitor indoor PM2.5 concentrations both before and after the upgrades. ISB Facilities personnel completed this monitoring using two TSI DustTrak II Aerosol Monitors. In addition, a plan was developed during the fall of 2013 to include student monitoring of indoor $PM_{2.5}$. During late August of 2013, high school students conducted six days of indoor $PM_{2.5}$ monitoring. The results student monitoring using TSI SidePak monitors were compared with the results of the facilities monitoring using the TSI DustTrak II monitors for the period following upgrades. This study attempts to illustrate that High School students can be trained to conduct indoor air quality assessments.

METHODOLOGIES

TSI SidePak and DustTrak II Aerosol Monitors are based on photometry, in which measurements of light scattering are assessed. Field calibration is needed to establish a valid calibration factor for each machine in a city's unique composition of pollutants. While using a factory installed calibration factor of 1.0 is known to produce observed mass values in excess of true mass (Heal et al., 2000), the relative differences determined comparing indoor and outdoor values are valid.

Procedure used for TSI DustTrak II Aerosol Monitors by ISB facilities staff

Monitoring of indoor $PM_{2.5}$ levels by ISB facilities staff occurred before the implementation of the upgrades (during 17 days in Feb/Mar 2013) and after implementation (during 24 days in July/Aug 2013). $PM_{2.5}$ levels were recorded using the TSI DuskTrak II Aerosol Monitor after zeroing and once the readings stabilized, usually within 30 seconds, at 26 indoor and 1 outdoor monitoring site each day. The specific times of monitoring each day were at 09:00, 13:00 and 16:00 and these times were selected to be shortly following major movements of people into or out of the building at the start of school, following lunch and after school. The two hand held TSI DustTrak II Aerosol Monitors (TSI models 8530 and 8532) used in this study were operated with PM2.5 inlets and a standard factory calibration factor of 1.0.

Procedure used for TSI AM510 SidePak by ISB students

Monitoring conducted by ISB high school students occurred twice daily at random hours between 08:30 and 15:30 on 6 days between August 22nd and August 29th. Six TSI AM510 SidePak Aerosol Monitors with $PM_{2.5}$ inlets were used. One of the SidePaks was field calibrated to the US Embassy's BAM, located in Chaoyang District, Beijing, through a street-side 1-hour test period. This SidePak required a 0.39 Calibration Factor. When all SidePaks were programed with a 0.39 Calibration Factor, readings during a side-by-side test varied less than 10%. The SidePaks were zeroed after warming up and the average value was recorded for 1-minute of sampling at each site.

Procedure used for correcting data for Relative Humidity (RH)

Because relative humidity can impact the mass readings from these $PM_{2.5}$ monitors (Chakrabarti et al., 2004), results from outdoor readings by the $PM_{2.5}$ monitors are inaccurate when humidity levels exceed approximately 50%; a level commonly exceeded during the summer months in Beijing. Wintertime humidity levels during the study were low. The HVAC system maintains humidity to levels below 50% year round indoors. Once humidity levels exceed approximately 50% the measured $PM_{2.5}$ values begin to become inflated with this effect becoming quite excessive at the highest levels. In order to get a valid measurement of outdoor $PM_{2.5}$ for the summertime monitoring period, the measured value must be adjusted. The following equation was employed to adjust the $PM_{2.5}$ values of summertime outdoor readings. RH levels for hours matching those monitored each day at ISB were obtained from Weather Underground records for the Beijing International Airport, located approximately 5 kilometers away from ISB. All of the data presented in this paper related to measurements of $PM_{2.5}$ values at ISB have been adjusted for RH with the equation (Chakrabarti et al., 2004):

$$PM2.5(a) = PM2.5(m) / (1 + 0.25 * ((RH^2)/(1-RH))) \tag{1}$$

Where PM2.5(a) is the adjusted/real PM2.5 value, PM2.5(m) is the measured PM2.5 value, and RH is the Relative Humidity of the air ($0 \le RH \le 1$)

RESULTS AND DISCUSSION

The results of the monitoring of indoor air quality by ISB Facilities Staff using the DustTrak II Monitors before and after the air handling system upgrades previously described can be demonstrated in the following 4 figures. Figure 1 represents a direct comparison between the average $PM_{2.5}$ concentration of each room before and after implementation with rooms with upgraded air handlers separated from those without; Figure 2 and Figure 3 individually represent the average indoor $PM_{2.5}$ compared to the average outdoor $PM_{2.5}$ on each data collection day of the period before and after implementation, respectively. Figure 3, the data after implementation, only incorporated the data of the upgraded rooms. Lastly, Table 1 presents the average indoor and outdoor concentrations observed and the ratio for the two periods are compared.

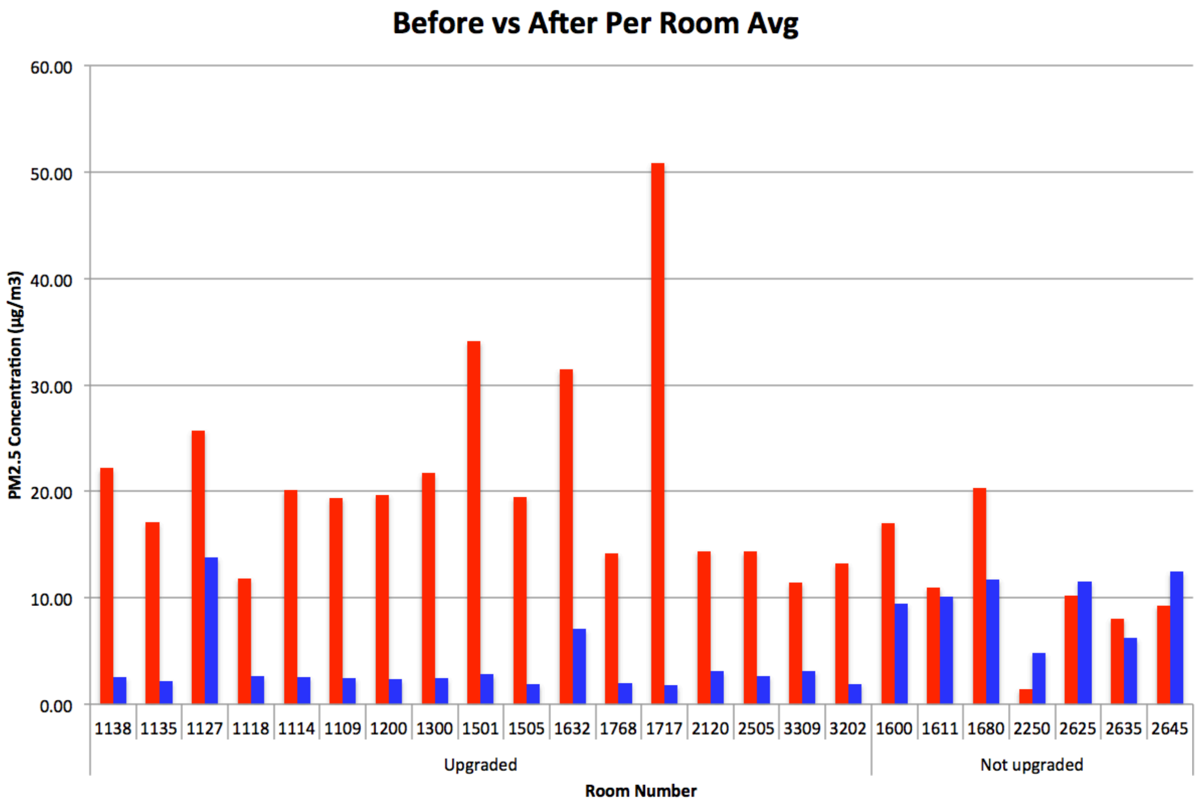

Figure 1: Average PM2.5 concentration of each room during the before (red) and after (blue) implementation periods, respectively.

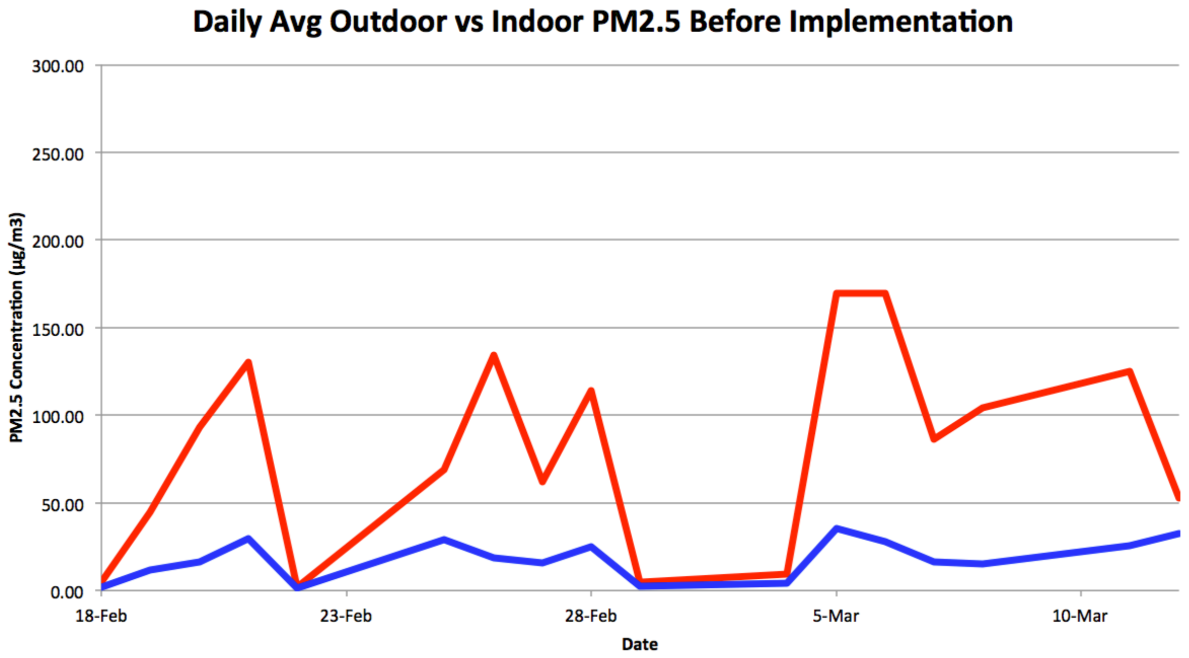

Figure 2: Daily average of outdoor (red) and indoor (blue) corrected $PM_{2.5}$ concentration before implementation of new AHUs.

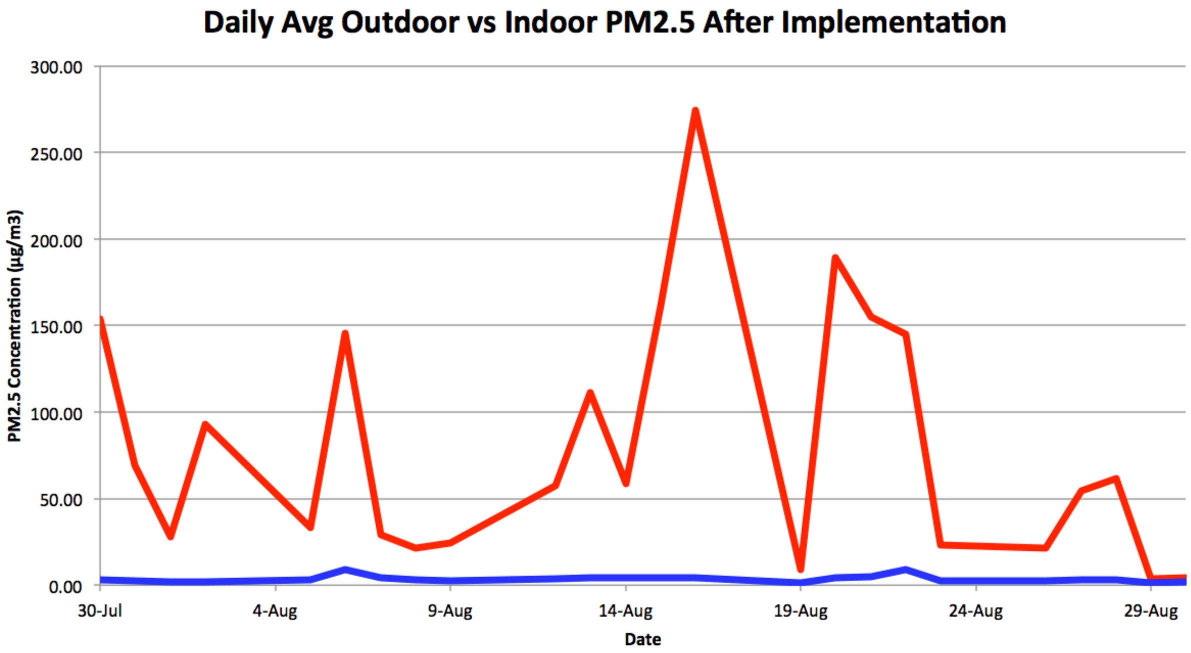

Figure 3: Daily average of outdoor (red) and indoor (blue) corrected $PM_{2.5}$ concentration after implementation of new AHUs.

	Before	**After**
Average Outdoor PM$_{2.5}$ (µg/m3)	80.9	80.3
Average Indoor PM$_{2.5}$ (µg/m3)	16.7	3.2
Percentage Reduction in PM$_{2.5}$ (%)	79.4	96.0

Table 1: Comparison between indoor and outdoor average PM$_{2.5}$ & the percentage reduction before and after implementation.

As indicated in Table 1, the average indoor PM$_{2.5}$ levels experienced an average of a 79.4% reduction compared to the average outdoor PM$_{2.5}$ before implementation, while the indoor PM$_{2.5}$ levels after implementation experienced a 96.0% reduction when compared to outdoor air quality measured during the same period. As indicated in the comparison between Figure 2 and 3, Fluctuations in indoor PM$_{2.5}$ concentrations were significantly reduced after the upgrades and maintained an average indoor PM$_{2.5}$ level of below 9 µg/m3 even though outdoor PM$_{2.5}$ values fluctuated between 5 µg/m3 and 274 µg/m3. Indoor monitoring sites that were specifically targeted by the upgrades showed even greater reductions in PM$_{2.5}$ concentrations.

In a related study conducted by ISB high school students using the SidePak Monitors, both outdoor (2 locations) and indoor (32 locations) PM2.5 concentrations were measured twice in each of 6 separate days after implementation. In addition to PM2.5, relative humidity was also measured for each PM2.5 recording. The data shown in Table 2, was compared to similar data measured by the school using the DustTrak II Monitors after implementation.

Day	**Indoor PM2.5 Average (µg/m3)**	**Outdoor PM2.5 Average (µg/m3)**
1 (8/22/13)	15.84	126.45
2 (8/23/13)	5.27	10.26
3 (8/26/13)	3.84	35.12
4 (8/27/13)	6.44	109.67
5 (8/28/13)	8.63	39.6
6 (8/29/13)	2.57	3.35

Table 2: Comparison between average indoor and average outdoor PM2.5 (µg/m3) concentration for student SidePak data taken after implementation (corrected for RH).

CONCLUSIONS

This study supports the effectiveness of air quality targeted upgrades at ISB when combined with overall building tightening. The installation of 35 new AHUs, which created positive building pressurization and 3-stage filtration, to include H-14 filters, markedly controlled degraded indoor air quality. These upgrades worked through fixing problems of infiltration of poor outdoor air at exits and operable windows due to negative building pressurization and inadequate filtration of fresh air intakes and the effects of these upgrades were most notable during days of very high $PM_{2.5}$ concentrations. Results show that with these upgrades, the average $PM_{2.5}$ concentration of indoor air dropped from 21% of the average outdoor $PM_{2.5}$ concentrations to 4% of the average outdoor $PM_{2.5}$ concentration. Further, the overall school system functioned well even when outdoor concentrations approached 300µg/m3. Therefore, schools in highly polluted cities can safeguard the health of students and staff through targeted air management improvements. The research also found that high school students could be trained to effectively conduct studies to assess indoor air quality conditions in their schools.

The importance of monitoring indoor air quality has become increasingly important in developing nations like China that face air pollution problems, and so is relevant to many similar areas around the world. Results from this study could mitigate the health effects of air pollution on members of institutions by such use of air filters and positive building pressurization.

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