Session 2.8: Innovations for Occupant Wellbeing (2)

Outdoor to Indoor Air Quality in Urban Environment

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ABSTRACT

The World Health Organisation (WHO) stated that air pollution is the world's largest single environmental health risk, and this risk is particularly high in urban areas (WHO, 2014). Heavy traffic, high population density and packed city morphology with deep street canyons have resulted in a very high level of harmful outdoor pollutants in major cities like Hong Kong. Nevertheless, buildings still need to take in "fresh air" from the outside for their occupants. As the outdoor air remains unhealthy, the impact of bringing it into the indoor air environment needs to be further clarified.

This study focuses on the relationship between indoor and outdoor air quality, and examines how outdoor air quality varies with height in the urban street canyon. Field measurements were conducted in a high-rise office building located in a densely populated district in Hong Kong. Using the data collected, analyses were performed to check if the indoor air quality could meet the WHO daily average PM2.5 standard of 25 µg/m^3 and CO_2 concentration of less than 1000 ppm.

Our result shows there can be an effective reduction of PM2.5 from outdoor to indoor, and a satisfactory CO_2 level in the building. Outside the building, our measurements show complex vertical variations of PM2.5 with the height that are different from what is expected from simple boundary layer theory. This may be related to the complex urban morphology and the vigorous vertical mixing within the urban street canyon. Nevertheless, even with such complexity, our results also show that it is still possible to have a building operate properly to provide a healthy indoor environment for the occupants, despite the relatively polluted outdoor environment.

Keywords: *indoor environmental quality, dense urban environment, street canyon, particulate matter, CO_2 concentration*

1. INTRODUCTION

With the release of hourly PM2.5 data in China in 2013, the public's concern for poor air quality has grown substantially. The improvement of local air quality has become a top priority in cities around the country. The air pollution problem is the most serious in major cities, where rapid urbanization and vehicular traffic in deep street canyons have led to serious deterioration of air quality.

Apart from outdoor pollution, one also needs to worry about indoor air quality, as people spend most of their time indoors. Indoor air quality relates to the health and comfort of the occupants inside a building. The US Occupational Safety and Health Administration estimated that poor indoor air quality costs employers US$15 billion annually, including death, sick leaves and worker inefficiency (Black, 2014).

2. METHODOLOGY

2.1. Site description

This study focuses on an 18-storey commercial building with a combination of shopping mall and commercial offices, located in Tsim Sha Tsui, one of the earliest districts developed after the British took control of Hong Kong in the 19th century. Tsim Sha Tsui has since evolved into a major commercial, shopping and tourist district, with a lot of shopping malls, restaurants, residential and office buildings, and heavy traffic throughout the day. The 18-floor building examined in this study is of average height in Tsim Sha Tsui, with both higher and lower buildings in its vicinity. This building is one block away from the main transport route, and hence the roads surrounding it are neither too quiet nor too congested. It is therefore a good candidate to study in order to understand the typical indoor impact of outdoor air pollutants in the district. Moreover, the building adopts a floor-based central air-conditioning system, and each floor has an individual fresh air-intake and distribution system. This enables us to also examine the variation of outdoor air quality as a function of height in the vicinity of the building.

2.2. Parameters

CO_2 and PM2.5 are the pollutants selected in this study. In the absence of indoor combustion sources, CO_2 levels in an enclosed environment are related to the number of occupants and the effectiveness of the ventilation system. Although there appears no long-term health impact from CO_2 at levels typically found in the urban indoor environment, an elevated level of CO_2 may cause drowsiness, headache and lower productivity. In Hong Kong, the Indoor Air Quality Objectives for Office Buildings and Public Places classify indoor CO_2 level lower than 1000 ppm as 'Good', and those under 800 ppm as 'Excellent' (HKEPD, 2003).

PM2.5 refers to airborne particles with aerodynamic diameter less than 2.5 micrometers, including dust, soot, smoke and liquid droplets. Their small size allows them to penetrate deep into our bodies, including our lungs, heart and other major organs, causing serious health impacts. Hence, PM2.5 is one of the most significant pollutants to be monitored. The WHO Air Quality Guidelines recommends that the 24-hour average PM2.5 concentration should not exceed 25 µg/m3 (WHO, 2005). In urban areas, vehicular emission is the main source of PM2.5 outdoors, and fuel combustion (e.g. cooking) is the main source indoors. In office buildings without combustion sources, indoor emission of PM2.5 should be quite limited.

2.3. Measurement protocol

In this study, the TSI Model 7575 Multifunction IAQ Meter with IAQ Probe 982 (QTrak) was used to measure CO_2, and the TSI DustTrak Aerosol Monitor 8530 (DustTrak) was used to measure PM2.5. In our study, these two portable pieces of equipment were placed together in a backpack, and two backpacks (i.e. two QTrak and two Dustrak sensors) were used in the field measurements. One backpack was used to measure the air quality outdoors and the other was for indoors.

To ensure data reliability, all the portable instruments were first calibrated against stationary, research-grade air quality instruments at the university. The PM2.5 and CO_2 measurements from the DustTrak and Qtrak were compared with corresponding measurements by the Thermo Scientific Synchronized Hybrid Ambient Real-time Particulate 5030 Monitor and the Teledyne Gas Analyzer 360E System, respectively.

During each day of the field measurements, two researchers collected the two backpacks at the university laboratory early in the morning, started the recording, and then carried them side-by-side to the building site via public transport. At the end of each day’s work, the two backpacks were also placed side-by-side for an hour in the building, and then they were carried back together to the laboratory for data download and equipment charging overnight. This protocol dictates that there would be three extended periods of collected data measurements by the two backpacks in different microenvironments. The accuracy and precision of the air quality data (PM2.5 and CO_2) from the portable sensors can hence be obtained. This protocol allows easy detection of drift and/or failure that is quite common for such portable sensors. Agreement of the collocated measurements at the beginning and the end of a day’s work can also assure us of the quality of the measurements when the backpacks were placed separately to measure the air quality indoors and outdoors. Finally, the researchers were also asked to keep logs of their positions, and to take pictures and log remarks if they come across events that may affect local air quality.

2.4. Measurement design

Figure 1 shows the typical floor plan of the sampled building. There was a fan room with louvers to allow air intake into a central air-conditioning system on each floor. In this study, measurements taken near the louvers in the fan room were used to represent the outdoor air quality, and measurements taken at the lift lobby were used to represent the indoor air quality for that floor. Moreover, measurements taken at a 2/F terrace were used to indicate the near ground outdoor air quality.

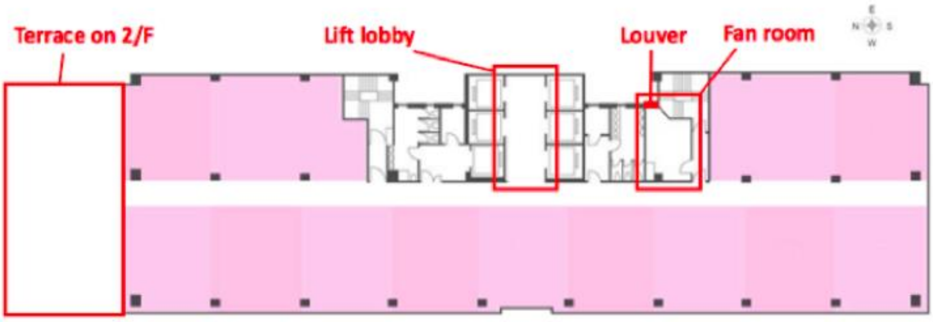

Figure 1: Floor plan of the sampled building

Two measurement programs were designed for the two objectives. For the indoor to outdoor ratio study, backpack 1 was used to measure indoor air quality at the lift lobby and backpack 2 was used to measure outdoor air quality in the fan room. The two backpacks started at the 4/F and moved up to 6/F, 8/F, 10/F, 12/F and 15/F in pairs every one hour. For the study of vertical variations in outdoor air quality, backpack 1 was placed at the 2/F terrace to measure the outdoor air quality at the reference floor throughout the measurement period, while backpack 2 was used to measure the outdoor air quality in the fan room from 4/F to 6/F, 8/F, 10/F, 12/F and 15/F for an hour each. These measurements were completed during the regular office hours from 9 am to 5 pm. Then, the two backpacks were placed together at 2/F for an hour of collocated measurements at the building site. Measurements were also carried out during the trips to and from the sampling site to allow rigorous data quality checks of the portable equipment throughout the measurement period.

3. ANALYSIS METHODOLOGY

3.1 Indoor to outdoor ratio

For both CO_2 and PM2.5, an hourly indoor to outdoor (IO) ratio and the five-day averaged IO ratio are calculated for each floor.

3.2 Vertical variations of outdoor air quality around the building

Vertical variations of outdoor CO_2 and PM2.5 concentrations as a function of height were determined by normalizing (dividing) the measured concentrations at different floors against those measured at the 2/F. Ratios greater or smaller than one indicate that the measured concentrations at the higher floors are larger or smaller, respectively, than the corresponding concentration at the 2/F. The Student's t-test with *p*-value 0.05 was used to check the statistical significance of data.

4. FINDINGS

4.1 Indoor to outdoor ratio for CO_2

Floor/ Date	18/01/16	19/01/16	20/01/16	21/01/16	22/01/16	Average
4/F	1.3	1.6	1.6	1.4	1.5	1.5
6/F	3.0	2.2	2.8	2.3	2.4	2.6
8/F	1.7	1.5	1.5	1.5	1.4	1.5
10/F	2.3	2.1	2.3	2.1	2.0	2.2
12/F	2.2	2.3	2.3	2.0	1.9	2.2
15/F	2.2	2.2	1.9	2.3	--	2.2*
18/F	2.1	1.9	2.1	1.8	--	2.0*

-- Equipment failure * 4-day averages

Table 1 Summary of the indoor to outdoor ratio for CO_2 in different days

Our results show that the CO_2 concentrations in indoor areas are higher than that of outdoor areas, and the averaged IO ratio for CO_2 ranging from 1.5 to 2.6. This is consistent with our understanding that indoor CO_2 concentrations should be higher as a result of the respiratory production of CO_2 by the building occupants.

Furthermore, we found that almost all the indoor CO_2concentrations were in the Excellent (< 800 ppm) or Good (< 1000 ppm) class (HKEPD, 2003), except for one case for the 6/F on 18th Jan, when the indoor CO_2 concentration was recorded as 1350 ppm. Our observation log noted heavier-than-normal human traffic during that morning, which may have contributed to the higher CO_2 concentration recorded.

Nevertheless, the CO_2 levels at all floors are considered safe and unlikely to cause adverse health impacts like headache, nausea or dizziness, as these symptoms are not expected for CO_2 concentrations less than 5000 ppm.

4.2 Indoor to outdoor ratio for PM2.5

Floor/ Date	18/01/16	19/01/16	20/01/16	21/01/16	22/01/16	Average
4/F	0.34	0.24	0.25	0.16	0.28	0.25
6/F	0.37	0.42	0.37	0.50	0.36	0.40
8/F	--	0.34	0.42	0.36	0.45	0.39*
10/F	--	0.24	0.25	0.25	0.21	0.24*
12/F	--	0.27	0.33	0.32	0.47	0.35*
15/F	0.41	0.41	0.51	0.36	0.48	0.43
18/F	0.21	0.17	0.38	0.19	0.29	0.27

-- Equipment failure * 4-day averages

Table 2: Summary of the indoor to outdoor ratio for $PM_{2.5}$ for different days

Our measurements show that all IO ratios of PM2.5 are significantly less than 1, showing substantial reduction of PM2.5 through the central air-conditioning and filtration system in the selected building. We further note that the hourly outdoor average PM2.5 levels were mostly above 25 µg/m^3, while all of the hourly indoor average PM2.5 levels were below 25 µg/m^3; the highest hourly indoor PM2.5 concentration of 17 µg/m^3 were measured on the 6/F on Jan 20th. 25 µg/m^3 is the WHO daily average Air Quality Guideline for PM2.5 (WHO, 2005). Our results showing that all the hourly average indoor PM2.5 concentrations were below this guideline value indicate that the central air-conditioning and filtration system in the sampled building has been effective in maintaining good air quality with respect to PM2.5 during our measurement period.

4.3 Vertical variations of outdoor CO_2

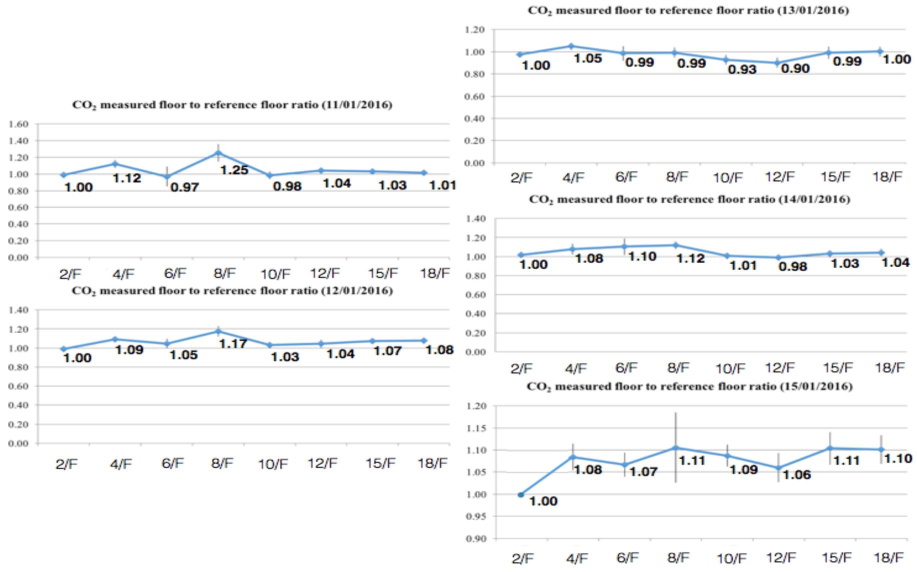

Figure 2:Normalized plots of CO_2 levels in measured floors to reference floor in different days (Error-bars denote ±1 standard deviation)

Figure 2 shows the average ratios of outdoor CO_2 concentrations at different floor heights with respect to the corresponding outdoor CO_2 concentration at the reference level on 2/F for different measurement days; error-bars at one standard deviation are also shown. It is found that the ratios were all very near one, suggesting that in the urban environment surrounding the selected building, the vertical variations of CO_2 from the surface to the top of this 18-storey building is very limited, if any.

4.4 Vertical variations of outdoor PM2.5

Figure 3 shows the average ratios of outdoor PM2.5 concentrations at different floor heights with respect to the corresponding outdoor PM2.5 concentration at the 2/F reference level for different measurement days; error-bars at one standard deviation are also shown. Different from CO_2, there appears more vertical variation with height in the outdoor PM2.5 concentrations, and the variations are quite complex.

In particular, there was an apparent concave shape in the vertical variations of PM2.5 concentration with height, with maximum PM2.5 level occurring between the 8/F to 12/F and lower PM2.5 concentrations above and below these levels for most days, except on the 13th Jan 2016 when the maximum PM2.5 level occurred around the 4/F. This is quite different from what one would have expected from simple boundary layer theory that predicts a gradual drop in PM2.5 with height.

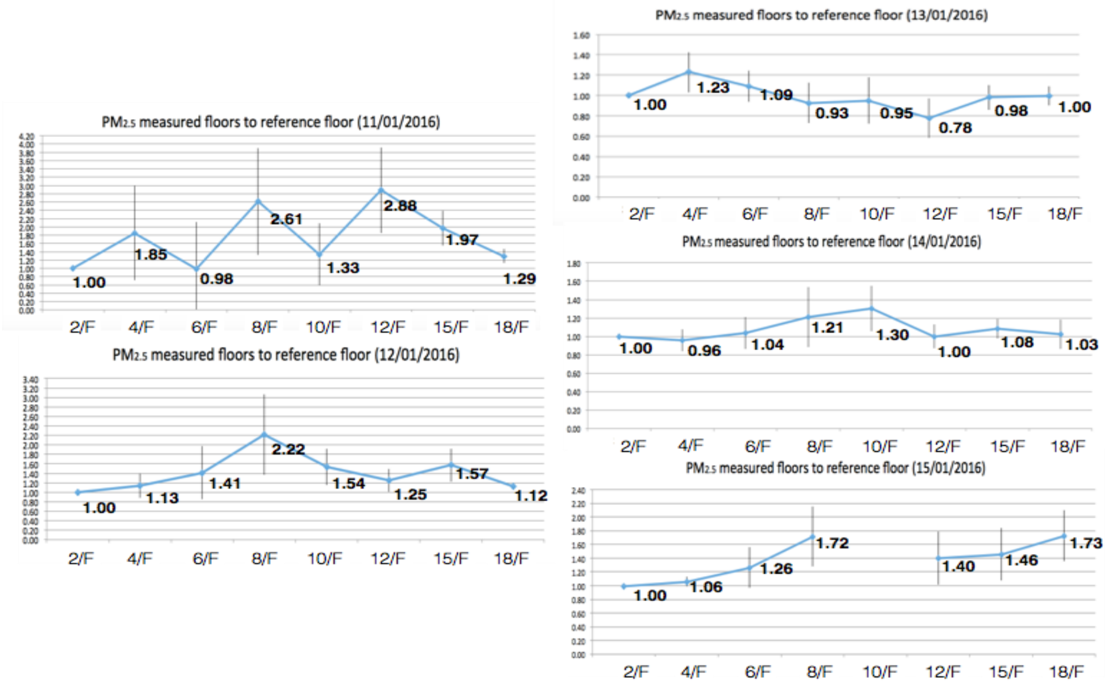

Figure 3: Normalized plots of $PM_{2.5}$ levels in measured floors to reference floor in different days
(Error-bars denote ±1 standard deviation)

To better understand the possible cause(s) of this unexpected vertical variation in PM2.5 concentration, we examined the built morphology around our sampled building. Figure 4 shows the building heights of our sampled building (shown in grey) and a few buildings around it along an east-west cross-section. We noticed that there is a shorter building to the immediate east of our sampled building and its roof is approximate at the same level as the 8/F of our sampled building. We also note that from Figure 1 that the fan rooms are on the eastern side of our sampled building.

These configurations make us suspect that the wind circulation may have become more complicated and have affected the average vertical distribution of PM2.5 on the eastern side of the sampled building. To assess that possibility, a computational fluid dynamics (CFD) run using the built morphology shown in Figure 4 was conducted. Average wind data recorded at the Hong Kong Observatory over the measurement period was used as background wind to drive the CFD model.

The prevailing wind direction during our sampling period was easterly, and the average wind speed simulated in the CFD model is shown in Figure 4, which shows a recirculation cell next to our sampled building and on the top of the roof of the shorter building to the east. Under the influence of such a recirculation cell, the wind speeds around the 8/F floor on top of the adjacent building would be reduced, and trapping enhancement of pollutants like PM2.5 could occur there.

Further, the recirculation cell can help re-suspend particulates deposited on the rooftop of the adjacent building, leading to a high concentration of PM2.5 just above its roof top level of 8/F in our sampled building. Lastly, we have not checked whether there was any exhaust on the rooftop of the shorter building, which (if exists) could also increase the local PM2.5 around that level.

In summary, our measurements show that, near our sampled building, the vertical variation of outdoor PM2.5 is complex, with maximum PM2.5 concentration between 8/F to 12/F, which is different from a decreasing distribution from the ground expected from simple boundary layer theory. The complex built morphology, the re-entrainment of pollutants from nearby rooftops, or exhaust emissions from nearby rooftops may have contributed to this difference.

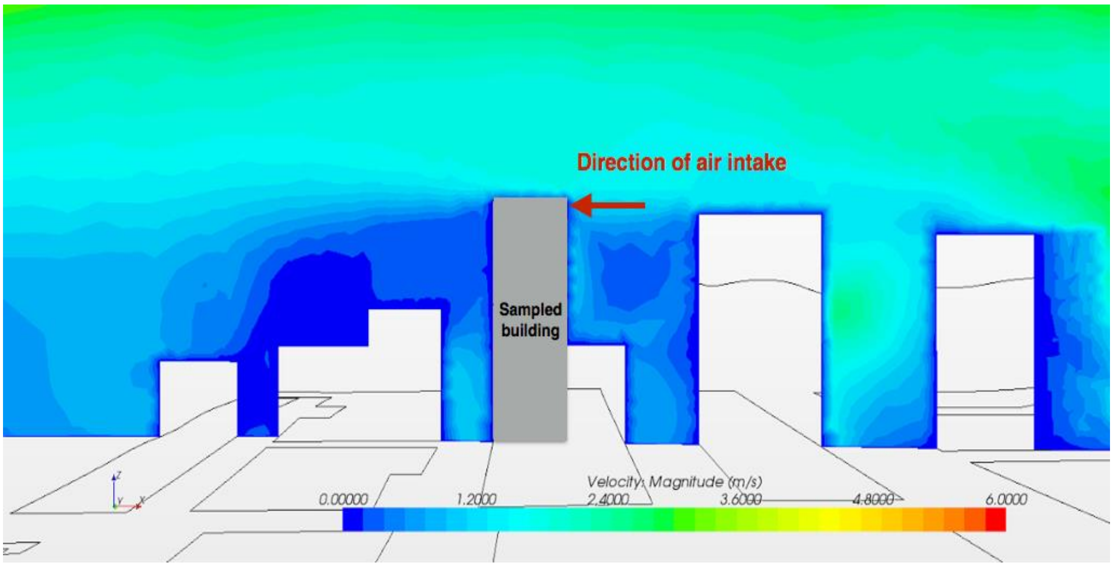

Figure 4 Simulation of wind motion at the sampled building during 11/1/2016-15/1/2016

5. CONCLUSION

This study examines the indoor to outdoor ratio of CO_2 and $PM_{2.5}$ in a typical commercial building in a densely populated urban metropolis. We found that the average indoor to outdoor ratio for CO_2 ranged from 1.5 to 2.6, and the average indoor to outdoor ratio for $PM_{2.5}$ ranged from 0.24 to 0.43 in our sampled building.

Moreover, the air-conditioning and filtration system of the building was able to keep most of the indoor CO_2 concentrations below 1000 ppm, and the hourly indoor $PM_{2.5}$ concentration below the WHO daily guideline for $PM_{2.5}$ at 25 μg/m^3, despite the outdoor $PM_{2.5}$ concentrations that exceeded this guideline level most of the time. These results show that it is possible to have a building managed properly to provide a healthy indoor environment for the occupants despite a relatively polluted outdoor environment.

Taking advantage of the fan rooms at different levels, we also examined the vertical variations of CO_2 and $PM_{2.5}$ in the outdoor environment. We found little vertical variation in CO_2 concentration from the ground to the top of our sampled building. On the other hand, we found that the vertical distribution of $PM_{2.5}$ around the sampled building to be more complicated (with highest $PM_{2.5}$ concentration between 8/F to 12/F) and different from what is predicted by simple boundary layer mixing theory. Subsequent CFD analysis suggests that this may be related to the microenvironmental flow created by the complex urban morphology. Hence, our results suggest that one should not assume pollutant concentrations must be decreasing with height in complex urban environments. More detailed analysis and simulations are needed.

6. ACKNOWLEDGEMENT

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