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Vertical dispersion of suspended particulates in urban area of Hong Kong

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Abstract

Field data are used to evaluate the vertical distribution of suspended particulates at different height levels in an urban area of Hong Kong. Four buildings in different street configurations and street environments were selected. According to the street configuration, they are classified into two groups: street canyon and open street. In street canyon, TSP and PM_{10} concentration varies with height exponentially. However, the rate of TSP, PM_{10} and $PM_{2.5}$ decrease with distance from the ground floor is in decreasing order of TSP, PM_{10} and $PM_{2.5}$. The particulate matter dispersion in street canyon is affected by the prevailing wind direction and the street configuration in particular the height-to-width ratio. In open streets, the vertical concentration depends on the vertical mixing, local dilution and other external factors such as sea breeze, as well as the proximity of trunk road and construction activity. Fine particulates contribute a major part of suspended particulates in Hong Kong and the impact can penetrate to the tenth floor and above. The $PM_{2.5}$ level is high in Hong Kong and above 80% of the $PM_{2.5}$ recorded in this field study exceeded the EPA NAAQS standards.

Keywords: Street canyon; Open street; Vehicle dispersion; Suspended particulate; Vehicular emission

1. Introduction

The suspended particulate problem has raised concern during the last decade. Particulate matter (PM) with aerodynamic diameter $\leqslant 10\,\mu m$ (PM_{10}), especially the finer particle fraction of PM_{10}, i.e. $PM_{2.5}$ (particulate matter with aerodynamic diameter $\leqslant 2.5\,\mu m$), was found to associate with urban health problems such as increase in daily mortality (Dockery and Pope, 1994) and asthma (Anderson et al., 1992).

According to the Hong Kong Environmental Protection Department (HKEPD), suspended particulates are one of the major air pollutants in Hong Kong (Hong Kong Environmental Protection Department, 1998). Total suspended particulates (TSP) and respirable suspended particulates (PM_{10}) have exceeded the Air Quality Objective of Hong Kong (AQO) for most of the past five years. In addition to TSP and PM_{10}, a $PM_{2.5}$ monitoring program was initiated in Hong Kong since 1995. The data of 1995–1997 showed that the annual mean levels of $PM_{2.5}$ for August 1995–July 1996 and August 1996–July 1997 were 34 and $36\,\mu g\,m^{-3}$, respectively (The Air Pollution Consultant, 1998). The levels are more than double the US EPA $PM_{2.5}$ annual standard of $15\,\mu g\,m^{-3}$.

These data clearly indicate the severity of Hong Kong's suspended particulate problem especially the fine particulate emission. The highest PM_{10} annual average was recorded at the roadside station in 1998, which was almost double of the annual EPA PM_{10} standard (Air Services Group, 1999). EPD has pointed out that the persistently high fine particulate emission is due to the widespread use of diesel fuel. There were 498 513 registered vehicles crowded into approximately 1869 km of roads in Hong Kong in 1999. Most of the trip mileage is traveled by vehicles, in particular taxis using diesel as

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their fuel for low cost. Hence, PM_{10} and $PM_{2.5}$ have become the major source of street-level air pollution.

Studies had been conducted on the dispersion of vehicular emission in street canyons in the past two decades. Variation in concentration at a given height depends on several factors, which include vehicle-generated turbulence, variation in traffic flow, meteorological parameter and geometry of the street such as the street orientation and aspect ratio. Streets with uniform building heights and configurations were commonly selected as observation sites in early studies. In recent years, the effect of street configuration and building shape on air dispersion and initial dispersion in the vehicular wake in the canyon have gained much attention. Qin and Kot (1993) measured three different typical street canyons in Guangzhou City. This study compared the air dispersion in different types of road in urban canyons and its result indicates that the configuration of a street is an important factor that influences air dispersion. Street measurements are influenced by local conditions and care must be taken in the interpretation of the result, in the estimation of urban air pollution levels, and in the comparison of air quality in different cities (Ruwim et al., 1996). In Hong Kong, due to the lack of space, buildings are usually in the form of high-rise towers and they are in close proximity. The residential, commercial and industrial areas are close and sometimes mixed together. Therefore, the road configuration and street environment are different from district to district. In this study, the vertical profiles of suspended particulates were measured in selected buildings within different street configurations in an urban area of Hong Kong. In addition to TSP and PM_{10}, we also measured the vertical dispersion of fine particles $PM_{2.5}$ which is less studied. The vertical coefficient of variation of PM will be helpful for the estimation of the representativeness of the HKEPD monitoring stations' measurement which is claimed to represent the exposure of the entire population living within the district.

2. Field study

The vertical distribution of TSP, PM_{10} and $PM_{2.5}$ in different street environments was measured in the field study. Minivol Portable Air Samplers (AIRMETRICS) were used for the suspended particulate sampling. Due to the limitation of equipment (only two $PM_{2.5}$ inlets for minivol samplers), the vertical distribution study was mainly focused on TSP and PM_{10} in this study. However, the $PM_{2.5}$ has attracted attention recently due to its potentially hampering health effect and it is anticipated to be subjected to control in the near future in Hong Kong, similar to the USA. Moreover, there are only limited studies on the vertical dispersion of $PM_{2.5}$ and their correlation with other PM. Thus $PM_{2.5}$ had also been measured in this study, although only two $PM_{2.5}$ measurement could be conducted at the same time.

Minivol portable air samplers (MiniVol) with a flow rate of $5\,l\,min^{-1}$ were used in this study. They were chosen in this survey study because they are portable, battery-operated and easy to mount on roadside light poles or outside a building. The flow rates were checked before and at the end of the study to ensure a constant flow rate through the size separator. Included in the daily quality-control reviews were checking for battery power, flow rate, volume of air sampled, elapsed time, leaks, and unusual filter conditions including damage, odor, discoloration, or loose particles on the filter. Any abnormal conditions were corrected and noted on the field forms. An open top balance (Mettler AE163) with accuracy of 0.01 mg was used to weigh the filter paper which was conditioned in an electronic desiccator before and after sample collection for 24 h. The balance was placed on an anti-vibration table on top of a concrete bench. The filter was stored flat in a petri dish and covered after conditioning or weighing.

The experiment was conducted from early November 1998 to mid-January 1999. These months were chosen because they are the months with the highest suspended particulate concentration due to dry weather. The prevailing wind direction was NE and the average relative humidity was about 70% during this period. The sampling duration was 24 h on three weekdays for each sampling site. The four mentioned streets represent different configurations with respect to different dispersion conditions. The location of sampling sites is shown in Fig. 1 and the main features are listed in Table 1. They are within the urban area and there is heavy road traffic next to them or nearby. According to their street configuration they are divided into two groups: street canyon and open street. Two street canyons with different height-to-width ratios and two types of open streets were selected. For the open street, the street is very board, with buildings only on one side of the street or far from each other (more than 10 m).

3. Site description

3.1. Street canyon

One of the important factors that influence the horizontal and vertical air dispersions in the street canyon is its configuration. The concentration distribution pattern varies with the canyon type and scale. To increase our understanding of the vertical dispersion of suspended particulates, two street canyons with different street configuration and street environment were studied. One is located in the central commercial area, in Causeway Bay (CWB) of Hong Kong Island while the other is located in an old residential district, Sham Shui Po (SSP) of

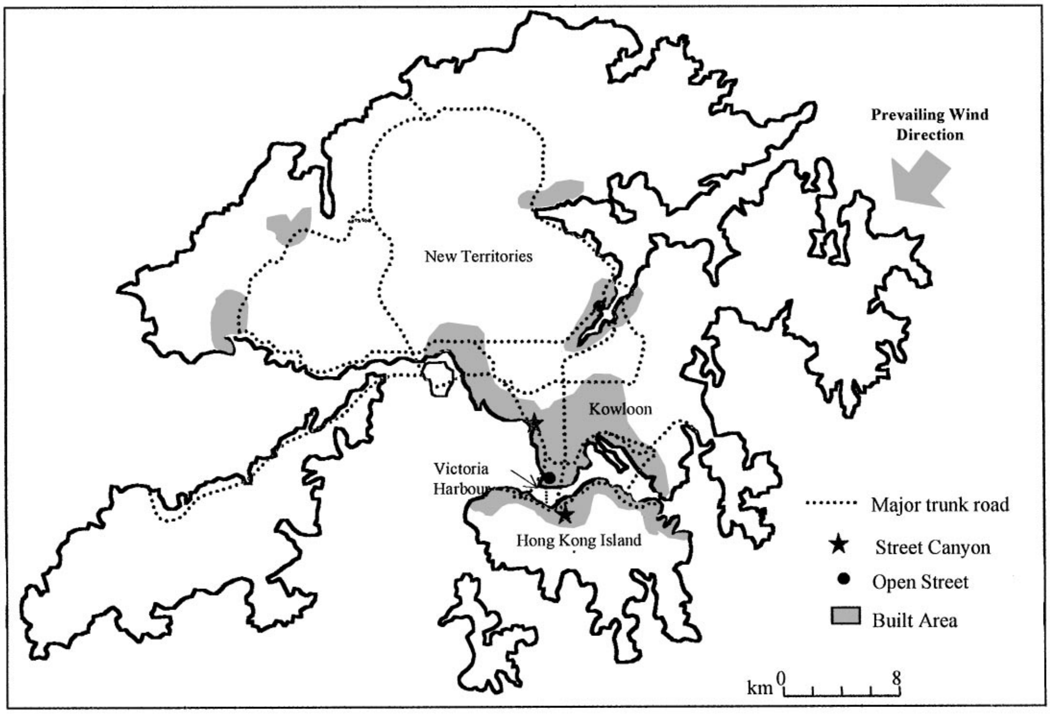

Fig. 1. Location of sampling sites.

Kowloon. There are variations in the configuration of the street, the ambient airflow and the road traffic.

In Lockhart Road, CWB, the buildings on both sides of the street are close together. Samples were collected in a 13-storey building. The buildings on both sides are relatively uniform in height (approximately 30 m). The traffic volume is quite high and the average annual daily traffic (AADT) volume is more than 17,000 vehicles per day. The height-to-width (H/W) ratio of the narrow street canyon is about 1.7 (Fig. 2a). It is a north-east–southwest oriented street. There are four divided lanes. Two lanes near the south side allow vehicles to run from east to west and the other two lanes allow vehicles to run from west to east. According to Hong Kong Observatory, the prevailing wind direction is 060–080°, which is parallel to the direction of the street. It does not create recirculation inside the street canyon, but the vehicle movement induces turbulence, which affects the mixing, dispersion and diffusion of the suspended particulates.

In Castle Peak Road, SSP, buildings on the south side of the street are lower than those buildings on the north side. Samples were collected in a six-storey (about 20 m) building. The H/W of the canyon is about 1.3 (Fig. 2b). It is a major northwest–southeast throughway across the city. The AADT of the road is relatively high which is more than 32,400 vehicles day^{-1}. It is a one way street with three traffic lanes. So the vehicular emissions at both sides of the street are quite similar. The direction of the prevailing wind is perpendicular to the direction of the street.

3.2. Open street

Not all the roads in the urban area are street canyon and thus two roadside buildings in relatively open streets were selected for the vertical distribution study. One is in a new town, Shatin (ST) and the other is in urban Kowloon facing the harbor.

For the measurement sites in Man Lai Road ST, the buildings on both sides of the northeast–southwest-orientated wide street are only 5–7 floor high and buildings are not close together (Fig. 3a). Many school buses park at roadsides and usually occupy a one-traffic lane. The traffic flow is very low but there are some heavy-traffic roads such as Shing Mun Tunnel Road, Tai Po Road and Kowloon Canton Railway nearby. Also, there were construction sites nearby during the sampling period which may have affected the SP concentration level. The prevailing wind direction is about 070° that is parallel to the direction of the street.

The site at Hong Kong Polytechnic University (HKPU), Kowloon is next to Hong Chong Road, which is connected to the Cross Harbor Tunnel from Kowloon

Table 1
Location and features of sampling sites

Type of street	Location	Land-use type	Usage of building	Road gradient	H/W ratio	Site environment
Open Street	Man Lai road, Shatin (ST)	New town	Educational	Flat	—	• Sampling point: 7, 10, 18 m • Low traffic flow but with heavy traffic road nearby • 5–7 floor high building on both sides
	Hong Chong road, Hung Hom (HKPU)	Urban Harbour front	Educational	Flat road + flyover	—	• Sampling point: 3, 8, 25 m • AADT[a] = 170,440 • Next to the Cross Harbor Tunnel • Next to Victoria Harbor
Street Canyon	Lockhart Road, Causeway Bay (CWB)	Old city, mixed commercial and residential area	Residential	Flat	1.7	• Sampling point: 3, 21, 26 m • AADT = 17,270 • Uniform street configuration (building height is around 30 m) • Northeast–southwest orientated street
	Castle Peak road, Sham Shui Po (SSP)	Old city, residential area	Educational	Flat	1.3	• Sampling point: 3, 14 m • AADT = 32,400 • Non-uniform street configuration (building height is 15–30 m) • Southeast–northwest orientated street

[a]AADT = average annual daily traffic.

to Hong Kong Island. Since the site faces the Victoria Harbor, strong winds blow from the sea and provide good air dispersion. The traffic volume of the road is extremely high which is more than 170,000 vehicles in annual daily average. Besides, there are other heavy-traffic roads such as Chatham Road South nearby. The buildings on the two sides of the northwest–southeast-oriented streets are not continuous and the buildings on the south side of the street are much taller than those on the north side. The road is elevated in this part and is about 3–4 m above the ground level. The prevailing wind direction, the traffic motion and the topography of the site created complex dispersion patterns of air within the area (Fig. 3b).

4. Result and discussion

Performance tests on MiniVol samplers had been conducted before the field study. One TSP high-volume sampler and one TSP mini-volume sampler; one PM_{10} high-volume sampler and one PM_{10} mini-volume sampler; one Partisol sampler with $PM_{2.5}$ inlet and one $PM_{2.5}$ mini-volume sampler were operated at the Hong Kong Polytechnic University (HKPU) roadside site at the same period in order to determine the correlation among these samplers. The samplers were placed on the pavement at about 0.5 m from the roadside where 24-h samples were collected. The TSP and PM_{10} concentrations plot for MiniVol sampler versus high-volume

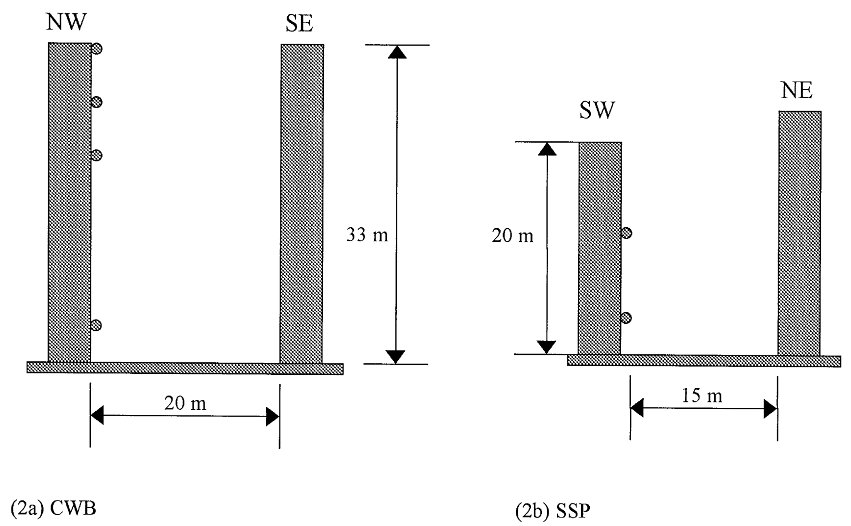

Fig. 2. Configuration of streets and location of monitoring points in street canyon (2a) CWB; (2b) SSP.

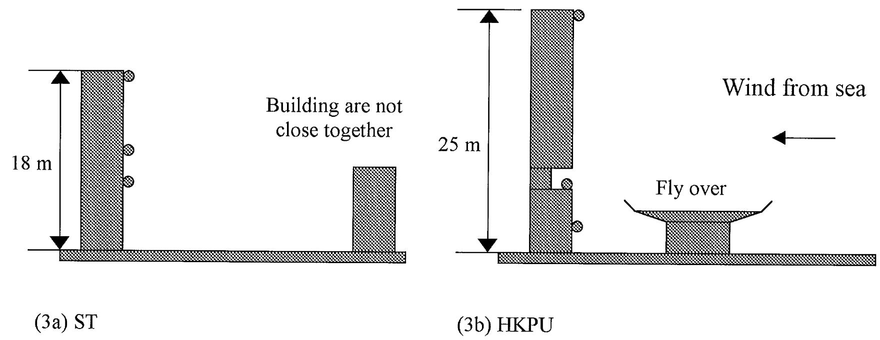

Fig. 3. Configuration of streets and location of monitoring points in open street (3a) ST; (3b) HKPU.

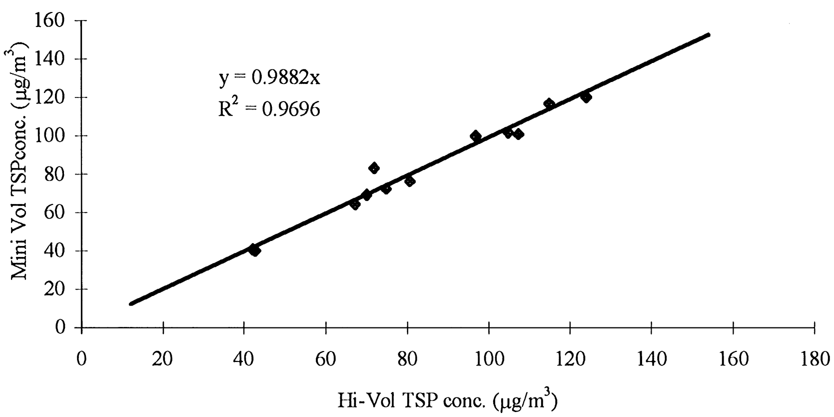

Fig. 4. Calibration of Hi-Vol TSP and MiniVol TSP.

sampler; the $PM_{2.5}$ concentrations plot for MiniVol sampler versus Partisol sampler, indicate that they have a good correlation (Figs. 4–6). The data collected by mini-volume sampler were converted to high-volume sampler or Partisol sampler scale to facilitate their comparison with other studies. The regression between the samplers is as follows:

MiniVol (TSP) = 0.9882 Hi-Vol (TSP); with $R^2 = 0.97$;
MiniVol (PM_{10}) = 1.1732 Hi-Vol (PM_{10}); with $R^2 = 0.98$;
MiniVol ($PM_{2.5}$) = 1.2078 Partisol ($PM_{2.5}$); with $R^2 = 0.99$.

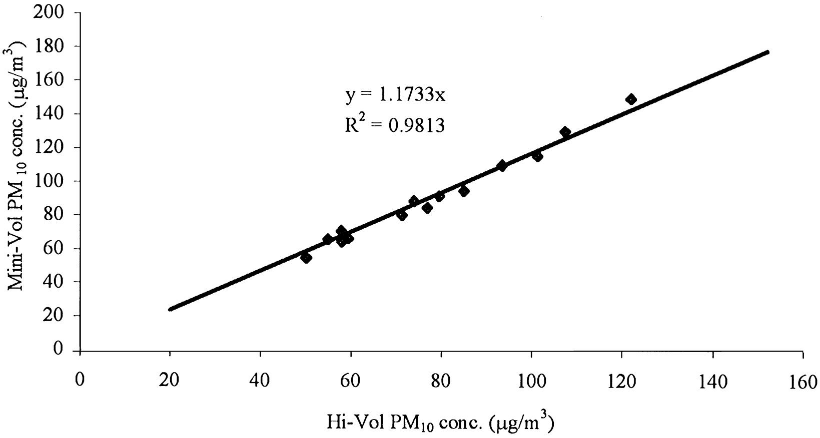

Fig. 5. Calibration of Hi-Vol PM_{10} and MiniVol PM_{10}.

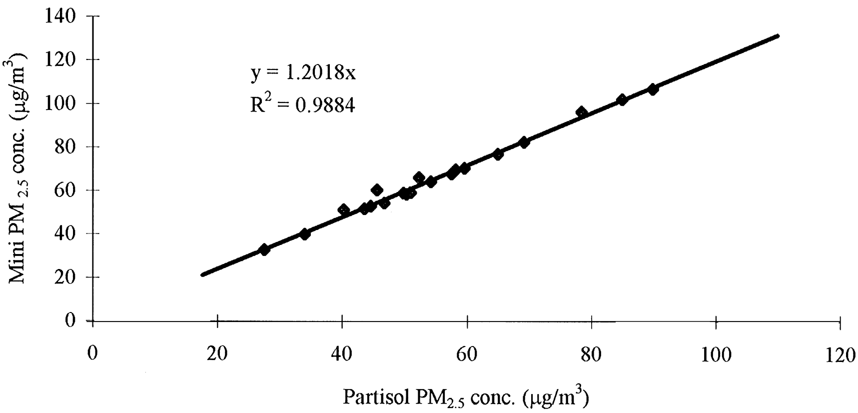

Fig. 6. Calibration of Partisol $PM_{2.5}$ and MiniVol $PM_{2.5}$.

5. Vertical distribution of suspended particulates in different street configurations

5.1. Street canyon

In Hong Kong, the urban PM concentration levels generally decreased with height and the particulate pollution is vehicular emission related. This feature was commonly observed in profiles measured in street canyon environments. The mean concentrations of particulates at each sampling point and the percentage of suspended particulate decrease from the ground floor in the two street canyons are presented in Table 2. We observe that the rate of decrease with distance from the ground floor is different for different classes of suspended particulates. For the CWB study, the sampling points were at 2.5, 21 and 26 m from the ground level. The percentage values of the average TSP, PM_{10} and $PM_{2.5}$ decrease from the ground floor to 26 m from the ground level are 35.30, 21.26 and 18.12% respectively. In SSP, the sampling points were at 2.5 and 14 m from the ground floor. The percentage values of the average TSP, PM_{10} and $PM_{2.5}$ decrease from ground floor to 14 m from the ground are 43.38, 37.18 and 34.55%, respectively.

The buildings on both sides of the street confined the air pollutants emitted by vehicles in the street canyon. The vertical concentration gradient of the same type of suspended particulate matter is different between the two street canyons. The magnitude of vertical concentration decrease recorded in CWB is smaller than that recorded in SSP for the same type of particulate and the indication is that the vertical dispersion of the PM in SSP is faster than that in CWB. The difference may be due to the combined effect of the street configuration and the prevailing wind direction. The result is similar to the observation of gaseous pollutants in a street canyon study in Copenhagen (Ruwim et al., 1996). The dependence on wind direction is due to the creation of wind vortex in the street. Also, it has been pointed out that as the aspect ratio increases (as the cavity becomes deeper), the outer

Table 2
Measurement results and percentage of particulate decrease from the ground floor (street canyon)

Particulate class	Sham Shui Po			Causeway Bay				
	G/F ($\mu g\,m^{-3}$)	14 m ($\mu g\,m^{-3}$)	% Decrease from G/F (%)	G/F ($\mu g\,m^{-3}$)	21 m ($\mu g\,m^{-3}$)	% Decrease from G/F (%)	26 m ($\mu g\,m^{-3}$)	% Decrease from G/F (%)
TSP	256.7	145.34	43.38	162.67	107.94	33.60	105.25	35.30
PM_{10}	166.8	104.78	37.18	121.74	100.49	17.34	95.73	21.26
$PM_{2.5}$	129.22	84.57	34.55	109.99	—[a]	—	86.67	18.12

[a]Only two $PM_{2.5}$ measurements can be conduct at the same time due to the equipment limitation G/F: 2.5 m from the ground.

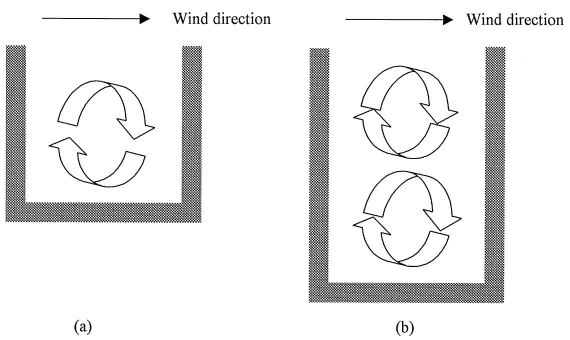

Fig. 7. Flow patterns in the street canyon with different H/W ratios: (a) single vortex, $H/W \sim 1.3$; (b) double vortex, $H/W > 1.7$.

stream of fresh air above the cavity becomes less efficient in moving pollutants (Lee and Park, 1994) (Fig. 7).

In CWB, the prevailing wind direction is parallel to the street and the H/W ratio of street canyon is quite high. Without the formation of vortex, vertical exchange was the primary means of transport of air pollutants in the street canyon. The vertical gradient mainly depends on the vertical distance from the source and decrease in concentration with height is characteristic of pollutants emitted at street level. Due to the limitation of available equipment, only a four-point PM_{10} vertical distribution measurements can be conducted simultaneously in CWB in this study. The sampling points were at 2.5, 21, 25 and 31 m from the ground level. The distribution of PM_{10} is shown in Fig. 8. TSP and PM_{10} were measured in three sampling points within the same period, their distributions were similar and varied with height exponentially (Fig. 9). The relationship between concentration and height can be expressed as

$$C = \mathrm{Co}\exp(-kx),$$

where Co is the concentration at ground floor, x the distance from the emission source, and k the coefficient, which is similar to a previous study (Capannelli et al., 1977). The effect of the street canyon in CWB is larger than SSP.

For the SSP street, the vertical dispersion is affected by the rooftop wind direction. It has been pointed out that a single vortex can be maintained within the canyon when the wind direction is perpendicular to the direction of the street and the H/W ratio of the cross-section of the street is approximately equal to 1–1.3. For the street canyon in SSP (H/W ratio = 1.3), the wind direction is usually perpendicular to the street during the sampling days. Thus, a single vortex may be formed within the street canyon and so the SP is easier to disperse out of the street canyon due to the influence of rooftop wind. (Fig. 7)

One important factor that influences air dispersion in the street canyon is its configuration. The concentration pattern varies with the canyon scale. Luria et al. (1990) and Qin and Kot (1993) reached the same conclusions, in their field study in Jerusalem and Guangzhou. The traffic volume in SSP street canyon is almost double that of the street canyon in CWB. However, the fine particle concentration measured in the ground floor of SSP was only one-fifth higher than its value in CWB. This illustrates the effect of single-vortex phenomenon on vertical fine particulate dispersion.

Moreover, the vertical gradients of different types of particulate are different in the same street canyon. In fact, the large-sized suspended particles are greatly affected by gravity and thus have a shorter residence time in air, leaving only the sub-micron-sized particles to diffuse upward to higher levels. It had been reported that of the total mass of particles $< 10\,\mu m$, at least 80% of the mass is accounted for by the mass of particles with a diameter smaller than $2.5\,\mu m$ (Monn et al., 1995). PM_{10} and $PM_{2.5}$ are dominantly sub-micron in size, and so behave more like a gas. They diffuse more easily upward and exhibit a smaller vertical dispersion rate than TSP.

5.2. Open street

Table 3 shows the concentration levels and percentage of suspended particulates decrease from the ground floor

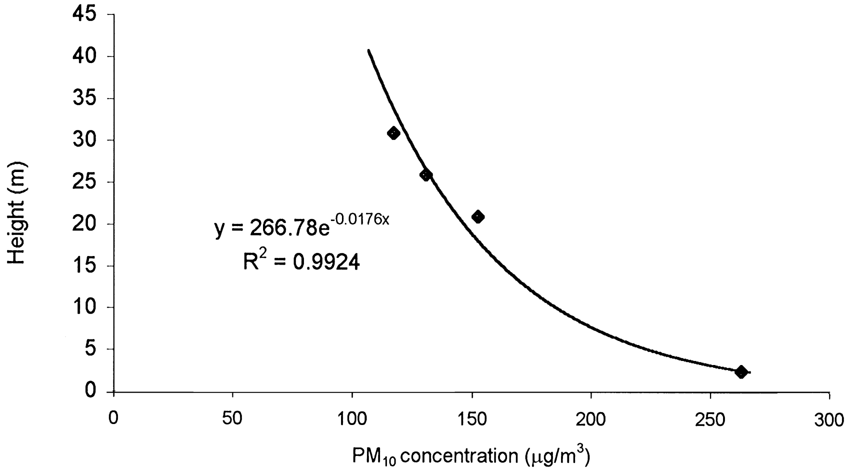

Fig. 8. The vertical distribution of PM_{10} in causeway bay (Lockhat Road).

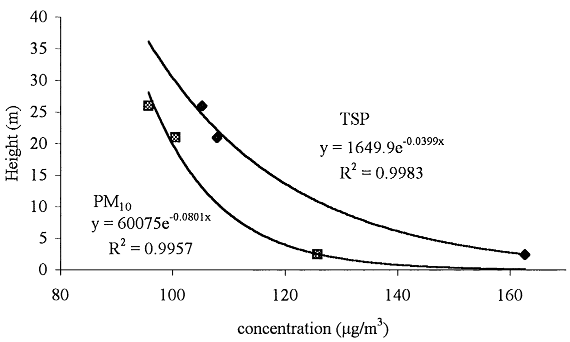

Fig. 9. The vertical distribution of TSP and PM_{10} in causeway bay (Lockhat Road).

at each sampling point. From the result shown in Table 3, the PM vertical dispersions in the two open streets are very different. For the site in ST, the TSP concentration recorded displays linear decrease with height (Fig. 10). As mentioned before, TSP is greatly affected by gravity and thus the vertical gradient mainly depends on the vertical distance from the source (primary dispersion). Due to the construction nearby, the TSP and PM_{10} may be transported to this site by wind. The dispersion pattern of PM_{10} hence was close to that of TSP, but at a lesser degree. For $PM_{2.5}$, no correlation was found between the concentration and the height. It is possible that some of them are transported from the major urban trunk roads nearby. Besides, without canyon-like buildings on both sides to confine the air pollutants emitted by vehicles on the road, low accumulation occurs, resulting in fairly homogenous PM mixing.

For the site in HKPU, the dispersion pattern is not the same since the street configuration and the environment are very different. The concentrations of each type of particulate matter recorded at the podium (8 m) of the HKPU are higher than expected (Fig. 11). The site is close to the harbor and the effect of the sea breeze made the situation more complicated. The effect of the sea breeze and the sea salt aerosol increase the TSP concentration at middle level, as can be seen for the concentration at 8 m from the ground. If only the TSP concentration level at ground floor and rooftop (i.e. 3 and 25 m) are compared, we find that the concentration at the ground level is just slightly higher than that at the rooftop level.

In general, due to the lack of obstruction, such as tall buildings on both sides, the dispersion of pollutant in the open street is greatly influenced by the prevailing wind speed, direction as well as other factors such as the sea breeze and the proximity of major trunk road and construction site. Thus, there is a large fluctuation in the vertical profiles in open streets

6. Air quality objectives and abatement

It was found that the mean TSP and PM_{10} measured at all sites are well within the 24-h TSP and RSP (PM_{10}) in HKAQO of 260 and 80 $\mu g\,m^{-3}$, respectively. However, when considering the TSP and RSP for individual sampling points, one 24-h average TSP and one 24-h average PM_{10} concentration exceeded the HKAQO TSP and RSP 24-h standard, and this occurred at the ground level in Sham Shui Po. For $PM_{2.5}$, the problem is more serious, more than 80% of the $PM_{2.5}$ measured exceeded the 24-h NAAQS of 65 $\mu g\,m^{-3}$. The $PM_{2.5}$ concentration is very high even at 20 m from the ground level.

Table 3
Measurement results and percentage of particulate decrease from the ground level (open street)

Particulate class	Shatin					HKPU				
	8 m ($\mu g\,m^{-3}$)	10 m ($\mu g\,m^{-3}$)	% Decrease from 8 m	18 m ($\mu g\,m^{-3}$)	% Decrease from 8 m (%)	*G/F* ($\mu g\,m^{-3}$)	8 m ($\mu g\,m^{-3}$)	% Decrease from *G/F* (%)	25 m ($\mu g\,m^{-3}$)	% Decrease from *G/F* (%)
TSP	132.61	126.03	4.96%	100.40	24.29	139.49	146.55	– 5.06[a]	134.36	3.67
PM_{10}	101.29	100.12	1.10%	80.54	20.49	77.17	63.68	17.48	69.02	10.56
$PM_{2.5}$	71.16	—	—	74.08	– 4.11	81.94	68.45	16.50	70.83	13.15

[a]Negative value means SP the concentration is higher than that in ground level.

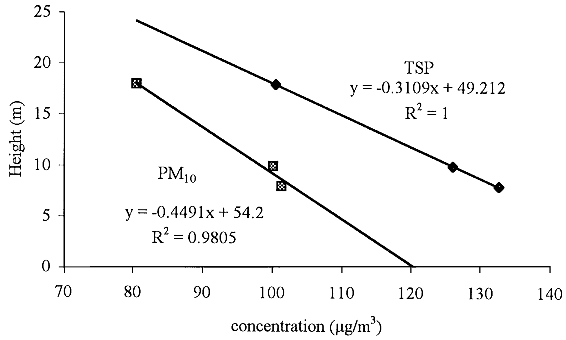

Fig. 10. Distribution of TSP and PM_{10} at different height levels in Shatin.

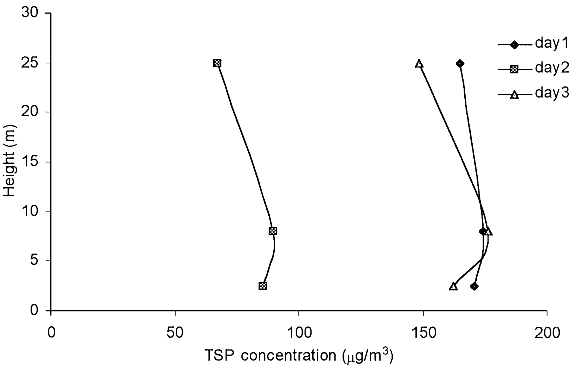

Fig. 11. Distribution of TSP at different height levels in HKPU.

7. Conclusion

Hong Kong has been suffering from serious suspended particulates pollution. This study investigates the vertical profiles of the suspended particulates in various urban areas of Hong Kong. Suspended particulate samples were collected at four sites including two open streets and two street canyons. In the street canyons, the distribution of TSP and PM_{10} concentration varies with height exponentially. However, the rate of TSP, PM_{10} and $PM_{2.5}$ decrease with distance from the ground floor is in decreasing order of TSP, PM_{10} and $PM_{2.5}$. The larger sized particles are greatly affected by gravity and the fine particles are more affected by diffusion. The PM dispersion in street canyon is also affected by the prevailing wind direction and its configuration. The suspended particulate is easier to disperse out of the street canyon in a street canyon which has a smaller height-to-width ratio.

For open streets, there is no fixed pattern. The vertical concentration depends on the vertical mixing, local dilution and other external factors such as sea breeze, as well as the proximity of trunk road and construction activity.

Fine particulates contribute a major part of suspended particulate in Hong Kong. The $PM_{2.5}$ pollution is serious, over 80% of the $PM_{2.5}$ recorded in this field study exceeded the EPA NAAQS 24-h standard of 65 $\mu g\,m^{-3}$. The level is very high in Hong Kong and the impact can penetrate to the 10th floor and above. $PM_{2.5}$ is found to pose a threat to the residents of Hong Kong. Considering the high emission of fine particulates due to the widespread use of diesel-driven automobiles, in particular the taxis on the street, more efforts should be made in the study and regulation of $PM_{2.5}$.

References

Air Services Group, 1999. Air Quality in Hong Kong 1998. Hong Kong Environmental Protection Department.

Anderson, K.R., Avol, E.L., Edwards, S.A., Shamoo, D.A., Peng, R.C., Linn, W.S., Hackney, J.D., 1992. Controlled exposures of volunteers to respirable carbon and sulfuric acid aerosols. Journal of Air and Waste Management Association 42, 770–776.

The Air Pollution Consultant, 1998. Asian cities have serious fine particulate problems 8 (5), 1.12–1.14.

Capannelli, G., et al., 1977. Nitrogen oxides: analysis of urban pollution in the city of Genoa. Atmospheric Environment 11, 719–727.

Dockery, D.W., Pope, C.A., 1994. Acute respiratory effects of particulate air pollution. Annual Reviews of Public Health 15, 107–132.

Hong Kong Environmental Protection Department, 1998. Environment Hong Kong, 1998.

Lee, I.Y., Park, H.M., 1994. Parameterization of the pollutant transport and dispersion in urban street canyons. Atmospheric Environment 28, 2343–2349.

Luria, M., Weisinger, R., Peleg, M., 1990. CO and NO_x levels at the center of city roads in Jerusalem. Atmospheric Environment 24B, 93–99.

Monn, Ch., Brandi, O., Schappi, G., Ackermann, U., Leuenberger, Ph., SAPALDIA Team, 1995. Particulate matter 10 and total suspended particulates in urban, rural and Alpine Air in Switzerland. Atmospheric Environment 29, 2656–2573.

Qin, Y., Kot, S. C., 1993. Dispersion of vehicular emission in street canyons, Guangzhou City, South China (P.R.C.). Atmospheric Environment 27B, 283–291.

Ruwim, B., Finn, P., Ole, H., Elisabetta, V., 1996. Using measurements of air pollution in street for evaluation of urban air quality – meteorological analysis and model calculations. Science of the Total Environment 189–190, 259–265.