Spatial Variation and Relationship of Indoor/Outdoor $PM_{2.5}$ at Residential Homes in Guangzhou City, China

H. Huang[1*], J.J. Cao[2], S.C. Lee[3], C.W. Zou[4], X.G. Chen[5], S.J. Fan[5]

[1] School of Chemistry and Environment, South China Normal University, Guangzhou, China.
[2] Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China.
[3] Hong Kong Polytechnic University, Hung Hum, Kowloon, Hong Kong.
[4] School of Environmental Science and Engineering, NanChang University, Nanchang, China.
[5] School of Environmental Science and Engineering, SunYatSen University, Guangzhou, China.

Abstract

Fine particles ($PM_{2.5}$) were measured using Airmetrics mini-volume portable samplers during 2nd July and 13th August, 2004 inside and outside nine homes located in generic urban area, roadside area and industrial plant area in Guangzhou city, China. The indoor and outdoor $PM_{2.5}$ average concentrations (67.7 and 74.5 μg/m^3) were about two times higher than the new guideline of WHO, and higher than the levels in other studies (New York, London, Amsterdam, Brisbane, Osaka and Hong Kong, etc). Both indoor and outdoor average $PM_{2.5}$ concentrations in roadside area (73.5 and 79.4 μg/m^3) and in industrial plant area (73.4 and 92.9 μg/m^3) were higher than those in generic urban area (56.2 and 51.2 μg/m^3). The average I/O ratio in generic urban area, roadside area and industrial plant area were 1.10, 0.93 and 0.79, respectively. The indoor/outdoor correlations of $PM_{2.5}$ in generic urban area, roadside area and industrial area were from strong (R^2 = 0.70, p < 0.001, n = 11) to moderate (R^2 = 0.54, p = 0.007, n = 12) and to poor (R^2 = 0.17, p = 0.088, n = 12). Strong indoor/outdoor $PM_{2.5}$ correlation with I/O > 1 in generic urban area indicated excellent ventilation condition at there, good indoor/outdoor $PM_{2.5}$ correlation with I/O < 1 in roadside area suggested that the indoor $PM_{2.5}$ were mainly from the outdoor air, and poor indoor/outdoor $PM_{2.5}$ correlation in industrial plant area was ascribed to seldom ventilation in one home (IS2).

Keywords: $PM_{2.5}$; Residential Homes; Indoor air quality; I/O ratio.

[*] Corresponding author. Tel.: +86-20-39310213, Fax: +86-20-39310213

E-*mail address*: huanghong@scnu.edu.cn

INTRODUCTION

Particulate matter (PM), especially respirable $PM_{2.5}$ (particles with aerodynamic diameter less than 2.5 μm), is the most ubiquitous and most complicated air pollutant in urban area (Ho *et al.*, 2003). There is now a large body of epidemiological evidences associating exposure to ambient particles with short and long-term effects on health (Anderson, 2000; Kim *et al.*, 2000; Kulkarni, 2006). With improvement of measurement techniques, the effects became clearer when smaller particle sizes were considered (Lippmann and Ito, 2000; Wichmann and Peters, 2000). Besides health effects, atmospheric fine aerosol particles play an important role in controlling a number of atmospheric processes such as the deposition of different compounds, the optical properties, etc (Molnár *et al.*, 1999). From these points of view, it is still crucial to know the concentration and distribution of the fine particles in order to develop effective strategy for the control of fine aerosol pollution and the remove of associated problems. PM is usually generated from many different outdoor sources, such as automobile exhaust, industrial production processes, secondary conversion from gaseous pollutants (Cao *et al.*, 2003) and also indoor sources, such as smoking (Cao *et al.*, 2005), cooking (Naeher *et al.*, 2000) and other activities (Chan, 2002). Generally, people spend most of their time indoor, but the majority of particulate concentration data is based on measurements conducted outdoors. Outdoor particulate concentrations may not be reliable indictors of indoor and personal particulate exposures (Geller *et al.*, 2002). During the past few decades, more and more researchers have been aware of that; accordingly researchers in different parts of the world have begun to conducted studies on indoor particle levels.

In Asia, Funasaka *et al.* (2000) from his study in Osaka, Japan concluded that the mean indoor $PM_{2.5}$ concentrations in roadside site A mainly effected by commuter vehicles, in roadside site B mainly effected by high volume of diesel traffic, and in background site C were 20, 22 and 18 $\mu g/m^3$, respectively, and the corresponding outdoor values were 37, 23 and 18 $\mu g/m^3$, respectively. Tsai *et al.* (2000) found that $PM_{2.5}$ levels in living room and in ambient were 137 and 140 $\mu g/m^3$ for shop houses in Bangkok, Thailand on moderately busy streets, 184 and 62 $\mu g/m^3$ for shop houses near busy streets, and 64 and 153 $\mu g/m^3$ for near less bust streets, respectively. In a study conducted by Cao *et al.* (2005) found that the average indoor and outdoor concentrations of 24 h $PM_{2.5}$ were 56.7 and 43.8 $\mu g/m^3$, respectively, at residential homes in Hong Kong. It was found that the concentrations of air particulates of indoors sometimes were much higher than that of outdoors (Lee *et al.*, 2000; Ramachandran *et al.*, 2000; Adgate *et al.*, 2002; Ramachandran *et al.*, 2003; Cao *et al.*, 2006). Therefore, studies on indoor particles characteristics are as important as the outdoors'.

Some PM studies had been done in overseas cities, but seldom were performed in Mainland China and the database there is not comprehensive. In Guangzhou city, China, studies on fine particles are scarce, and no specific research on simultaneous indoor and outdoor $PM_{2.5}$

characteristics has been carried out. The main objective of this study is to provide quantitative information on the indoor and outdoor mass concentrations of $PM_{2.5}$ at 9 selected locations of three type areas (generic urban, roadside and industrial plant area) in Guangzhou city and to investigate spatial variation in different areas.

METHODS

Guangzhou city (22º36′-24º18′N, 112º33′-114º35′E) is one of most developed and industrialized city in south China (Cao *et al.*, 2003), with high population density of 1600 person/km^2 now, where the amount of population and motorcar is increasing year by year, excessive air pollutants are released, and atmospheric haze happen more often. Urban development and economy growth along with the acutely increasing population, motor vehicles and industrial activities would result in constantly elevated pollution levels.

Nine sampling sites (indoor and outdoor simultaneously) classified in 3 kinds of areas (general urban area, roadside area, the area around industrial plant) of Guangzhou city were selected for this study. All indoor environments were located in domestic home. Three sampling sites (GS1, GS2 and GS3) were selected in general urban area without impacts of heavy vehicle traffic and industrial production, three sampling sites (RS1, RS2 and RS3) were selected by roadside with heavy motor vehicle traffic, and three sampling sites (IS1, IS2 and IS3) were selected around industrial plant. The nearest distance between two sites of all nine sites was about 1 kilometer, and the farthest distance between two sites was over 20 kilometers. The purpose of considering the distance was to avoid the interaction with each other sites. Detailed properties of nine sampling sites are given in Table 1. The locations of sites were shown in Fig. 1. Indoor and outdoor source characters please see later analysis in the paper.

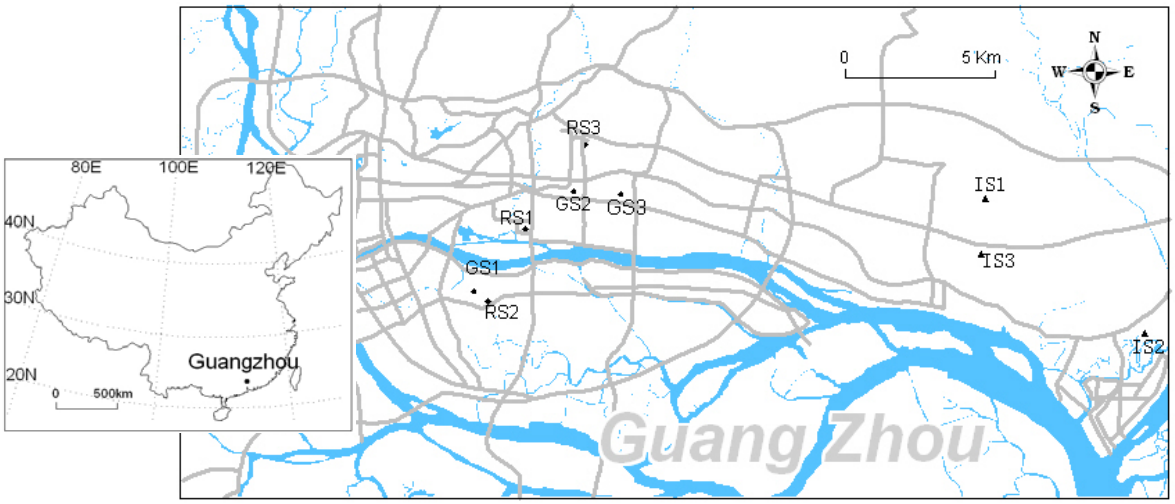

Fig. 1. Location of the sampling sites.

Table 1. Properties of indoor/outdoor sampling locations in Guangzhou city.

Site no.	Floor	Height from ground (m)	Size (m^2)	Build year	Decoration year	Indoor sources	Outdoor main sources
GS1	4	12	100	2000	2000	Cooking, Decoration and furniture volatile	City exhaust gas
GS2	6	18	100	2000	2001	Cooking, Decoration and furniture volatile	City exhaust gas
GS3	5	15	86	1989	1990	Cooking, Decoration and furniture volatile	City exhaust gas
RS1	6	18	106	1992	1998	Cooking, Decoration and furniture volatile	Motor exhaust
RS2	7	21	95	1986	1997	Cooking, Decoration and furniture volatile, Smoking	Motor exhaust
RS3	6	18	70	2000	2000	Cooking, Decoration and furniture volatile	Motor exhaust
IS1	1	6	220	2000	2000	Cooking, Decoration and furniture volatile	Industrial fuel combustion emission and production exhaust
IS2	1	6	150	1997	1998	Cooking, Decoration and furniture volatile	Power plant coal combustion emission
IS3	6	18	60	1990	1993	Cooking, Decoration and furniture volatile	Industrial fuel combustion emission

Both the indoor and outdoor $PM_{2.5}$ samplings were collected simultaneously from 2 July to 13 August 2004 by using two mini-volume portable samplers (Airmetrics, USA) with a $PM_{2.5}$ cyclone operating with the flow rates of 5 L/min for continuous 24 hours. Two samplers were checked and calibrated in Hong Kong Polytechnic University and then sent to Guangzhou for $PM_{2.5}$ sample collection. All the samples were collected on 47 mm Whatman quartz micro-fibre filters. After collection, loaded filters were stored in a refrigerator at about 4^{o}C before weighing and chemical analysis. The total particulate mass was determined by weighing on an electronic microbalance with 1 μg sensitivity (Mettler M3, Switzerland). Each of the measured residences

had an indoor $PM_{2.5}$ sampler located in the center of living room and kept above 1 meter distance to any objects indoors to prevent the sampler from closing to possible source emissions points. And the outdoor one located in the balcony/platform, similarly keeping above 1 meter distance to outside wall and any possible object outside the residence. The indoor sampling heights were in the range of 1-1.5 m above ground in order to simulate the breathing zone and to avoid potential interferences from excessive re-suspension of particles. During the summer sampling period, sampling in every site repeated 4 days.

Within the sampling period, the mode wind direction was dominantly southeast and south. And the direction of all of the residences is mainly to south. The wind speed of 10 m above the ground level fell into the range of 0.8-3.5 m/s, and the average wind speed being 2.2 m/s. The temperature ranged from 25 ^{o}C-37 ^{o}C and ambient pressure varied insignificantly between 998.3 and 1007.2 hPa. The relative humidity (RH) was between 50-90%.

RESULTS AND DISCUSSION

Spatial distribution of $PM_{2.5}$ in generic urban, roadside and industrial plant area

The indoor and outdoor $PM_{2.5}$ mass concentrations for a total of 72 samples during summer sampling period at nine sites in generic urban area, roadside area and industrial plant area were summarized in Table 2.

The indoor 24 hours $PM_{2.5}$ concentrations in generic urban area, roadside area and industrial plant area ranged from 20.9-81.7 μg/m^3, 28.7-123.1 μg/m^3, and 22.6-110.9 μg/m^3, respectively, while the corresponding outdoor concentrations ranged from 24.9-75.1 μg/m^3, 38.1-111.6 μg/m^3 and 45.8-128.7 μg/m^3, respectively. The average ranges of indoor concentrations were found wider than that of corresponding outdoor concentrations in three type areas, which was consistent with the fact that the indoor $PM_{2.5}$ is not only from outdoor environment but also from indoor activities/sources. Wider ranges were also found in roadside area and industrial plant area than in generic urban area. The range of indoor and outdoor 24 hours $PM_{2.5}$ mass concentrations in roadside area were 1.8 times and 1.5 times of that in generic urban area, the range of indoor and outdoor 24 hours $PM_{2.5}$ mass concentrations in industrial plant area were 1.7 times and 1.7 times of that in generic urban area, respectively. According to our investigation, Road 1, Road 2 and Road 3 have 2500, 7000 and 4000 car/trucks per hour flux, respectively. HuangPu power plant and HengYun power plant, Sinopec Guangzhou Petrochemical Complex and ethylene plant of Guangzhou around the sites of IS1 IS2 and IS3, contributed a great lot of fuel combustion emission and industrial production techniques emission. Therefore, above $PM_{2.5}$ comparison result in different areas represented a significant amount variation of $PM_{2.5}$ emission source in roadside and industrial environments. Different traffic flow rate during daily different period might be the main reason of large range in roadside environment. Intermittent industrial exhaust

emission and production differences between daytime and nighttime might be the main reasons of large range in industrial environment.

Table 2. Statistics for $PM_{2.5}$ measurement at nine monitoring sites ($\mu g/m^3$).

Sites	Indoor						Outdoor						I/O
	N	Mean	SD	Max.	Min.	Range	N	Mean	SD	Max.	Min.	Range	
GS1	4	58.0	7.1	63.3	47.8	15.5	4	52.4	15.8	63.1	29.2	33.9	1.11
GS2	3	67.1	21.3	81.7	42.6	39.1	4	56.5	14.1	75.1	41.0	34.1	1.19
GS3	4	43.6	21.3	61.8	20.9	40.9	4	44.7	16.7	60.4	24.9	35.5	0.98
Average	11	56.2	17.1	81.7	29.2	52.5	12	51.2	15.0	75.1	24.9	50.2	1.10
RS1	4	62.2	22.5	76.8	28.7	48.1	4	69.5	11.6	83.8	59.1	24.7	0.90
RS2	4	71.1	5.2	78.1	65.6	12.5	4	88.6	8.6	99.5	78.9	20.6	0.80
RS3	4	87.1	32.2	123.1	48.0	75.1	4	80.1	31.4	111.6	38.1	73.5	1.09
Average	12	73.5	23.3	123.1	28.7	94.4	12	79.4	19.8	111.6	38.1	73.5	0.93
IS1	4	65.7	15.4	84.3	49.0	35.3	4	66.0	19.0	87.8	45.8	42	1.00
IS2	4	54.6	25.0	81.0	22.6	58.4	4	111.2	18.9	130.1	89.4	40.7	0.49
IS3	4	99.8	13.8	110.9	80.6	30.3	4	101.5	22.0	128.7	78.4	50.3	0.98
Average	12	73.4	26.3	110.9	22.6	88.3	12	92.9	27.2	128.7	45.8	80.9	0.79

The indoor average $PM_{2.5}$ concentrations in generic urban area, roadside area and industrial plant area were 56.2, 73.5 and 73.4 $\mu g/m^3$, respectively, while the corresponding outdoor concentrations were 51.2, 79.4 and 92.9 $\mu g/m^3$, respectively. Both indoor and outdoor average $PM_{2.5}$ concentrations in roadside area and in industrial plant area were higher than those in generic urban area. It indicated that traffic exhaust and industrial exhaust were the major outdoor source for concentrations of $PM_{2.5}$.

For the sites in generic urban area, the highest indoor and outdoor 24 hours average concentrations of $PM_{2.5}$ were 67.1 and 56.5 $\mu g/m^3$ in GS2, while the lowest indoor and outdoor 24 hours average concentrations of $PM_{2.5}$ were 43.6 and 44.7 $\mu g/m^3$ in GS3, the values in GS1 (58.0 and 52.4 $\mu g/m^3$ for indoor and outdoor environments) were the medial. Analyzing the characteristics of indoor and outdoor environment and sources (Table 2), approximately there was no special obvious difference in indoor environment and sources among the three sites, except that the building and decoration year of GS3 was the oldest, the number of occupancies was the fewest, and the frequency of cooking was the lowest, to some extent which explain the result that the levels in GS3 were the lowest. According to the further investigation, the reason why the levels in GS2 were the highest might be the influence from a road 500 m far from with moderate motor vehicle emission (4000 car/trucks per hour).

For the sites in roadside area, the outdoor 24 hours average concentrations of $PM_{2.5}$ were 88.6, 80.1 and 69.5 $\mu g/m^3$ in RS2, RS3 and RS1 respectively, presenting descending order. It was consistent with the traffic flow rate of three roads. Road 2 was the busiest road with above 7000 car/trucks passing per hour, Road 3 was the moderate busy road with about 4000 car/trucks per

hour, and Road 1 was the sub-moderate busy road with about 2500 car/trucks per hour. However, the highest indoor 24 hours average concentrations of $PM_{2.5}$ (87.1 μg/m^3) were not in RS2, but in RS3. It demonstrated there were more indoor sources for $PM_{2.5}$ in RS3. The indoor sources in RS3 was suspected to be the high frequency of cooking and a child of 4 years old often playing in indoor environment.

For the sites in industrial plant area, the higher two outdoor 24 hours average concentrations of $PM_{2.5}$ were 111.2 and 101.5 μg/m^3 in IS2 and IS3, which were also the top two values in nine sites, the lowest outdoor 24 hours average concentrations of $PM_{2.5}$ were 66.0 μg/m^3 in IS1, while the highest indoor 24 hours average concentrations of $PM_{2.5}$ were 99.8 μg/m^3 in IS3 and the lowest indoor 24 hours average concentrations of $PM_{2.5}$ were 54.6 μg/m^3 in IS2. As shown in Table 1, IS2, IS3 and IS1 were adjacent to power plants (HuangPu and HengYun), Sinopec Guangzhou Petrochemical Complex and ethylene plant of Guangzhou, respectively. Thus it can be seen the industrial exhaust from power plant and petrochemical plant affected the $PM_{2.5}$ outdoor concentrations much more severely. The indoor concentration of $PM_{2.5}$ in IS2 was the lowest, though IS2 had highest outdoor concentration. The main reason is ventilation condition in IS2 was very poor, because the door and windows of IS2 residence were always closed.

$PM_{2.5}$ mass concentration and comparison

The average indoor and outdoor $PM_{2.5}$ mass concentrations of total 72 samples in this study were given in Table 3. Also the results of other studies on $PM_{2.5}$ were compared and summarized in Table 3. The average indoor and outdoor $PM_{2.5}$ concentrations in nine sites were 67.7 and 74.5 μg/m^3, respectively, with the indoor $PM_{2.5}$ concentrations ranging from 20.9-123.1 μg/m^3 and the outdoor $PM_{2.5}$ concentrations ranging from 24.9-130.1 μg/m^3. A significant difference was observed between the value in this study and that in other studies of some US and Europe cities. The concentrations of $PM_{2.5}$ in Guangzhou were 0.1~3.9 times and 3.4~6.2 times more than that of US in indoors and outdoors, and 1.5~5.8 times and 2.0~5.4 times more than that of Europe's, respectively. It indicated that both indoor and outdoor air qualities in Guangzhou were much worst than those US and Europe cities. By comparing with other Asia studies, the concentrations of $PM_{2.5}$ in this study were around 2.1~2.8 times and 1.0~3.1 times higher than Japan's for indoors and for outdoors, respectively, and were 0.2 times and 0.7 times higher than indoor and outdoor concentrations of Hong Kong. The outdoor concentration for $PM_{2.5}$ was 0.7 times higher than that of Korea, but was slightly lower than that in Kaohsiung, Taiwan. The ratio of indoor $PM_{2.5}$ concentration of Bangkok, Thailand to that of this study was 0.95~2.7, and the corresponding ratio for outdoors was 0.8~2.1. It indicated that the indoor and outdoor $PM_{2.5}$ concentrations in Asia were similar, the fine particulate pollution level in Guangzhou was moderate but on the high side, comparative to Taiwan, better than Thailand, but worse than Japan,

Table 3. Indoor and outdoor $PM_{2.5}$ mass concentrations in this study and comparison with other urban.

Locations		Sampling period	Mean $PM_{2.5}$ concentration ($\mu g/m^3$)		References
			Indoor	Outdoor	
This study, Guanzhou, China		2 July to 13 August 2004	67.6	74.5	
Hong Kong		March and April 2004	56.7	43.8	Cao *et al.* (2005)
Chongju, Korea		October 1995 to August 1996		44.2	Lee H.S. *et al.* (2001)
Kosan, Korea (background of Chongju)		March 1996, December 1996, January 1997 and December 1997		16.6	Lee J.H. *et al.* (2001)
Osaka, Japan	Roadside(commuter vehicles)	November 1994	20.0	37.0	Funasaka *et al.* (2000)
	Roadside(diesel traffic)	October 1995	22.0	23.0	
	background	December 1997	18.0	18.0	
Kaohsiung, Taiwan		November 1998 to April 1999		68.0	Lin and Tai (2001)
Bangkok, Thailand	Shop house on moderately busy streets	22 January to 7 March 1996	137	140	Tsai *et al.* (2000)
	Shop house near busy streets		184	62	
	Shop house near less busy streets		64	153	
Suffolk, New York, US[a]		6 January and 15 April 1986	17.3(N) 18.1(W) 22.0(K) 49.3(S) 38.0(SW) 61.4(SK) 30.3(SKW)	16.9	Leaderer *et al.* (1994)
Minneapolis-St. Paul metropolitan area, US		Spring, summer and fall of 1999	13.9	10.3	Ramachandran *et al.* (2003)
London, UK (near a busy road)		April-October 1998	14.0	18.0	Riain *et al.* (2003)
Oslo, Norway		1992-1993	22	13	Øie and Magnus (1997)
Amsterdam, Netherlands	High traffic homes	January-February and March-April 1995	27	25	Fischer *et al.* (2000)
	Low traffic homes		12	21	
Brisbane, Australia		March and August 1999	4.4~15.3	4.7~18.4	Morawska *et al.* (2001)
A university, Athens, Greece		6 January 2000 through 9 April 2000	11.4		Yanosky *et al.* (2002)

[a] W: wood burning; K: kerosene; S: smokers; KW: kerosene & wood burning; SW: smokers & wood burning; SK: smokers & kerosene; SKW: smokers, kerosene & wood burning

Korea and Hong Kong. The high $PM_{2.5}$ concentrations in this study were due to the huge population and motor vehicles and industrial production.

The new guideline of WHO for suspended particles requires $PM_{2.5}$ daily averages to be less than 25 μg/m^3 (WHO, 2006). In this study, the sampling lasted over one month, but the average $PM_{2.5}$ concentration even exceeded the daily average limit value of $PM_{2.5}$ in NAAQS. The $PM_{2.5}$ levels in Guangzhou city are very high; so more efforts should be taken for the control of fine particulate pollution, and the constitution of associated strategy and regulations. Currently there is no $PM_{2.5}$ guideline in China; therefore, more efforts also should be taken towards the establishment of a $PM_{2.5}$ guideline.

I/O ratios, indoor/outdoor correlation of $PM_{2.5}$ and source implications

The I/O ratio is an indicator for evaluating the difference between indoor concentrations and the corresponding outdoor level (Li and Lin, 2003). The I/O ratios of $PM_{2.5}$ in nine sites were shown in Table 2. It was found that I/O ratios of $PM_{2.5}$ in this study ranged from 0.49-1.19, the I/O ratios in GS1, GS2 and GS3 were 1.11, 1.19 and 0.98 with the average I/O ratio in generic urban area larger than 1 (1.10). The I/O ratios in RS1, RS2, RS3 and in IS1, IS2, IS3 were 0.90, 0.80, 1.09 and 1.00, 0.49, 0.98, with the average I/O ratio in roadside area and in industrial plant area smaller than 1 (0.93 and 0.79), respectively. It indicated that the indoor $PM_{2.5}$ levels are not always better than outdoors', especially in generic urban area and implied that there were major sources of $PM_{2.5}$, such as smoking, cooking and cleaning solvent in indoors, which should be concerned thoroughly. Table 2 also showed that with the outdoor fine particulate concentrations increasing in roadside area and in industrial plant area, the I/O ratios were smaller accordingly. It was consistent with the results reported by Funasaka *et al.* (2000) and Riain *et al.* (2003), who found that the I/O ratio of $PM_{2.5}$ in roadside area of Osaka, Japan in December 1997 was 0.54, and the I/O ratio of $PM_{2.5}$ near a busy road in London, UK was 0.78, respectively.

The value of the coefficient of determination (R^2) between the indoor and outdoor data was used as an indicator of the degree to which $PM_{2.5}$ measured indoors is attributed to infiltration from outdoors (Colome *et al.*, 1992; Clayton *et al.*, 1993). The correlations between indoor and outdoor $PM_{2.5}$ concentrations in three different environments were shown in Fig. 2 (a-d) and tested using Pearson paired t-test. It was found that R^2 were 0.7028 ($p < 0.001$, n = 11), 0.5391 ($p = 0.007$, n = 12), and 0.1749 ($p = 0.088$, n = 12) for samples in generic urban area, roadside area and industrial area, respectively. The indoor/outdoor correlations of $PM_{2.5}$ in generic urban area, roadside area and industrial area were from strong to moderate to poor. It indicated that the compositions of $PM_{2.5}$ in industrial plant area were the most abundant, and the compositions of $PM_{2.5}$ in roadside area were more abundant than that in generic urban area in both indoors and outdoors. In addition, it is important to note that generally strong indoor/outdoor correlation of $PM_{2.5}$ suggests that fine particles of indoor are mainly from the outdoor environment and/or good

ventilation, and poor indoor/outdoor correlation suggests indoor sources existing or very poor ventilation. In this study, in the site of generic urban area it was suspected there were much indoor sources based on the I/O ratio analysis above, therefore the reason explaining the strong correlation between indoor and outdoor $PM_{2.5}$ in generic urban area must be excellent ventilation condition and high air exchange rate. In the site of roadside, good indoor/outdoor $PM_{2.5}$ correlation accompanying with I/O ratio smaller than 1 suggested that indoor $PM_{2.5}$ were mainly from the outdoor air. In the site of industrial plant area, poor correlation between indoor and outdoor $PM_{2.5}$ was ascribed to seldom ventilation in IS2, since the correlation between indoor and outdoor $PM_{2.5}$ for the samples in IS1 and in IS3, was very strong ($R^2 = 0.9065$, $p < 0.001$, n = 8) shown in Fig. 2 (d), which indicated that the indoor fine particulate in IS1 and in IS3 were mainly from the infiltration of outdoor air.

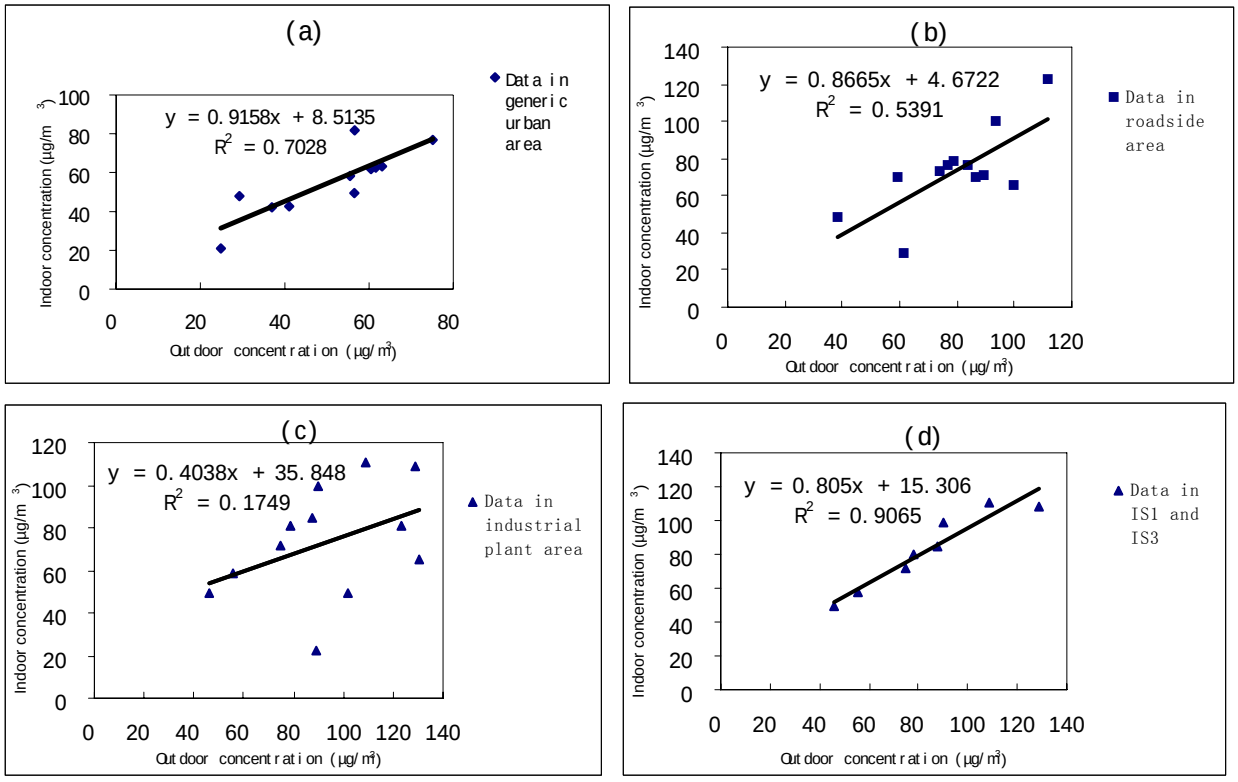

Fig. 2. Relationships between indoor and outdoor concentrations of $PM_{2.5}$ in generic urban area (a), in roadside area (b), in industrial plant area (c) and in both IS1 and IS3 (d).

CONCLUSIONS

This study has firstly quantified the concentrations of $PM_{2.5}$ in both indoor and outdoor air at nine locations in Guangzhou city. The average indoor and outdoor $PM_{2.5}$ concentrations during one half of month were 67.7 and 74.5 $\mu g/m^3$, respectively, much higher than some US, Europe cities, higher than several cities in Asian, and even exceeded the newly daily limit value of $PM_{2.5}$

in WHO. These results suggested more efforts should be taken for the control of fine particulate pollution in Guangzhou city and the constitution of associated regulations. The average I/O ratio in generic urban area, roadside area and industrial plant area were 1.10, 0.93 and 0.79, respectively. The indoor/outdoor correlations of $PM_{2.5}$ in generic urban area, roadside area and industrial area were from strong to moderate to poor, which indicating the compositions of $PM_{2.5}$ in industrial plant area were most complicated. In generic urban area, the reason explaining the strong indoor/outdoor $PM_{2.5}$ correlation with I/O > 1, was excellent ventilation condition and high air exchange rate. In roadside area, good indoor/outdoor $PM_{2.5}$ correlation with I/O < 1, suggested that indoor $PM_{2.5}$ were mainly from the outdoor air. In industrial plant area, poor indoor/outdoor $PM_{2.5}$ correlation was ascribed to seldom ventilation in IS2.

ACKNOWLEDGMENTS

This research was supported by the research grants from China (NSFC-40121303) and also supported by the Research Grants Council of Hong Kong (PolyU5197/05E, PolyU5145/03E). Special thanks must be paid to all those who were willing to share their homes with us in making the field data available.

REFERENCES

Adgate, J.L., Ramachandran, G., Pratt, G.C., Waller L.A. and Sexton K. (2002). Spatial and Temporal Variability in Outdoor, Indoor, and Personal $PM_{2.5}$ Exposure. *Atmos. Environ.* 36: 3255–3265.

Anderson, H.R. (2000). Differential Epidemiology of Ambient Aerosols. *The Royal* Soc. 358: 2771-2785.

Cao, J.J., Lee, S.C., Ho, K.F., Zhang, X.Y., Zou, S.C., Fung, K., Chow, J.C. and Watson, J.G. (2003). Characteristics of Carbonaceous Aerosol in Pearl River Delta Region, China during 2001 Winter Period. *Atmos. Environ.* 37: 1451-1460.

Cao J. J., Lee S. C., Chow J. C., Cheng Y., Ho K. F., Fung K., Liu S. X. and Watson J. G. (2005). Indoor/Outdoor Relationships for $PM_{2.5}$ and Associated Carbonaceous Pollutants at Residential Homes in Hong Kong–Case Study. *Indoor Air*, 15: 197–204.

Cao J.J., Lee S.C., Ho K.F., Fung K., Chow J. C. and Watson J. G. (2006). Characterization of Roadside Fine Particulate Carbon and its Eight Fractions in Hong Kong. *Aerosol Air Qual. Res*. 6: 106-122.

Chan, A.T. (2002). Indoor-Outdoor Relationships of Particulate Matter and Nitrogen Oxides Under Different Outdoor Meteorological Conditions. *Atmos. Environ.* 36: 1543-1551.

Clayton, C. A., Perritt, R. L., Pellizzari, E. D., Thomas, K. W., Whitmore, R. W., Wallace, L. A., Ozkaynak, H. and Spengler, J. D. (1993). Particle Total Exposure Assessment Methodology (PTEAM) Study: Distributions of Aerosol and Elemental Concentrations in Personal, Indoor and Outdoor Air Samples in a Southern California Community. *J. Exposure Anal. Environ. Epidemiol* 3: 227-250.

Colome, S., Kado, N., Jaques, P. and Kleinman, M. (1992). Indoor-Outdoor Air Pollution Relations: Particulate Matter Less than 10 μm in Aerodynamic Diameter (PM_{10}) in Homes of Asthmatics. *Atmos. Environ.* 26: 2173-2178.

Fischer, P.H., Hoek, G., Reeuwijk, H.V., Briggs, D.J., Lebret, E., Wijnen, J.H.V., Kingham, S. and Elliott, P.E. (2000). Traffic-Related Differences in Outdoor and Indoor Concentrations of Particles and Volatile Organic Compounds in Amsterdam. *Atmos. Environ.* 34: 713-3722.

Funasaka, K., Miyazaki, T., Tsuruho, K., Tamura, K., Mizuno, T. and Kuroda, K. (2000). Relationship between Indoor and Outdoor Carbonaceous Particulates in Roadside Households. *Environ. Pollution* 110: 127-134.

Gartrell, G. and Friedlander, S. K. (1975). Relating Particulate Pollution to Source - the 1972 California aerosol Characterization Study. *Atmos. Environ.* 9: 279-289.

Geller, Michael, D., Chang, Mingchih, Sioutas, Constantinos, Ostro, Bart D. and Lipsett, Michael J. (2002). Indoor/Outdoor Relationship and Chemical Composition of Fine and Coarse Particles in the Southern California Deserts. *Atmos. Environ.* 36: 1099-1110.

Ho, K. F., Lee, S. C., Chan, Chak K., Yu, Jimmy C., Chow Judith C. and Yao, X. H. (2003). Characterization of Chemical Species in $PM_{2.5}$ and PM_{10} Aerosols in Hong Kong. *Atmos. Environ.* 37: 31-39.

Kim, C.S. and Jaques, P.A. (2000). Respiratory Dose of Inhaled Ultrafine Particles in Healthy Adults. *The Royal Soc.* 358: 2693-2705.

Kulkarni, M.M. (2006). Source Apportionment of Human Exposure to Particulates in Mumbai, India. *Aerosol Air Qual. Res*. 6: 281-294.

Leaderer, B.P., Koutrakis, P., Briggs S.L.K. and Rizzuto, J. (1994). The Mass Concentration and Elemental Composition of Indoor Aerosols in Suffolk and Onondaga Counties, New York. *Indoor Air* 4: 23-34.

Lee, H.S. and Kang, B.W. (2001). Chemical Characteristics of Principal $PM_{2.5}$ Species in Chongju, South Korea. *Atmos. Environ.* 35: 739-746.

Lee, J.H., Kim, Y.P., Moon, K.C., Kim, K.K. Lee, C.B. (2001). Fine particle Measurements at Two Background Sites in Korea between 1996 and 1997. *Atmos. Environ.* 35: 635-643.

Lee, S.C. and Chang, M. (2000). Indoor and Outdoor Air Quality Investigation at Schools in Hong Kong. *Chemosphere* 41: 109-113.

Li, C.S. and Lin, C.H. (2003). Carbon profile of Residential Indoor PM_1 and $PM_{2.5}$ in the Subtropical region. *Atmos. Environ.* 37: 881-888.

Lin, J.J. and Tai, H.S. (2001). Concentrations and Distributions of Carbonaceous Species in Ambient particles in Kaohsiung City, Taiwan. *Atmos. Environ.* 35: 2627-2636.

Lippmann, M. and Ito, K. (2000). Contributions that Epidemiological Studies Can make to the Search for a Mechanistic Basis for the Health Effects of Ultrafine and Larger Particles. *The Royal Soc.* 358: 2787-2797.

Molnár, A., Mészáros, E., Hansson, H.C., Karlsson, H., Gelencsér, A. Kiss, G.Y. and Krivcsy, Z. (1999). The Importance of Organic and Elemental Carbon in the Fine Atmospheric Aerosol Particles. *Atmos. Environ.* 33: 2745-2750.

Morawska, L., He, C., Hitchins, J., Gilbert, D. and Parappukkaran, S. (2001). The Relationship between Indoor and Outdoor Airborne Particles in the Residential Environment. *Atmos. Environ.* 35: 3463-3473.

Naeher, L.P., Smith, K.R., Leaderer, B.P., Mage, D. and Grajeda, R. (2000). Indoor and Outdoor $PM_{2.5}$ and CO in High- and Low-Density Guatemalan Villages. *J. Exposure Anal. Environ. Epidemiol.* 10: 544-551.

Ramachandran, G., Adgate, J., Kill, N. and Sexton, K. (2000). Comparison of Short-Term Variations (15-minute averages) in Outdoor and Indoor $PM_{2.5}$ Concentrations. *J. Air & Waste Manage. Asssoc.* 50: 1157-1166.

Ramachandran, G., Adgate, J.L, Pratt, G.C. and Sexton, K. (2003). Characterizing Indoor and Outdoor 15 Minute Average $PM_{2.5}$ Concentrations in Urban Neighborhoods. *Aerosol Sci. Technol.* 37: 33-45.

Riain, C.M.N., Mark, D., Davies, M., Harrison, R.M. and Byrne, M.A. (2003). Averaging Periods for Indoor-Outdoor Ratios of Pollution in Naturally Ventilated Non-Domestic Buildings Near a busy road. *Atmos. Environ.* 37: 4121-4132.

Tsai, F.C., Smith, K.R., Vadakan, N.V., Ostro, B.D., Chestnut L.G. and Kungskulniti N. (2000). Indoor/outdoor PM_{10} and $PM_{2.5}$ in Bangkok, Thailand. *J. Exposure Anal. Environ. Epidemiol.* 10: 15-26.

Wichmann, H.E. and Peters, A. (2000). Epidemiological Evidence of the Effects of Ultrafine Particle Exposure. *The Royal Soc.* 358: 2751-2769.

WHO (World Health Organization) (2006), WHO Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide-Global Update 2005-Summary of Risk Assessment, http://www.who.int/phe/health_topics/outdoorair_aqg/en/index.html.

Yanosky, J.D., Williams, P.L. and MacIntosh, D.L. (2002). A Comparison of Two Direct-Reading Aerosol Monitors with the Federal Reference Method for $PM_{2.5}$ in Indoor Air. *Atmos. Environ.* 36: 107-113.

Received for review, March 19, 2007
Accepted, June 21, 2007