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Investigation of indoor air quality at residential homes in Hong Kong—case study

Shun Cheng Lee*, Wai-Ming Li, Chio-Hang Ao

Research Centre for Urban Environmental Technology and Management, Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hung Hum, Kowloon, Hong Kong

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Abstract

Indoor air quality (IAQ) has been a matter of public concern in Hong Kong. Recently, the Hong Kong Government has recognized the potential risk and problems related to indoor air pollution, and it is striving to establish IAQ objectives for different types of indoor environments. This study attempts to provide more information about the present IAQ of local resident flats. Air pollutants measured in this study included carbon dioxide (CO_2), respirable suspended particulate matter (PM_{10}), formaldehyde (HCHO), volatile organic compounds (VOCs) and airborne bacteria. The results of this study indicate that the 8-h average concentrations of CO_2 and PM_{10} in the domestic kitchens investigated were 14% and 67% higher than those measured in the living rooms. The indoor air pollution caused by PM_{10} was more serious in domestic kitchens than in living rooms as almost all of the kitchens investigated had higher indoor levels of PM_{10}. The majority of the domestic living rooms and kitchens studied had average concentrations of airborne bacteria higher than 500 CFU/m^3. The mean total bacteria count recorded in kitchens was greater than that obtained in living rooms by 23%. In homes where occupants smoke, the negative impact of benzene, toluene and *m*, *p*-xylene on the IAQ was greatly enhanced. The use of liquefied petroleum gas (LPG) stove has more significant impact on indoor VOCs than the use of cooking stoves with natural gas as cooking fuel. © 2002 Published by Elsevier Science Ltd.

Keywords: Home; Hong Kong; Indoor air quality; Suspended particulate matter (PM_{10}); Total bacteria count (TBC); Volatile organic compounds (VOCs)

1. Introduction

Hong Kong is one of the most densely populated cities in the world. This metropolitan city accommodates 6.84 million people on the 1098 km^2 of the land (Census and Statistics Department, 2000a). Due to limited land supply, many residential areas are situated in close proximity to industrial premises and heavily trafficked areas in Hong Kong. The outdoor air quality of residential premises is therefore directly influenced by nearby industrial activities and traffic conditions (Chan et al., 2000; Lee et al., 1999a, b, 2001, 2002; Chan and Wu, 1993). Vehicular emission is one of the factors that contribute to the outdoor air pollution. In Hong Kong, many districts are full of high-rise buildings surrounding narrow traffic roads with heavy traffic conditions. The air pollutants emitted by vehicular exhausts are not easily dispersed inside the highly populated areas and readily accumulated to levels that can pose adverse health effects to people living or working there (Perry and Gee, 1994). The emissions from motor vehicles contribute to a considerable amount of airborne fine particles in local districts (Lam et al., 1998). The influence of the fine particles from outdoor air on Hong Kong people will be greatly enhanced when the weather

*Corresponding author. Tel.: +852-276-66011; fax: +852-2334-6389.

E-mail addresses: ceslee@polyu.edu.hk (S.C. Lee), 98900785r@polyu.edu.hk (W.-M. Li), 00900524r@polyu.edu.hk (C.-H. Ao).

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is frequently dry and wind speed is low. Some local and overseas studies have indicated that the air quality of a residential home varies in relation to outdoor air quality (Jones et al., 2000; Lee et al., 1999a; Baek et al., 1997).

Many studies have found that the concentrations of suspended particulate matter were higher indoors than outdoors when there were sources of indoor particulate in domestic homes (Jones et al., 2000; Chao et al., 1998; Wallace, 1996; Kamens et al., 1991; Spengler et al., 1981). Incremental concentrations of fine particles were attributed to tobacco smoking and operation of gas stoves for cooking. Spengler et al. (1981) found that concentrations of fine particle were as high as 300 $\mu g/m^3$ when a smoker kept smoking for up to 30 min until the cigarette had burnt out, also the 24-h average concentrations of fine particles could be elevated by 20 $\mu g/m^3$. In Hong Kong, the effects of cooking on indoor concentrations of fine particulate matter had been investigated in homes (Chao et al., 1998; Kamens et al., 1991). The ratio of indoor and outdoor concentrations of suspended fine particulate matter was higher in homes using gas stoves than in those without combustion devices for cooking (Monn et al., 1997). In addition to cooking and smoking, some housekeeping activities such as sweeping and vacuuming lead to an increase in large particulate concentration within a home, because the household cleaning may cause the re-suspension of indoor particulate matters from domestic floors and furniture (Corsi and Chiang, 2000; Byrne, 1998). Corsi and Chiang (2000) reported that the indoor concentrations of PM_{10} were usually elevated to above 100 $\mu g/m^3$ when vacuuming was carried out.

On average, the annual amount of rainfall over the territory of Hong Kong is 2214 mm, and the annual temperature is 23°C (Census and Statistics Department, 2000b). The Hong Kong humid and warm climate makes Hong Kong a favorable environment for the growth of airborne bacteria. Many households in Hong Kong are installed with window type air conditioners. If the air conditioners are not frequently cleaned, they can be coated with dust and pathogenic bacteria. One of the contributing factors affecting indoor concentrations of airborne bacteria is the hygienic quality of a residence. Jaffal et al. (1997) found that the houses with low hygienic standards had higher bacteria counts. The age of a residential building, the frequency of housekeeping and ventilation were predominant factors associated with the concentrations of airborne bacteria within a domestic home (Lee and Chang, 1999).

The VOC pollutants in a domestic environment originate from a variety of sources. Risto (1995) reported that domestic furniture such as leather sofas could generate high indoor concentrations of trichloroethene and 1,4-dichlorobenzene. Also, the researcher found that the highest concentration of tetrachloroethene was obtained at a residence that was converted from an old laundry. Aromatic VOCs such as toluene and benzene are closely related to the use of consumer products. For instance, 1,4-dichlorobenzene results from the emission of moth-balls and room deodorants, these two consumer products are commonly found in Hong Kong residences (Bouhamra et al., 1997). Some previous studies in other countries found that households with no smokers experienced less exposure to airborne benzene compared to smokers' homes (Edwards et al., 2001; Guerin et al., 1992). Airborne chloroform and halogenated VOC compounds can be emitted from chlorinated water and detergents. Tobacco smoking, gas stoves and Chinese incense are potential sources of formaldehyde in a household. The smoke emitted from burning Chinese incense and the operation of a gas stove could lead to high levels of formaldehyde in living rooms and kitchens (Jia and Yao, 1993). Garrett et al. (1997) found that the operation of unvented gas heaters in Australian homes could increase indoor formaldehyde concentrations, the elevated concentrations of formaldehyde reached an average level of 145 $\mu g/m^3$ over an exposure period of four days. In Hong Kong, the indoor air quality (IAQ) at residential areas has become an issue of public concern. However, limited data are available on the general understanding about present IAQ of local residences. Therefore, the objectives of this study are to characterize the indoor and outdoor concentrations of selected air pollutants at six homes in Hong Kong and to evaluate the potential indoor sources in these selected homes.

2. Material and methods

Public rental and private housing are two major types of housing in Hong Kong. In 1999, 3.3 million of Hong Kong people lived in 952,900 flats of public residential buildings. A total of 2 million people have private domestic households in Hong Kong. Homes were selected on the basis (a) prevalence of housing type, (b) locations with relatively high population densities and (c) the homes have not been decorated within previous five years and did not contain newly purchased furniture during air sampling. The locations of the sampling sites are shown in Fig. 1. Three of the surveyed households are public rental houses located in the most highly populated housing estates, including Home 1, Home 3 and Home 5. Homes 4 and 6 are private housing. Home 2 is a roadside home that is adjacent to a road with heavy traffic. Except for Home 2, other homes are urban flats on different floors of multi-storey residential buildings. During the periods of air sampling, each of the monitored homes was occupied. The living rooms of all homes selected are ventilated by window typed air-conditioners or through open windows. For domestic kitchens, ventilation could be provided by

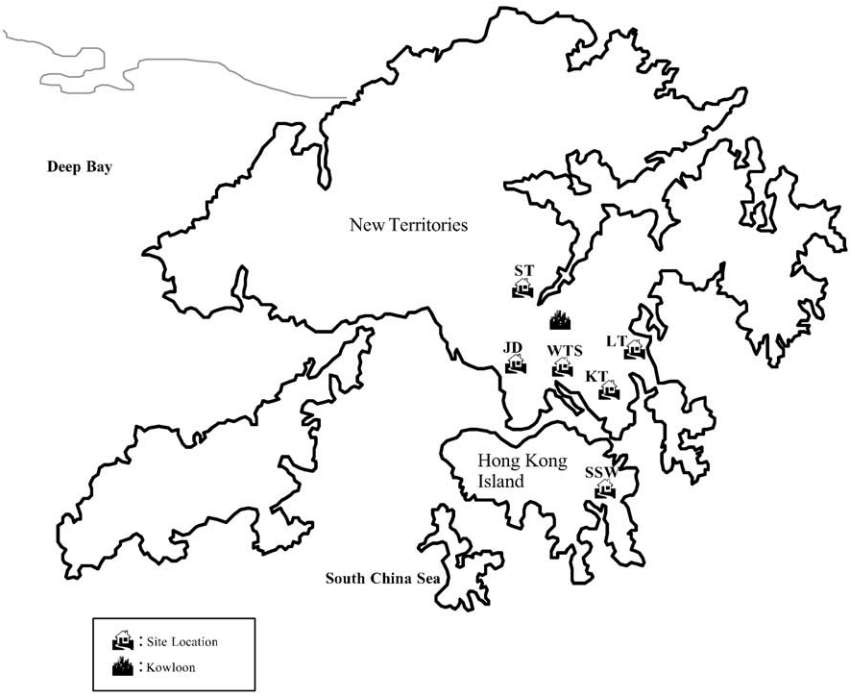

Fig. 1. The sampling locations in Hong Kong.

operation of exhaust fans or hoods or through open windows. Brief information concerning the monitored homes is shown in Tables 1 and 2.

3. Sampling and analytical methods

This study was conducted from July to October 1999. The air pollutants included carbon dioxide (CO_2), carbon monoxide (CO), respirable suspended particulate (PM_{10}) matter, formaldehyde (HCHO), volatile organic compounds (VOCs) and total bacteria count (TBC). During the air measurement, indoor temperature, relative humidity and the age of the building were also recorded. Each home was monitored on 2–3 occasions. Indoor and outdoor air samples were taken simultaneously at each sampling site. Indoor air samples were collected both in living rooms and kitchens. All of the outdoor air samples were taken at street levels or near to the front of the homes. The concentrations of CO_2 and PM_{10} were measured for a period of 8 h (11:30 a.m. to 7:30 p.m.). This sampling period covered the times of preparation of lunch and dinner. 8-h average concentrations of VOC and HCHO were collected for living rooms and kitchens. Two air samples of airborne bacteria were taken for 9 min, one in the kitchen and the other in the living room. Indoor air instruments were positioned as close as possible to the center of the living rooms and kitchens, and placed at 1.5 m above the ground and at least 1 m away from potential sources of air pollutants. Identical air samplers and monitors for outdoor sampling were used and housed in a waterproof and locked steel box. This box was placed at a height of 1.7 m from the ground. Air inlets of the air samplers and monitors were extracted from the box during the periods of air sampling for outdoor air sample.

A portable Q-Trak monitor (Model 8551, TSI Inc.) was used to monitor the indoor and outdoor CO_2 concentrations, temperature and relative humidity. The CO_2 analyzer is able to detect CO_2 based on the mechanism of non-disperse infrared detection. This analyzer is equipped with a thermistor and a thin film capacitive sensor for temperature and relative humidity measurements. A Dust-Trak air monitor (Model 8520, TSI Inc.) was used to measure PM_{10} concentrations in both indoor and outdoor air, respectively. The monitor can measure particulate matters based on the method of light scattering. The Dust monitor measured PM_{10} at 1-min interval at a flow-rate of 1.7 l/min. Before sampling, the Q-Trak was calibrated with span CO_2 gas at a known concentration. Pre- and post-zero checking of these two air monitors was carried out. The Dust-Trak monitor cannot directly give the mass of collected airborne particles as it is designed to measure aerosol concentration. Therefore, a separate calibration test should be done to convert the results given by the Dust-Trak monitor into corresponding concentrations obtained by gravimetric methods. The Dust-Trak air

Table 1
General description of sampling location in Hong Kong

Site/district	District condition	Home type	Home age (yr)	Floor	Home height (m)	Living room area (m^2)	Kitchen area (m^2)	Indoor finishing material	Ventilation condition
Home 1 (Kwum Tong)	Mixed residential, industrial and commercial area, high population and vehicle density, high and medium traffic flow.	Public rental	10	14th	2.5	10	3.9	Plastering wall, vinyl floor	Natural ventilation all the time
Home 2 (Jordon)	Mixed commercial and industrial area, high traffic flow	Private	15	1st	2.2	28	3.1	Plastering wall tile floor	Natural ventilation in daytime, air-conditioned in the evening
Home 3 (Shatin)	Residential area, high population density, low traffic flow	Public rental	12	7th	2.4	14	3.8	Wall paper wood floor	Natural ventilation in daytime, air-conditioned in the evening
Home 4 (Lam Tin)	Residential area, moderate population density, medium traffic flow	Private	3	22nd	2.5	20	2.8	Wall paper wood floor	Natural ventilaion in daytime, air-conditioned in the evening
Home 5 (Wong Tai Sin)	Residential area, high population density, medium traffic flow	Public rental	10	19th	2.6	18	3.6	Plastering wall tile floor	Natural ventilaion in daytime, air-conditioned in the evening
Home 6 (Siu Sai Wan)	Residential area, high population density, medium traffic flow	Private	6	8th	2.8	22	4	Wall paper tile floor	Natural ventilaion in daytime, air-conditioned in the evening

Table 2
Description of indoor activities in the six homes

Site/district	Number of occupants	Number of smokers	Frequency of household cleaning during sampling	Cooker type	Cooking fuel	Incense burning	Pets
Home 1 (Kwum Tong)	3	2	Weekly cleaning	Gas stove	Natural gas	Yes	No
Home 2 (Jordon)	7	0	Infrequent cleaning	Gas stove	LPG gas	No	No
Home 3 (Shatin)	3	0	Frequent cleaning	Gas stove	LPG gas	No	No
Home 4 (Lam Tin)	5	3	Infrequent cleaning	Gas stove	Natural gas	No	No
Home 5 (Wong Tai Sin)	5	2	Weekly cleaning	Gas stove	LPG gas	No	No
Home 6 (Siu Sai Wan)	4	0	Daily cleaning	Gas stove	Natural gas	Yes	No

monitors used in this study were calibrated against an Andersen Hi-Vol sampler for PM_{10}. Each filter used for gravitational sampling was conditioned at approximate 50% relative humidity for 24 h before and after sampling. The blank and sampled filters were weighed at least three times using an electronic micro-balance (Model A200 S-D1B, Sartorius Ltd.). The least square regression lines for PM_{10} results have the following equations: PM_{10} (Dust-Trak) $= 1.73 \pm 0.2 \times PM_{10}$ (Hi-Vol Sampler).

The correlation lines of PM_{10} have R^2 coefficients > 0.92, respectively. A Burkard single stage impactor (Burkard Manufacturing Co. Ltd.) with an agar plate is used to sample the airborne bacteria. Plate count agar filled in the plate was used as a nutrient media. The bacteria samples were taken at 10 ml/min for 9 min. The bacteria samples were incubated at 35°C in an oven for 2 days to obtain the total bacteria counts. The colonies of bacteria were counted under a light microscope. The bio-aerosol sampler was sterilized with isopropyl alcohol prior to sampling. After sampling, the plates were kept refrigerated and shipped back to a laboratory oven for incubation. In order to monitor contamination during storage, transport and sample collection, blank samples for bacteria measurement were carried into the sampling sites but remained unopened and sent back with fields samples to the laboratory for analysis.

Indoor and outdoor formaldehyde samples were collected using a SKC formaldehyde monitoring kit. Three pairs of bubblers were used for sampling HCHO at both indoor and outdoor sampling locations. In a pair of bubblers, one of them used as a blank sample remained closed with a solid cap during transportation and sampling. The other one used as a sample bubbler was sealed with a small holed cap whose opening had already been covered with a Knudsen diffusive disk with a specific disk factor. In brief, airborne formaldehyde is absorbed into a 0.05% aqueous solution of 3-methyl-2-benzothiazolinone-hydrazone hydrochloride (MBTH) contained in both blank and sampled bubblers. During the air sampling, the blank and sample bubblers were inverted to make contact between the absorbing liquid and the Knudsen disks. After sampling, the screw septum caps of the sample bubblers were removed and replaced by solid caps, and then the actual samples as well as the blank samples were refrigerated and protected from sunlight and immediately sent to the air laboratory for analysis within 1-h. HCHO absorbed in the samples was determined by colorimetric analysis and then the measured readings were converted to give average concentrations of indoor and outdoor samples. Aliphatic aldehydes can react with MBTH solution to produce colored products. In order to minimize the interference of other aliphatic aldehyde compounds, a separate calibration test should be carried out to compare the results given by SKC passive formaldehyde samplers with the respective concentrations determined by active air sampling using adsorbent cartridges coated with 2,4-dinitrophenylhydrazine (2,4-DNPH). The formaldehyde samples measured by active sampling were analyzed according to the TO-11 method recommended by the United State Environmental Protection Agency (USEPA, 1998). A series of measurements was carried out in different areas representing different concentrations of airborne formaldehyde. Each parallel measurement was conducted over a 24-h period. The passive HCHO measurements were converted to the corresponding concentrations measured by active sampling methods according to the regression line as shown in Fig. 2.

For VOC sampling, a batch of pre-cleaned canisters for sample collection was evacuated before sampling. Integrated VOC air samples were obtained using mass flow controllers (Model No. FC4104CV-G, Autoflow lnc.) at flow rates of 0.011 l/min for 8-h air sampling. Canister samples were collected both indoors and outdoors. After sampling, the canisters were immediately transported to the air laboratory for analysis within 1 h. A Nutech Cryogenic Concentrator (Model 3550A) first concentrated canister samples, and then the trapped VOC samples were subsequently separated by Hewlett Packard Gas Chromatography (GC) (Model

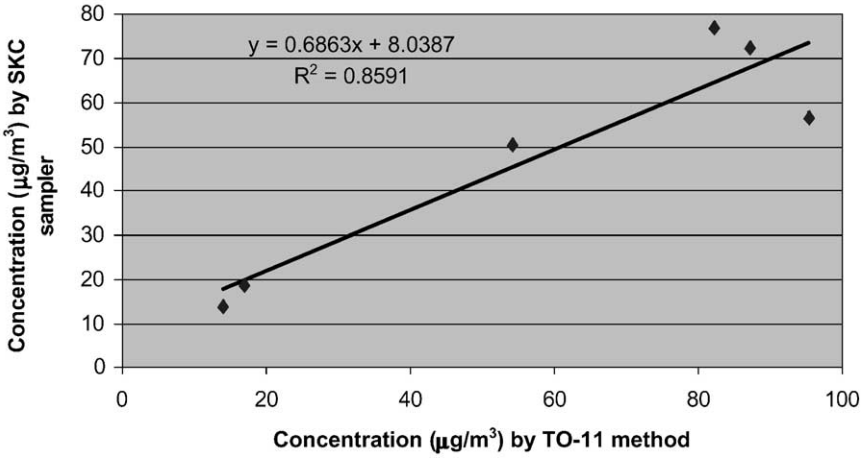

Fig. 2. Correlation of HCHO concentrations determined by USEPA TO-11 method and SKC passive HCHO sampler.

Table 3
Detection range and limits of the sampling methods

Air parameter	Detectable mechanism	Detectable range	Precision expressed as RSD (%)
Carbon dioxide (CO_2)	Non-dispersive infrared (NDIR)	1–5000 ppm	2.5
Formaldehyde (HCHO)	Colorimetric method	0.1–1.5 ppm	4.1
Respirable suspended particulate (PM_{10})	Light scattering	0.001–100 mg/m^3	2.8
Airborne bacteria/	Impacting on agar with incubation, followed by colony counting	0–2200 cfu/m^3	10.2
Benzene	VOC air sample trapped by cryogenic concentrator, analyzed by GC/MS system using TO-14 method	0.2–5000 µg/m^3	2.5
Toluene		0.2–5000 µg/m^3	4.3
m, *p*-xylene		0.2–5000 µg/m^3	2.6
o-xylene		0.2–5000 µg/m^3	2.6
Ethylbenzene		0.2–5000 µg/m^3	2.6
1,3,5-Trimethylbenzene		0.2–5000 µg/m^3	3.7
Trichloroethene		0.2–5000 µg/m^3	2.8
Tetrachloroethene		0.2–5000 µg/m^3	3.5
1,4-dichloroebenzene		0.2–5000 µg/m^3	4.2
Chloroform		0.2–5000 µg/m^3	3.6
Methylene chloride		0.2–5000 µg/m^3	2.7

HP6890) and quantified by a Mass Selective Detector (MS) (Model HP5973). For VOC sampling, sequential evacuating and pressurizing with humidified zero air was used to clean SUMMA canisters. Background checks were performed on 25% of the pre-cleaned canisters to certify that all target compounds were found to be <0.2 ppbv. Using the GC/MS analytical system, the method detection limits of individual VOCs can be measured. TO-14 standard calibration gas (Toxi-Mat-14M Cerfitied Standard (Matheson)) was analyzed using the GC/MS system seven times at 0.2 ppbv, the method detection limits (MDLs) can be obtained by multiplying the standard deviation of the seven replicate analyses and the *t*-test value for 99% confidence. Table 3 summarizes the detection range and limits of the sampling methods.

4. Results and discussion

Fig. 3 illustrates the indoor levels of CO_2 obtained in the living rooms and kitchens of residences. The average CO_2 concentrations in the living rooms ranged from 520 to 780 ppm with an average of 622 ppm. These CO_2

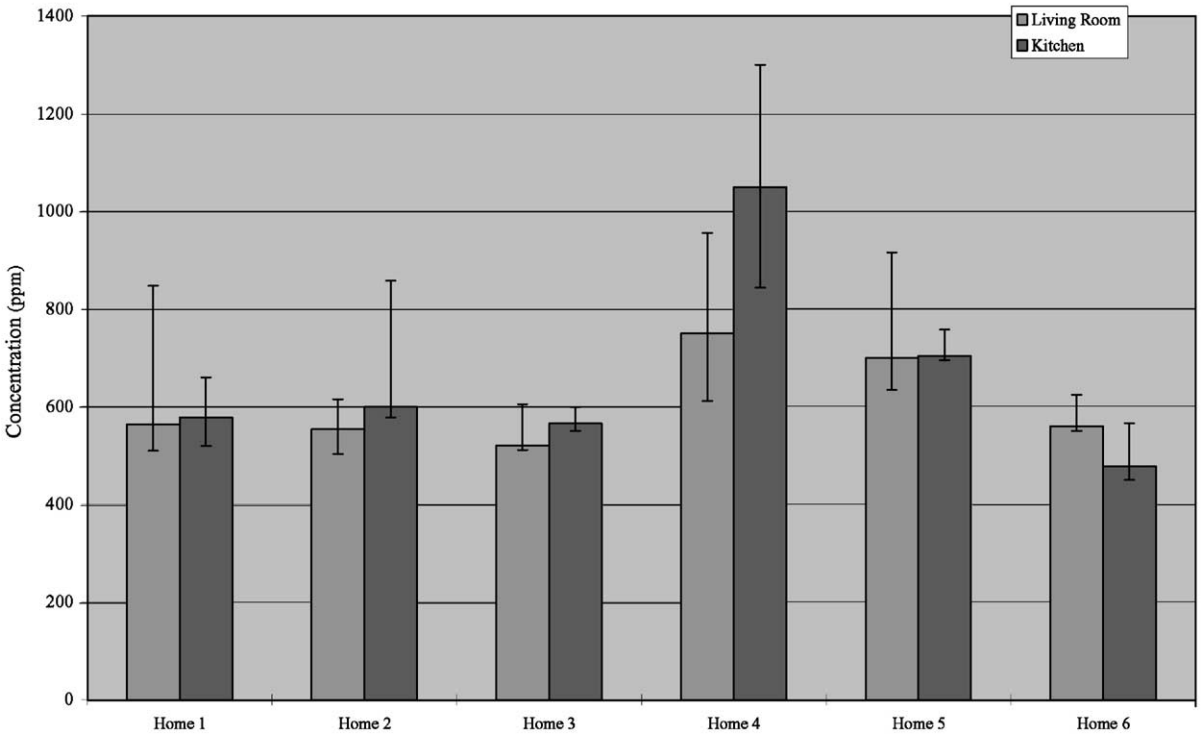

Fig. 3. Indoor concentrations of carbon dioxide (CO_2) in living room and kitchen of a domestic home.

Table 4
Recommended indoor air quality objectives for office buildings and public places in Hong Kong (Indoor Air Quality Management Group, 1999)

Air parameter	Unit	8-hour average based	
		Level 1	Level 2
Carbon dioxide (CO_2)	ppm	<800	<1000
Respirable suspended particulate (PM_{10})	$\mu g/m^3$	<20	<180
Formaldehyde (HCHO)	$\mu g/m^3$	<30	<100
Airborne bacteria	CFU/m^3	<500	<1000

levels did not exceed the HKIAQO Level I standard of 800 ppm, as shown in Table 4 (Environmental Protection Department, 1999). On the other hand, the mean CO_2 concentrations in the kitchens ranged from 578 to 1046 ppm with an average of 710 ppm. 33% of the monitored kitchens had higher indoor concentrations of CO_2 than the HKIAQO Level I standard. In homes where people smoke including Homes 1, 4 and 5, the mean indoor levels of CO_2 recorded in the living rooms were similar to those measured in homes with no smokers. During the periods of air sampling, the kitchens in Homes 2 and 4 were ventilated by exhaust fans with closed windows. The results show that the elevated CO_2 levels observed in these domestic kitchens were related to insufficient ventilation. Therefore, small size of the kitchens enhanced the influence of the emissions from combustion sources in Hong Kong so that higher concentrations of CO_2 were found in kitchens than in living rooms.

As shown in Fig. 4, the mean concentrations of PM_{10} recorded in the investigated living rooms were lower than those measured in the domestic kitchens. Most of the domestic living rooms were below the HKIAQO Level II standard of 180 $\mu g/m^3$. The majority of the kitchen environments had indoor concentrations of PM_{10} higher than the Level II standard. In comparison, the average levels of PM_{10} in the kitchens exceeded those in the living rooms by a range of 20% to 154%. The average indoor levels of homes with and without smokers were 155 $\mu g/m^3$ and 148 $\mu g/m^3$, respectively. Peak outdoor concentration measured in Home 6 was as high as 190 $\mu g/m^3$. As the windows of Home 6 were kept open during air sampling, the effect of outdoor air infiltration into the home could lead to an increase in indoor concentrations of PM_{10} in its kitchen and living room.

In addition to tobacco smoking and outdoor air pollution, household cleaning is a predominant indoor activity associated with increased concentrations of PM_{10} within a home. In comparison, the household cleaning such as vacuuming and sweeping was less

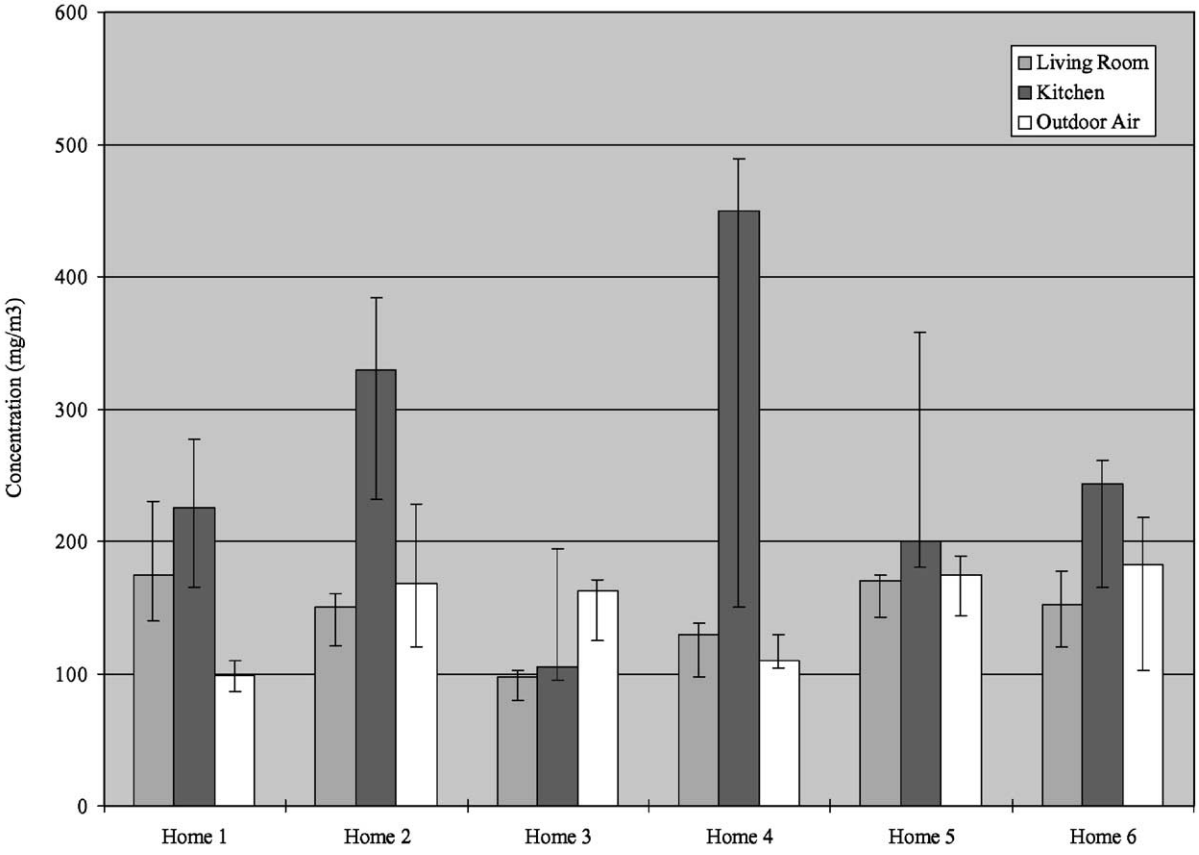

Fig. 4. Indoor and outdoor concentration of respirable suspended particulate (PM_{10}) in individual domestic home.

frequent in highly occupied Homes 1 and 3. Airborne particles could be deposited on the surfaces of floors and furniture. The occupant's activities could lead to re-suspension of the airborne particles settling from the surfaces of the household furnishing (Corsi and Chiang, 2000; Byrne, 1998; Miguel et al., 1995). It was found that higher levels of PM_{10} recorded in the living areas of Homes 1 and 5 were probably associated with the infrequent housekeeping. Airborne PM_{10} can originate from cooking within a home. Several studies found that airborne particles levels were considerably affected by cooking style such as frying (Kamens et al., 1991; Chao et al., 1998). All of the surveyed homes use Chinese cooking. Frying in a wok is a common food preparation process of Chinese cooking. The indoor levels of PM_{10} in the kitchen environments were probably attributable to cooking activity. The kitchens of Homes 2 and 4 were comparatively poorly ventilated as indicated by the higher indoor concentrations of CO_2 found in these two indoor environments. Inadequate ventilation could increase the levels of suspended particulate matter in these two kitchen environments.

Fig. 5 illustrates the indoor and outdoor concentrations of airborne bacteria measured in the six homes. There was a large variation in indoor concentration of airborne bacteria among these six residences. The average levels of total bacteria counts recorded in the kitchen environments were greater than those in both living areas and outdoor air. The average concentrations of airborne bacteria in kitchens were $>23\%$ of the mean concentrations measured in living rooms. About 60% of the kitchen environments had an average concentration $>800\,CFU/m^3$. The results shows that outdoor concentrations of airborne bacteria ranged from 220 to $400\,CFU/m^3$. High concentrations of airborne bacteria that exceeded the HKIAQO Level II standard of $1000\,CFU/m^3$ were obtained in inadequately ventilated kitchens of Homes 2 and 4. In addition to the effect of ventilation, some factors including number of occupants living in the home, home age, and hygienic quality of the home and occupants. In comparison, Homes 2 and 4 had higher levels of airborne bacteria in their living rooms and kitchens, the elevated total bacteria counts were possibly linked to less frequency of household

cleaning and inadequate ventilation occurring in their crowded living environments. Correlation analysis was performed between indoor concentrations of airborne bacteria, number of occupants, home age, and some environmental parameters in living and kitchen areas. The results of the correlation coefficients are shown in Table 5. Average indoor total bacteria counts were reasonably correlated with the number of occupants in both areas. No significant associations between indoor bacteria levels and temperatures, relative humidity and building age were observed in these two indoor environments.

The 8-h average of indoor formaldehyde levels recorded in the living rooms and kitchen areas of the homes investigated were 16 and 14 $\mu g/m^3$, respectively. Fig. 6 shows the variation of indoor and outdoor concentrations of HCHO in selected homes. These two levels were both below the HKIAQO Level I standard. The mean outdoor concentration of HCHO in these residences was 7.7 $\mu g/m^3$ with a range from 3.2

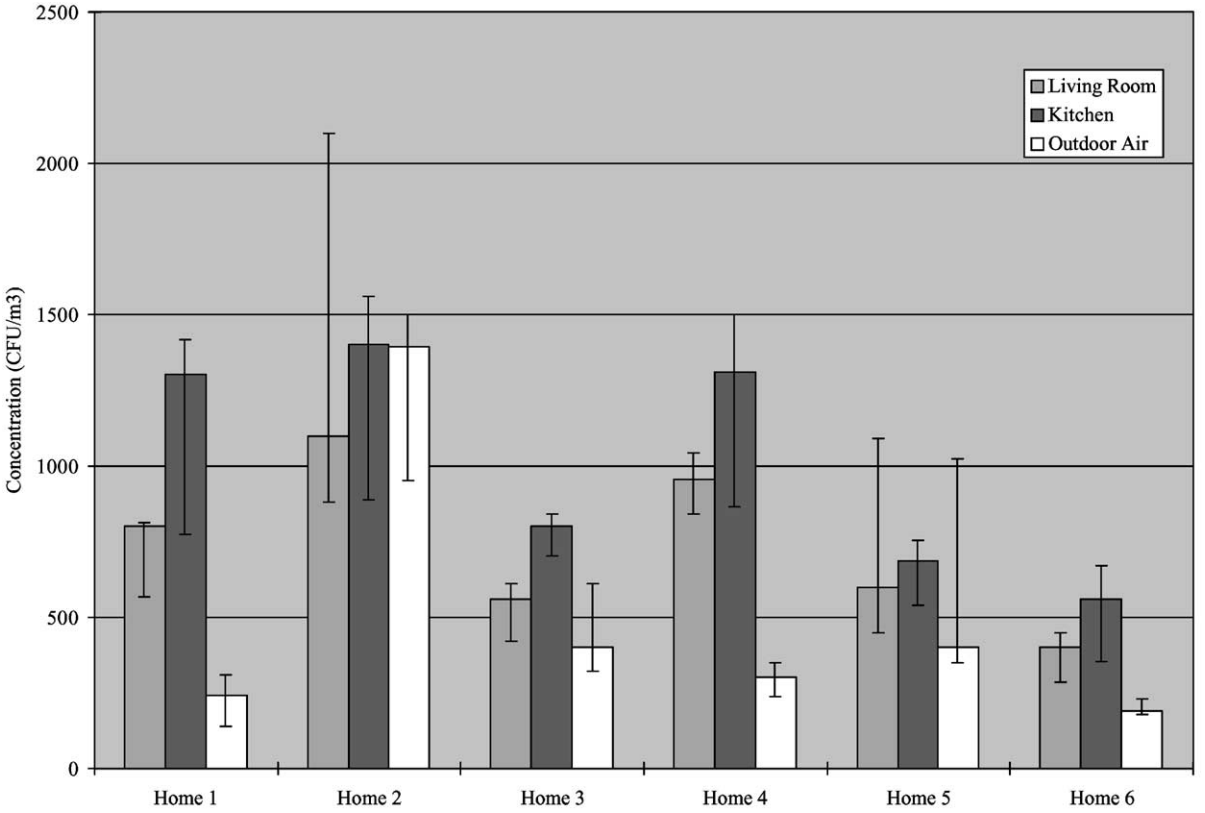

Fig. 5. Indoor and outdoor total bacteria count (TBC) in each domestic home.

Table 5
Correlation between indoor total bacteria count (TBC) and number of resident, building age and environmental parameters in both living rooms and kitchens[a]

	TBC (CFU/m^3)	Number of occupants	Home age (yr)	Room temperature (°C)	Relative humidity (%)
TBC (CFU/m^3)		0.78[b]	0.11	0.2	0.012
Number of occupant	0.72[b]		0.25	0.28	−0.24
Home age (yr)	0.23	0.25		0.38	−0.34
Room temperature (°C)	0.38	−0.1	0.58		−0.05
Relative humidity (%)	−0.29	−0.35	−0.59	−0.33	

[a] Upper triangular block represents the correlation in living rooms and lower triangular block represents the correlation in kitchens.
[b] $p<0.05$.

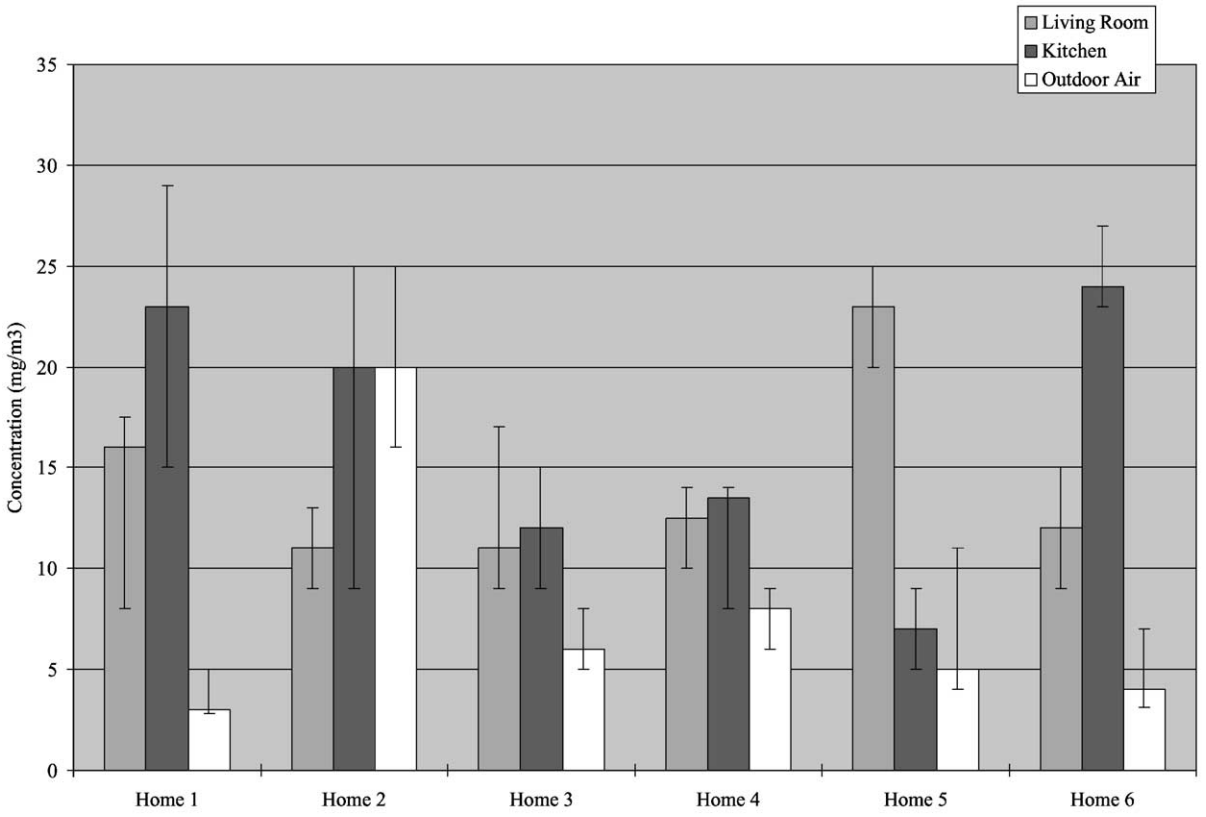

Fig. 6. Indoor and outdoor concentration of airborne formaldehyde in each domestic home.

to 20.1 μg/m^3. The mean ratios of indoor and outdoor concentrations were generally >1, indicating that indoor sources of formaldehyde were predominant in selected domestic environments. In home, new press wooden furniture, decorative wooden wall and floor covering are found to be potential sources of formaldehyde (Bayer and Black, 1989). During the periods of air sampling, none of the homes monitored had newly purchased wood furniture and furnishing constructed from pressed wood materials. The highest indoor HCHO level was observed at Home 1. The potential sources of HCHO in Home 1 are heavy smoking and Chinese incense burning in its small living room. Relatively higher outdoor level of HCHO above 20 μg/m^3 was observed in the roadside Home 2 due to the emission from industrial solvents at nearby garages and vehicle exhausts. Average indoor HCHO levels in the domestic environments in Hong Kong ranged from 11 to 22 μg/m^3. The formaldehyde levels in Hong Kong were similar to those in Australia (Garrett et al., 1999) but about twice as high as the HCHO concentrations in residential homes in Taiwan (Jia and Yao, 1993).

The most commonly found VOCs in the indoor air of the domestic environments were benzene, toluene, *m*, *p*-xylene, *o*-xylene, ethylbenzene, 1,3,5-trimethylbenzene, chloroform, methylene chloride, trichloroethene, 1,4-dichlorobenzene and tetrachloroethene. Table 6 (Environmental Protection Department, 1999) and Table 7 show the IAQ Objectives for Individual VOCs and the statistical summary of selected VOCs, respectively. All of the VOCs were below the HKIAQO Level I and II standards. Most of the VOCs investigated had similar

Table 6
Indoor air quality objectives for individual volatile organic compounds (Indoor Air Quality Management Group 1999)

Volatile organic compound (VOCs)	Levels 1 and 2 (μg/m^3)
Benzene	16.1
Formaldehyde	30,100
Carbon tetrachloride	103
Trichloroethylene	770
Tetrachloroethylene	250
Chloroform	163
1,2 (1,3)-Dichlorobenzene	500
1,4-Dichlorobenzene	200
Ethylbenzene	1447
Toluene	1092
Xylene	1447

concentrations in both living rooms and kitchens. Benzene, toluene, *m*,*p*-xylene, *o*-xylene, ethylbenzene and methylene chloride were found to be more abundant among the monitored VOCs. In comparison, indoor concentrations of benzene and *o*-xylene were more variable in living rooms than in kitchens. In addition, the influence of VOCs caused by smoking and the use of gas stoves on the IAQ of the homes investigated was evaluated by comparing I/O ratios of indoor and outdoor concentrations of the VOCs selected in both living and kitchen areas. Fig. 7 shows the comparison of I/O ratios of the monitored VOCs in homes with and without smokers. For most of the VOCs, the I/O ratios were higher in homes where smoking occurred than homes without smokers. Tobacco smoking could increase the levels of benzene, toluene and *m*,*p*-xylene. Cooking has also been regarded as an indoor source of VOCs. There are two major types of cooking stoves that are commonly used in Hong Kong households. One is liquefied petroleum gas (LPG) and the other one

Table 7
Statistical summary of the selected volatile organic compounds (VOCs) in the six homes[a]

VOCs (μg/m^3)	Living room				Kitchen area				Outdoor air			
	Maximum	Minimum	Mean	S.D.	Maximum	Minimum	Mean	S.D.	Maximum	Minimum	Mean	S.D.
Benzene	9.9	1.5	4.7	0.5	6.4	2.1	4.1	0.5	5.2	1	2	0.3
Toluene	77.2	26	52.1	8.4	80.1	26	58.6	9.9	142.5	1.7	40.3	14
m,*p*-xylene	7.7	1.6	3.9	1.2	9.2	1.5	5.2	1.6	21.4	2.5	6.2	1.7
o-xylene	10.8	1	4.5	0.4	7	3	4	0.7	12.5	1.1	4.1	2.4
Ethylbenzene	4.7	N.D.	2.6	0.8	6.6	1.3	3.6	0.4	15.7	0.6	4.8	1.8
1,3,5-trimethylbenzene	4.5	N.D.	1.8	0.4	4.4	1.1	1.7	0.4	4.9	0.1	2.2	0.9
Trichloroethene	2.1	N.D.	1.8	0.2	2.5	1.6	2.1	0.4	2	0.3	1.7	0.9
Tetrachloroethene	4.4	N.D.	2.5	0.2	3.9	N.D.	2.3	0.8	19.8	0.6	4.8	2.4
1,4-dichlorobenzene	4.3	1.2	2.6	0.3	4.4	1.2	3	0.4	6.5	1.5	2.9	1.9
Chloroform	3.6	1.6	2.6	0.9	4.9	1.9	3.1	0.2	1.9	N.D.	1.3	0.6
Methylene Chloride	10.2	6.8	8.8	0.8	11.9	8.1	8	0.8	21.9	0.9	9.5	1.5

[a] S.D., Standard deviation; N.D., Non-detectable.

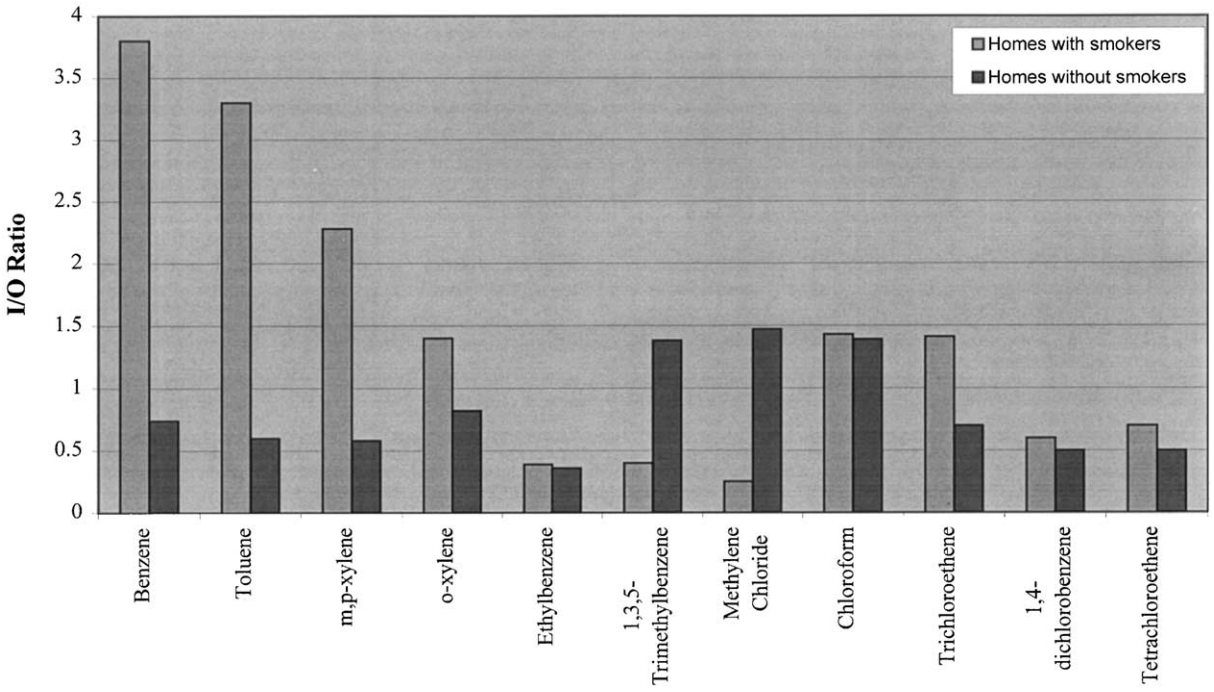

Fig. 7. Comparison of mean indoor and outdoor ratios of selected VOCs in domestic living rooms with and without smokers.

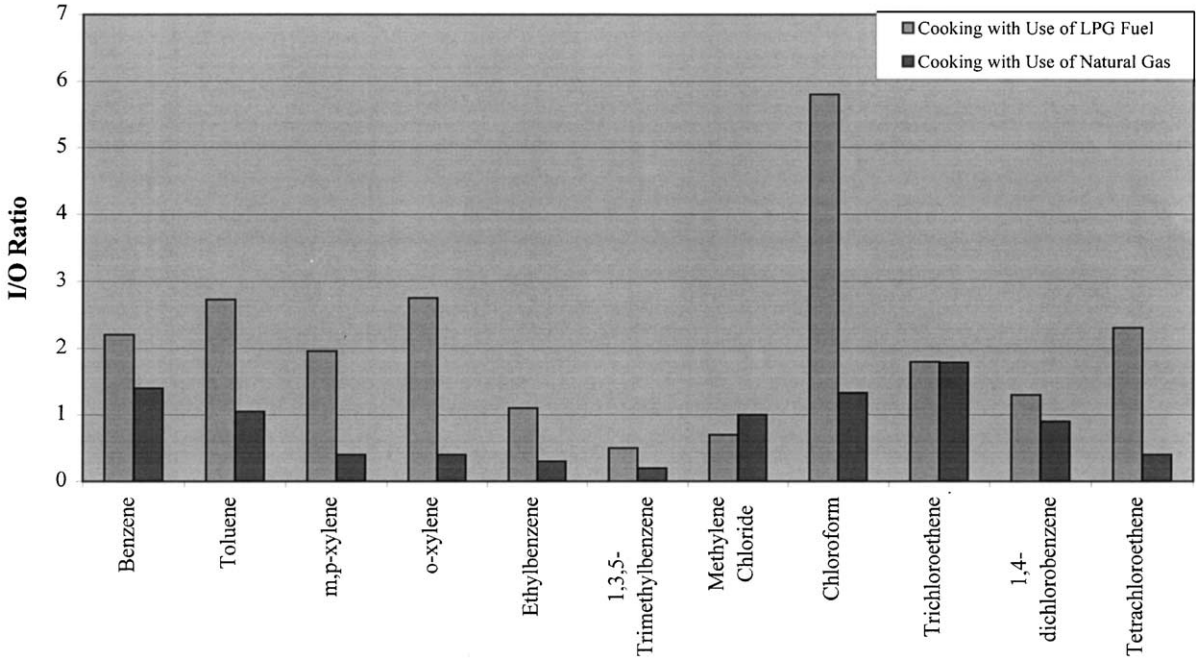

Fig. 8. Comparisons of mean indoor and outdoor ratios of selected VOCs in domestic kitchens.

employs natural gas for cooking. The impact of these two different types of gas stoves on VOC concentrations in the monitored domestic kitchens was studied. Fig. 8 indicates that the use of LPG gas stoves negatively affected indoor VOC levels in the domestic kitchens. The use of alternative fuel for cooking such as natural gas might improve the IAQ of a kitchen environment.

5. Conclusion

The 8-h average CO_2 and PM_{10} concentrations in the domestic kitchens exceeded those measured in the living rooms of the homes by 14% and 67%, respectively. In comparison, the CO_2 levels in living rooms indicated that the indoor CO_2 levels of homes with no smokers accounted for 80% of the CO_2 levels measured in smoking homes. Furthermore, the elevated levels of CO_2 in domestic kitchens were probably related to inadequate ventilation. The indoor air pollution caused by PM_{10} was more serious in the domestic kitchens than in the living rooms as almost all of the kitchens investigated had indoor PM_{10} concentrations exceeding the HKIAQO Level II standard of $180\,\mu g/m^3$.

The average concentrations of airborne bacteria obtained in approximately 60% of the domestic living rooms and kitchens were 20–40% higher than the HKIAQO Level I standard. The mean TBC recorded in the kitchens was greater than that obtained in the living rooms by 23%. Insufficient ventilation combined with a crowded indoor environment and reduced hygienic quality could elevate the indoor concentrations of airborne bacteria in a residential flat in Hong Kong. All of the homes surveyed had average indoor levels of HCHO below the HKIAQO Level 1 standard. The 8-h averages of HCHO measured in living room and kitchen were 16 and $14\,\mu g/m^3$, respectively. High HCHO levels recorded in the living rooms were related to tobacco smoking and burning Chinese incense. The adverse impacts arising from the elevated levels of benzene, toluene and *m*, *p*-xylene on the IAQ were intensified in a home where residents smoke, cooking with use of LPG gas stoves was possibly one of the factors contributing to the elevated levels of selected VOCs.

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