



Characteristics and health impacts of VOCs and carbonyls associated with residential cooking activities in Hong Kong

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ABSTRACT

Cooking emission samples collected in two residential kitchens were compared where town gas (denoted as dwelling A) and liquefied petroleum gas (LPG) (denoted as dwelling B) were used as cooking fuels. A total of 50 different volatile organic compounds (VOCs) were quantified during the 90 min cooking periods. None of any carcinogenic compounds like formaldehyde, acetaldehyde or benzene are detected in the raw fuels, confirming that those are almost entirely derived due to cooking activity alone. Alkenes accounted for approximately 53% of the total measured VOCs collected at dwelling A, while alkanes contributed approximately 95% of the VOCs at dwelling B during the cooking periods. The concentration of aromatic hydrocarbons such as benzene and toluene also increased during the cooking periods. The total amount of carbonyls emitted from the cooking processes at dwelling A (2708 μg) is three times higher than that at dwelling B (793 μg). Acetaldehyde was the most abundant carbonyl at the dwelling A but its emission was insignificant at the dwelling B. Carcinogenic risks on chronic exposure to formaldehyde, acetaldehyde, and benzene for housewives and domestic helpers were evaluated. Formaldehyde accounts for 68% and close to 100% of lifetime cancer risks at dwelling A and B, respectively.

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1. Introduction

A number of volatile organic compounds (VOCs) have been detected and their concentrations were much higher in indoor environment (i.e., residential area or working offices) than those of outdoor due to existence of indoor pollution sources [1]. The VOCs in a domestic environment originate from a variety of sources, including the utilization of consumer products (e.g., detergents and air fresheners), adhesives, furnishing and clothing, building materials, and incense burning [2,3].

Cooking processes can generate large quantities of harmful products, such as particulate matter (PM) [4], polycyclic aromatic hydrocarbons (PAHs) [5], VOCs [6] and carbonyls [7] when food is fried, stir-fried, or grilled using cooking oil at a high temperature. These pollutants have adverse health impacts on the city population and actively participate in atmospheric reactions [8]. Many studies have evaluated the amounts and chemical compositions of the fine PM emitted during food cooking processes [9–11].

Relatively less investigation of gaseous emissions from cooking activities has been done. Mugica et al. [6] reported the non-methane organic compounds (NMOC) composition of cooking emissions from restaurants, tortillerias, rotisseries and fried food places in Mexico. The results indicated that cooking emission is an important indoor pollution source of NMOC under crowded conditions in closed places. Another study [12] measured the emission rates of VOCs from commercial-scale meat charbroiling operations which ethylene, formaldehyde, and acetaldehyde were found to be the predominant products. In Hong Kong, Lee et al. [13] has investigated the indoor air quality (IAQ) of four restaurants, including a Korean barbecue style restaurant, a Chinese hot pot restaurant, a Chinese dim sum restaurant and a Western style canteen. The operations of pan-frying food and boiling food with soup in a hot pot were demonstrated to generate considerable quantities of gaseous pollutants. Moreover, it should be emphasized that the combustion of cooking fuels can also release various hazardous materials. For example, aromatic VOCs, mercury and trace metal were identified from barbecue charcoal combustion [14–16]. Ellegard investigated the association between exposure to air pollutants from cooking fuels (wood, charcoal, electricity and liquefied petroleum gas (LPG)) and health aspects [17].

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Table 1
A summary of dishes prepared in the domestic kitchens in this study.

Dish	Oils (amount)	Ingredients (amount)	Condiments (amount)	Cooking styles	Cooking duration (min)	Oil temp (°C)
Deep fried pork chops	Canola oil (200 mL)	Pork Chop (525 ± 25 g), egg (2 pieces)	Bread crumbs (124 ± 24.8 g), corn starch (16.7 g), salt (3.3 g), sugar (5.3 g)	Deep-fry	27.9 ± 3.7	164.0 ± 2.9
Curry chickens with potatoes	Canola oil (50 mL)	Chicken (500 ± 25 g), potato (350 g), water (200 ± 100 mL)	Curry powder (11.5 g), corn starch (5.6 g), salt (4.0 g), sugar (5.3 g)	Stir-fry and boil	28.4 ± 3.6	133.7 ± 8.8
Stir fried beefs with vegetables	Canola oil (50 mL)	Lean beef (150 g), Chinese cabbage (300 g), water (50 mL)	Sugar (prepare + cook) ^a [7.4 g (=5.3 + 2.1 g)], corn starch (prepare + cook) ^a [5.6 g (=2.8 + 2.8 g)], soy sauce (2 mL), salt (2.7 g)	Stir-fry	8.1 ± 1.1	143.5 ± 14.4
Stir fried Choy Sum ^b	Canola oil (50 mL)	Choy Sum ^b (600 g)	Salt (4.0 g)	Stir-fry	7.8 ± 1.8	134.8 ± 11.4
Steamed fish	Canola oil (15 mL)	Fish (350 ± 50 g), ginger (50 g), onion (10 g)	Soy sauce (15 mL), salt (2.7 g)	Stream	11 ± 1.8	97.1 ± 0.7
Red and green carrots with pork soup	None	Red carrot (450 g), green carrot (375 ± 25 g), pork (450 g), water (2.5 L)	Salt (13.3 g)	Boil	90	N.A. ^c

^a Condiments were used in both food preparation step and cooking processes.

^b A common vegetable available in Hong Kong market.

^c No oil was used to prepare this dish.

Carbonyl compounds have received more attention due to their potential adverse health effects on human and their important roles in atmospheric chemistry which can act as precursors to free radicals, ozone, and peroxyacyl nitrates [7]. A few studies have documented that cooking oils and combusting fuel under heating emitted a variety of hazardous airborne agents, such as benzene and carbonyls [18–21]. Ho et al. [7] have quantified 13 carbonyls in cooking exhausts from 15 commercial kitchens with various cooking styles. Formaldehyde was found to be the most abundant carbonyl with a contribution ranging from 12% to 60% to the total carbonyls. Schauer et al. [18] measured the emission rates of 14 alkanals (C₁–C₄ and C₆–C₁₅), three dicarbonyls (C₂–C₄), seven 2-alkanones (C₉–C₁₅ and C₁₆), and three 2-alkenals (C₃, C₁₀, and C₁₁) from frying vegetables in seed oils. Similar study [19] reported the emissions of seven alkanals (C₂–C₇ and C₉), eight 2-alkenals (C₃–C₁₀), and 2,4-heptadienal from heating canola oil and olive oil in cooking fumes using direct gas chromatographic (GC) analysis method.

Hong Kong is one of the most densely populated cities in the world. More than 70% people live in a small apartment with an area averagely <70 m² [22]. Due to limited landscapes, tall commercial and residential buildings are closely developed which blocks natural winds and leads inefficient exhausts and dilution from indoor to outdoor environment. As a result, any residential emission sources such as cooking process and incense burning would affect the IAQ in Hong Kong. In addition, unlike Western open-kitchen, the traditional residential kitchen is a close-door design. Toxic substances emitted from cooking would greatly affect the health of household cooks, mainly housewives and maids.

Toxicologists found that many hazardous airborne species emitted during cooking processes are potential human carcinogens [23]. Compared to other countries, the rate of lung cancer in Chinese women was relatively high [13,24]. The VOCs emissions from oils heated in woks are mutagenic in several in vitro short-term test systems and consistent positive associations are found between the risk of lung cancer and a variety of indices of exposure to indoor air pollution arising from Chinese-style cooking [25]. However, most of the studies only focused on commercial cooking exhausts. The emission profiles of residential cooking emissions are uncertain owing to many distinct differences between commercial and residential kitchens, such as ventilation systems, air exchange rates and cooking styles [26]. To our best knowledge, few studies are carried out on investigating the emission profiles of VOCs and

carbonyls from residential cooking processes, especially in Hong Kong.

In this study, the emission profiles of VOCs and carbonyls from cooking processes were determined in two residential kitchens using town gas and LPG as cooking fuels, respectively. Six typical local-style dishes were prepared inside the kitchens during the sampling. The amount of receipts and ingredients and the chef adopted are the same in the cross-sectional study. The lifetime cancer risks related to formaldehyde, acetaldehyde, and benzene exposure *via* inhalation for housewives and maids during cooking activities were evaluated as well.

2. Experimental

2.1. Sampling locations

Two typical dwellings in Hong Kong were selected in this study. Dwelling A, for a family of five members, is an apartment with a total flat area of 70 m². Its kitchen is equipped with a 4-head stove, which town gas was used as cooking fuel. The kitchen volume is 17.6 m³. Dwelling B is a two-resident apartment with a flat area of 48 m². Its kitchen is equipped with a 2-head stove and LPG was used as cooking fuel. The kitchen volume is 11.7 m³. No other indoor emission sources were found in the apartments and kitchens.

2.2. Sample collections and analysis

Sampling was conducted inside the kitchens. The sampling probes for collection of VOCs and carbonyls were directly placed 0.5 m above the cooking appliance. The air exchange rate was determined which has been discussed in Section 3.3. Four cooking emission samples plus background and field blank samples were collected at each dwelling on four sampling days. Six common local-style dishes were prepared during the sampling periods, including (1) deep fried pork chops, (2) curry chickens with potatoes, (3) stir fried beefs with vegetables, (4) stir fried Choy Sum (a common vegetable in Hong Kong), (5) steamed fish and (6) red and green carrots with pork soup. A summary of the dishes is shown in Table 1. The dishes prepared in this study covered the major domestic cooking styles in Hong Kong such as deep-fry, stir-fry, steam and boil. The quantities of foods were designed to serve as dinner for a family of six members. All ingredients and condiments were purchased from a local supermarket and their

amounts used were measured and consistent at each dwelling on every sampling date. Two stoves were used at the same time during the cooking periods. One stove was for boiling the soup (Dish 6) while the other one was for preparing other dishes (Dish 1–5). In order to have the best control of consistency between the two dwellings, the chef and the cooking times for every dish were the same. Electronic thermographs were taken to measure the oil temperature every time before the ingredients being poured into wok or pan. The total cooking times for the six dishes were 90 min. Background sample was collected at the same flow rate for 90 min inside the kitchen before the cooking activities were carried out. Trace VOCs in the LPG and town gas fuels were quantitatively detected by a GC/MS (6890 GC/5973 MS, Hewlett Packard, Palo Alto, CA) with the U.S. EPA TO-14 method [27]. In the LPG, no VOCs other than major components of pentane and butane were measured above detection limit. Our result is consistent with the findings of Mugica et al. [6]. However, a few VOCs were detected only as impurities in the town gas, including nonane (C_9H_{20}), 5-isopropylidene-1,3-cyclopentadiene (C_8H_{10}), 2,6-dimethyloctane ($C_{10}H_{22}$), 1,2,3-trimethylbenzene (C_9H_{12}), decane ($C_{10}H_{22}$), and undecane ($C_{11}H_{24}$).

Ambient volatile organic canister samplers (AVOCS) (Andersen Instruments Inc. Series 97-300, Atlanta GA) were used to collect VOCs into pre-cleaned and pre-evacuated 2-L stainless steel canisters at a flow rate of 22 mL min^{-1} for 90 min, which was identical to the whole cooking duration. The sampling flow rates were checked in the field before and after each run using a certificated flow meter (BIOS, model DryCal DC-Lite, Butler, NJ). After the sampling, the filled canisters were safely shipped to the laboratory of the University of California, Irvine (UCI) for analyses of carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and non-methane hydrocarbons (NMHCs) within two weeks. The stability of the target compounds was demonstrated by preparing a purified air filled canister injected with a known amount of certified gas mixture. A close to 100% recovery was shown for each of the target compounds. This demonstrates the VOCs are stable in such shipping and storage methods.

Carbon monoxide analyses were carried out using a hydrogen gas methanizer upstream of a gas chromatograph (HP 5890) equipped with a flame ionization detector (FID) and a 3 m molecular sieve column. Methane was also analyzed using an HP 5890 GC equipped with an FID detector. The samples were injected into an 1/8-in. stainless steel 0.9 m column packed with 80/100 mesh Sphercarb. The analytical system used to analyze NMHCs, halocarbons and alkyl nitrates involved the cryogenic pre-concentration of $1520 \pm 1 \text{ cm}^3$ (STP) of air sample in a stainless steel tube filled with glass beads (1/8-in. diameter) and immersed in liquid nitrogen (-196°C). A mass flow controller with a maximum allowed flow of 500 mL min^{-1} controlled the trapping process. The trace gases were revolatilized using a hot water bath and then reproducibly split into five streams directed to different detector/column combinations. Electron capture detectors (ECD, sensitive to halocarbons and alkyl nitrates), flame ionization detectors (FIDs, sensitive to hydrocarbons), and quadrupole mass spectrometer detectors (MSD, for unambiguous compound identification, selected ion monitoring) were employed. The first column-detector combination (abbreviated as “DB5ms/MSD”) was a DB-5ms column (J&W; 60 m, 0.25 mm I.D., 0.5 mm film thickness) output to a quadrupole MSD (HP-5973). The second combination (“DB1/FID”) was a DB-1 column (J&W; 60 m, 0.32 mm I.D., 1 mm film thickness) output to a FID (HP-6890). The third combination (“PLOT-DB1/FID”) was a PLOT column (J&W GS-Alumina; 30 m, 0.53 mm I.D.) connected in series to a DB-1 column (J&W; 5 m, 0.53 mm I.D., 1.5 mm film thickness) and output to an FID. The fourth combination (“Restek1701/ECD”) was a RESTEK 1701 column (60 m, 0.25 mm I.D., 0.50 mm film thickness) which was output to an ECD. The fifth combination

(“DB5-Restek1701/ECD”) was a DB-5 (J&W; 30 m, 0.25 mm I.D., 1 mm film thickness) column connected in series to a RESTEK 1701 column (5 m, 0.25 mm I.D., 0.5 mm film thickness) and output to an ECD. The DB5ms/MS, DB1/FID, PLOT-DB1/FID, Restek1701/ECD, and DB5-Restek1701/ECD combinations received 10.1%, 15.1%, 60.8%, 7.2%, and 6.8% of the sample flow, respectively.

Additional analytical details and the measurement detection limit, accuracy, and precision vary by compound and were quantified by Colman et al. [28]. Briefly, the detection limit is 5 ppbv for CO and CO_2 , 0.01–10 pptv for halogenated hydrocarbons, and 3 pptv for other NMHCs (CH_4 is always above its detection limit). The accuracy of our measurements is 5% for CO and CO_2 , 1% for CH_4 , 2–20% for halogenated hydrocarbons and 5% for other NMHCs. The measurement precision is 2% for CO and CO_2 , 2% for CH_4 , 1–5% for halogenated hydrocarbons, and ranges from 0.5% to 5% for other NMHCs.

An acidified 2,4-dinitrophenylhydrazine (DNPH) cartridges (Waters Sep-Pak DNPH-silica, Milford, MA) equipped with a Desert Research Institute (DRI) standard carbonyl sampler was used to collect carbonyls from the cooking emissions [29]. Carbonyls react with DNPH to form hydrazones which are analyzed using high pressure liquid chromatography (HPLC) with a ultra-violet (UV) detector. It has been established that ozone could lead to sampling artifacts in the determination of airborne carbonyls [30–32]. An ozone scrubber (Waters) was thus positioned upstream of the DNPH-silica cartridge. The flow rate passing through the DNPH-silica cartridge with the ozone scrubber was measured by the BIOS flow meter before and after the sampling. The samples were collected at a flow rate of 1 L min^{-1} for 90 min. After the sampling completed, the DNPH-silica cartridges were capped and wrapped in pouches provided by Waters and stored in a refrigerator at 4°C . Trace carbonyls in the LPG and town gas fuels were measured. In each raw fuel sample, no carbonyls were measured at quantifiable ranges.

Chemical analysis of DNPH-silica cartridges was carried out at Hong Kong University of Science and Technology (HKUST) within two weeks after samples were collected. Each DNPH-silica cartridge was eluted with 2.0 mL of acetone-free acetonitrile (HPLC/GC grade, Mallinckrodt Laboratory Chemicals, Phillipsburg, NJ) to a volumetric flask. Test has been done to demonstrate that no more DNPH and its derivatives remained in the cartridge after the 2 mL elution. Certified calibration standards of 15 DNPH-carbonyl hydrazones were purchased from Supelco (Bellefonte, PA) and diluted into concentration ranges of $0.05\text{--}5.0 \text{ mg mL}^{-1}$ for formaldehyde and $0.05\text{--}2.0 \text{ mg mL}^{-1}$ for the other carbonyls. Linearity was indicated by a correlation of determination (r^2) of at least 0.999. The samples and standards were analyzed by injecting $20 \mu\text{L}$ of the solutions to an HP gradient HPLC 1100 system (Santa Clara, CA) equipped with a photodiode array detector (DAD). The column for separation was a $4.6 \times 150 \text{ mm}$ Hypersil ODS $5 \mu\text{m}$ reversed phase column (Alltech, Deerfield, IL) at room temperature. The mobile phase consisted of two solvent mixtures: mixture A, 60:30:10 (v/v) of water/acetonitrile/tertahydrofuran; mixture B, 40:60 (v/v) of water/acetonitrile. The gradient program was 100% A for 1 min, followed by a linear gradient from 100% A to 100% B in 10 min. The flow rate was 1.5 mL min^{-1} for the first 15 min, increased to 1.7 mL min^{-1} in 2 min, and maintained at this flow until the end of the analysis. Absorbance at 360 nm was used for quantification of the DNPH-carbonyl derivatives. The Limit of Detection (LOD) was done by analyzing a minimum of seven replicates of a standard solution containing the analytes at a concentration of 0.02 mg mL^{-1} . It is estimated using the equation:

$$\text{LOD} = t(n-1, 1-\alpha=99\%) \times S, \quad (1)$$

where $t(n-1, 1-\alpha=99\%)$ is the Student's t -distribution value at $n-1$ degrees of freedom, and S is the standard derivation of the

Table 2
Carcinogenic potency factors for selected VOCs in the Integrated Risk Information System (IRIS)^a.

Volatile organic compounds	Carcinogenic potency factor (mg kg ⁻¹ day ⁻¹) ⁻¹
Formaldehyde	0.045
Acetaldehyde	0.0077
Benzene	0.029

^a [34].

replicates. The LODs of the target carbonyls ranged from 0.002 to 0.010 mg mL⁻¹, which can be translated to 1.8–11.7 ng with the assumption of a sampling volume of 0.09 m³.

2.3. Health risk calculation

The carcinogenic risks on chronic exposure to the VOCs and carbonyls were assessed in this study. The risk estimation with a cancer endpoint is expressed in terms of the probability of developing cancer from a lifetime of continuous exposure to a VOC or carbonyl. Chronic daily intake (CDI) of a carcinogenic contaminant was controlled by various factors, such as exposure frequency, exposure duration, and the body weight of the receptor. The equation used to calculate CDI in the unit of mg kg⁻¹ day⁻¹ is:

$$CDI = \frac{C_a \times IR \times ET \times EF \times ED}{BW \times AT \times 365}, \quad (2)$$

where C_a is the contaminant concentration (mg m⁻³), IR is the inhalation rate (m³ h⁻¹), ET is the exposure time (h day⁻¹), EF is the exposure frequency (day year⁻¹), ED is exposure duration (year), BW is the body weight (kg), and AT is the average lifetime (year). The United States Environmental Protection Agency (U.S. EPA) suggests standard values for the average body weight and the amount of air breathed per day for adults and children [33]. For adults, the exposures were converted to a daily dose by assuming 20 m³ inspired air per day and average body weights of 70 kg for men and 60 kg for women.

The lifetime cancer hazard risk (R) is calculated using the equation:

$$R = CDI \times PF, \quad (3)$$

where PF is the cancer potency factor in the unit of kg day⁻¹ mg⁻¹ of a specific cancer substance. The values of PF are obtained from the Integrated Risk Information System (IRIS) developed by U.S. EPA [34]. Table 2 shows the PF values for formaldehyde, acetaldehyde, and benzene.

3. Results and discussion

3.1. Volatile organic compounds

Forty-five VOCs were identified and quantified in the residential kitchen samples. These compounds include CO, CO₂, CH₄, 16 C₂–C₇ saturated hydrocarbons, 13 C₂–C₅ unsaturated hydrocarbons, and 13 C₆–C₉ aromatic hydrocarbons. Table 3 summarizes average concentrations of the VOCs in the background and cooking samples collected at the two dwellings.

It is noted that the concentrations of few compounds were higher in the background samples than those in the samples collected during cooking periods. Along these pollutants, their background concentrations are generally within or very close to the derivation of the mean sample concentrations. This proves that they are negligible in the cooking emissions. Exceptional cases are *n*-hexane, *m*-ethyltoluene, *o*-ethyltoluene, 1,3,5-trimethylbenzene and 1,2,4-trimethylbenzene at dwelling B. Much higher concentrations were found in the background samples. Certainly, the cooking

processes would not update or consume these compounds in the air. The phenomenon can be explained by the variations of sampling and analysis because only one background sample was collected.

It is not surprise that combustion products such as CO and CO₂ had sharp rise in concentrations during the cooking periods. Combustion of fuels (i.e., towngas and LPG) over cooking stoves is their major source. CO₂, a complete combustion product, had its concentrations elevated by a similar magnitude at the two dwellings. However, a different trend has been observed for the incomplete combustion products of CO. Its net increase was 175,543 μg at dwelling A versus a much higher values of 599,443 μg at dwelling B. The increase of CO may represent insufficient oxygen for the cooking fuel combustions. LPG, used at dwelling B, is a fraction from refining of petroleum mainly consisting of propane and butane [6]. The major constituents compositions of towngas used in dwelling A are much smaller molecules, including hydrogen (49%), CH₄ (28.5%), CO₂ (19.5%), and CO (3%) [35]. Fig. 1 shows the compositions of the cooking fuels used in this study. It is expected that complete combustion of LPG would be more difficult than that of towngas. Direct evaporation of the cooking fuel is also proved as another source of the VOCs released during the cooking period. The concentration of CH₄ increased at dwelling A but no any rise was found at dwelling B. The different emissions in CO might also be caused by the working conditions of the burners in the two kitchens. For the NMHCs, unsaturated hydrocarbons were the most abundant VOC species accounting for 53% of the total VOCs detected at dwelling A during the cooking processes, followed by saturated and aromatic hydrocarbons. At dwelling B, alkane was the most abundant species accounting for 95% of the total identified VOCs, followed by unsaturated and aromatic hydrocarbons.

Ethene was the most abundant unsaturated hydrocarbon with the net weight increases of 2255 and 2058 μg at dwelling A and B, respectively, during the cooking periods. As reported by Schauer et al., the non-methane C₁–C₁₀ VOC emissions from meat charbroiling consisted of 10.5% ethene, which was the highest one among other detected species [12]. This is consistent with findings in our study. Significant contribution increases in ethyne were also found at the two dwellings. Mugica et al. [6] interpreted that the presences of C₂ hydrocarbons, including ethane, ethene and ethyne, are the results of incomplete combustion products of meat, grease and charcoal used in restaurants, instead of combustion of cooking fuels. Their experiment demonstrated that the combustions of LPG contributed little to the existence of C₂ hydrocarbons.

For the saturated hydrocarbons, ethane, *n*-pentane, *n*-butane, *i*-butane and *n*-octane, in descending order, were the five dominant species in dwelling A while *n*-butane, *i*-butane, propane, ethane and *i*-pentane, in descending order, were dominant in dwelling B during the cooking period. Incomplete combustions of meat and grease are possible explanations for the high contributions of alkanes in the samples. Schauer et al. [12] reported the emission rate of ethane, ~663 mg kg⁻¹ of meat cooked, was the highest along the VOCs from meat charbroiling. Other emission rates of propane, *n*-butane and pentane were 190, 107 and 87 mg kg⁻¹, respectively, from meat charbroiling. Evaporation loss of cooking fuel is another source of alkanes. Sharp increases in abundances of propane, *n*-butane, and *i*-butane were found at dwelling B as they are the major components in the cooking fuel of LPG. The increases in abundances of propane, *n*-butane, and *i*-butane were insignificant at dwelling A. However, some species such as *n*-pentane, *n*-heptane, *n*-octane, 2-methylhexane and 3-methylhexane had slightly higher increases in abundances at dwelling A than that of dwelling B. Trace amounts of impurities in the different fuels may cause the small variations.

Benzene, toluene, and ethylbenzene are the three dominant aromatic hydrocarbons in the two kitchens. During the cooking periods, their increases in abundances were much significant at dwelling A than that of dwelling B. In addition, more other

Table 3
Comparisons of VOCs concentrations affected by the cooking activities in the kitchens of the two dwellings.

Chemicals	Dwellings A (towngas)			Dwellings B (LPG)			Net weight increased (μg) ^a	
	Background concentration ($\mu\text{g m}^{-3}$)	Cooking period concentration ($\mu\text{g m}^{-3}$)		Background concentration	Cooking period concentration ($\mu\text{g m}^{-3}$)			
		Mean	SD		Mean	SD		
CH ₄	837	1,797	222	16,889	805	783	234	–
CO	330	10,304	824	175,543	2,764	36,824	7,163	599,443
CO ₂	1,736	14,905	702	231,786	3,629	18,007	1,941	253,066
Non-methane hydrocarbon (NHMC)								
Alkane								
Ethane	0.8	21.6	4.5	366	13.1	46.1	9.2	386
Propane	2.5	7.3	3.5	84.7	964.4	3050	4.1	24,398
<i>i</i> -Butane	2.6	10.7	3.2	143	994.8	3225	5.1	26,092
<i>n</i> -Butane	3.3	15.3	5.8	211	2049	6242	5.5	49,055
<i>i</i> -Pentane	2.6	3.4	2.5	14.6	bd	29.1	4.8	340
<i>n</i> -Pentane	1.3	16.9	4.2	274	3.9	12.1	2.8	96.2
<i>n</i> -Hexane	28.9	26.9	13.4	– ^b	27.1	4.6	1.0	– ^b
<i>n</i> -Heptane	6.0	13.7	1.6	135	2.2	3.8	0.5	18.3
<i>n</i> -Octane	0.3	8.1	2.3	137	2.4	4.3	0.8	21.8
<i>n</i> -Nonane	0.5	1.0	0.4	8.0	4.5	4.3	1.1	– ^b
Decane	1.7	1.9	0.4	4.2	6.3	8.2	3.5	22.4
2,3-Dimethylbutane	22.0	21.3	13.2	– ^b	1.3	1.3	0.8	– ^b
2-Methylpentane	34.1	26.6	14.5	– ^b	1.4	1.6	0.8	2.2
3-Methylpentane	24.7	21.6	14.2	– ^b	0.9	0.9	0.7	– ^b
2-Methylhexane	0.9	2.7	1.8	31.6	1.6	0.8	0.3	– ^b
3-Methylhexane	1.2	3.4	1.9	37.2	1.4	0.8	0.4	– ^b
Alkenes								
Ethene	1.4	130	30.5	2,255	67.2	243	33.4	2,058
Ethyne	0.6	32.9	9.3	568	6.3	25.0	2.90	219
Propene	0.3	26.6	7.2	462	62.7	177	26.9	1,333
1-Butene	0.2	11.2	2.9	193	25.5	48.4	10.2	268
<i>i</i> -Butene	0.6	1.6	0.5	16.9	35.1	79.2	15.3	515
<i>trans</i> -2-Butene	0.1	0.5	0.10	7.1	11.9	29.6	6.8	207
<i>cis</i> -2-Butene	0.1	0.3	0.05	3.3	9.2	18.3	4.5	107
1,3-Butadiene	0.1	13.8	20.5	241	2.1	5.3	1.7	36.9
1-Pentene	1.4	79.8	0.9	1381	17.2	7.1	0.9	– ^b
Isoprene	7.1	6.2	0.10	– ^b	2.4	2.7	0.7	4.0
<i>trans</i> -2-Pentene	0.1	0.7	0.06	9.7	0.4	0.3	0.3	– ^b
<i>cis</i> -2-Pentene	0.1	0.4	2.3	5.5	0.2	0.2	0.2	0.1
2-Methyl-2-butene	0.2	0.2	0.4	– ^b	0.4	0.2	0.3	– ^b
Aromatic hydrocarbons								
Benzene	0.4	9.7	3.1	164	1.2	1.3	0.5	1.2
Toluene	29.3	40.2	13.4	192	23.5	27.6	3.2	48.0
Ethylbenzene	1.6	2.4	1.8	15.2	6.2	3.1	2.2	– ^b
<i>m</i> -Xylene	3.8	2.8	0.9	– ^b	6.5	2.7	1.8	– ^b
<i>p</i> -Xylene	1.2	1.2	0.8	– ^b	3.0	1.8	1.0	– ^b
<i>o</i> -Xylene	2.4	1.9	0.7	– ^b	5.0	2.6	0.7	– ^b
<i>iso</i> -Propylbenzene	0.05	0.10	0.07	0.8	0.7	0.3	0.3	– ^b
<i>n</i> -Propylbenzene	0.2	0.5	0.2	4.0	1.6	0.7	0.4	– ^b
<i>m</i> -Ethyltoluene	1.2	1.2	0.2	– ^b	7.5	2.9	0.6	– ^b
<i>p</i> -Ethyltoluene	0.07	0.08	0.08	0.3	0.4	0.2	0.2	– ^b
<i>o</i> -Ethyltoluene	0.6	0.6	0.2	– ^b	2.8	1.1	0.1	– ^b
1,3,5-Trimethylbenzene	0.5	0.4	0.2	– ^b	3.3	0.9	0.3	– ^b
1,2,4-Trimethylbenzene	3.7	2.5	0.4	– ^b	18.6	6.2	1.5	– ^b

^a Net amount increased was calculated as the net concentration increased multiplied by the kitchen volume.

^b The average concentration of the VOC in the cooking period was below its background sample.

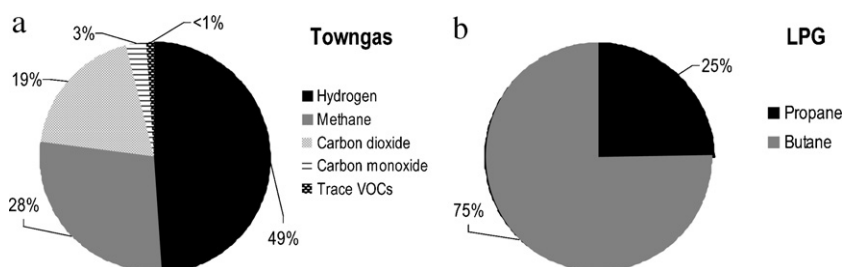


Fig. 1. Chemical compositions in raw cooking fuels: (a) towngas and (b) LPG.

Table 4

Comparisons of carbonyls concentrations affected by the cooking activities in the kitchens of the two dwellings.

Chemicals	Dwellings A (towngas)			Net amount increased (μg) ^a	Dwellings B (LPG)			
	Background concentration ($\mu\text{g m}^{-3}$)	Cooking period concentration ($\mu\text{g m}^{-3}$)			Background concentration ($\mu\text{g m}^{-3}$)	Cooking period concentration ($\mu\text{g m}^{-3}$)		Net amount increased (μg) ^a
		Mean	SD			Mean	SD	
Carbonyls								
Formaldehyde	26.7	60.4	30.4	592	100	151	45	590
Acetaldehyde	8.7	65.9	36.1	1,007	5.6	4.5	3.5	– ^b
Acetone	52.1	49.9	18.7	– ^b	bd	bd	bd	– ^b
Acrolein	bd	24.2	12.6	427	bd	17.7	6.7	207
Propionaldehyde	bd	21.4	13.4	376	bd	bd	bd	– ^b
Hexaldehyde	bd	48.7	35.4	857	11.6	15.7	3.2	48.5
Sum of carbonyls	87.5	241	33.6	2,708	117	185	45.3	793

^b The average concentration of the carbonyl in the cooking period was below its background sample.^a Net amount increased was calculated as the net concentration increased multiplied by the kitchen volume.

aromatic hydrocarbons such as ethylbenzene, *iso*-propylbenzene, *n*-propylbenzene and *p*-ethyltoluene were found to increase in abundances at dwelling A. However, the abundances of aromatic species except benzene and toluene did not increase at dwelling B during the cooking periods. Our findings were equivalent to previous reports that the emission of aromatic hydrocarbons was negligible in the combustion of LPG [6]. The existences of benzene and toluene at dwelling B can be ascribed to the ingredients adopted during the cooking processes. The sources of relatively higher contributions of aromatic hydrocarbon were uncertain at dwelling A. Evaporation loss of impurities in the fuels was a possible cause.

3.2. Carbonyls

The average carbonyls concentrations determined in the background and cooking emission samples collected in the kitchens were shown in Table 4. Any carbonyls excluded in the analytical list with U.S. EPA TO-11A method were not quantified in this study [36]. At the dwelling A, three carbonyls, including formaldehyde, acetaldehyde and acetone, were found in the background samples. Acetone was the most abundant carbonyl at an average concentration of $52.1 \mu\text{g m}^{-3}$. The average concentrations of formaldehyde and acetaldehyde were 26.7 and $8.7 \mu\text{g m}^{-3}$, respectively. During the cooking periods, three other carbonyls, including acrolein, propionaldehyde and hexaldehyde, were detected. Significant concentration increases were also shown for formaldehyde and acetaldehyde. Acetaldehyde was the most abundant carbonyl emitted from cooking with a net increase of $57.2 \mu\text{g m}^{-3}$. Hexaldehyde, undetectable in the background, was the next abundant carbonyl with an average concentration of $48.7 \mu\text{g m}^{-3}$. Other carbonyls, except for acetone, also had a range of 21.4 – $33.7 \mu\text{g m}^{-3}$ net increases. The concentrations of acetone remained unchanged. This represents that the domestic cooking activity using towngas as cooking fuel is unlikely a source of acetone.

At the dwelling B, formaldehyde, acetaldehyde and hexaldehyde were detected in the background samples. Formaldehyde, at an average of $100 \mu\text{g m}^{-3}$, was the most abundant carbonyl. The location of dwelling B is near a heavy traffic roadside. Vehicular emission is a possible source for the high abundance of formaldehyde in the background. During the cooking periods, in addition to the three carbonyls, acrolein was detected as well. Formaldehyde was the most abundant carbonyl in the cooking emission which had a net increase of $50.4 \mu\text{g m}^{-3}$. Acrolein was the next abundant carbonyl which was in an average concentration of $17.7 \mu\text{g m}^{-3}$. Hexaldehyde had a small net increase of $4.1 \mu\text{g m}^{-3}$ as well. However, there was no significant change in the concentrations of acetaldehyde. This demonstrates that the domestic LPG-cooking activity is not a pollution source of acetaldehyde. The increase of carbonyl concentrations during the cooking periods can be ascribed to emissions from stir-frying vegetables (Choy Sum), and also to stir-frying beefs with vegetables [37].

Fig. 2 compares the chemical compositions of the carbonyls emitted from the cooking activities in the two dwellings. Six carbonyls were found at dwelling A while only three at dwelling B. Formaldehyde was the dominant carbonyl at dwelling B which contributed 69% to the total carbonyls. A much lower contribution of formaldehyde, 18%, was found at dwelling A. Acetaldehyde was the dominant carbonyl in the cooking emissions at dwelling A which had a contribution of 31%, but it was not found at dwelling B. In addition, our results indicate significant contribution of acrolein, which were 13% and 25% at dwelling A and B, respectively. Frying foods in seed oil is a major source of acrolein [18]. Hexaldehyde had a contribution of 26% and 6% at dwelling A and B, respectively.

Table 4 also shows the net weights of carbonyls emitted from the cooking activities. The values were calculated as the net concentration changes multiplied by the kitchen volumes. The total weight of carbonyls emitted from the cooking at dwelling A is three times higher than that of dwelling B. Even though the emission amounts of formaldehyde were almost the same at the two dwellings, large

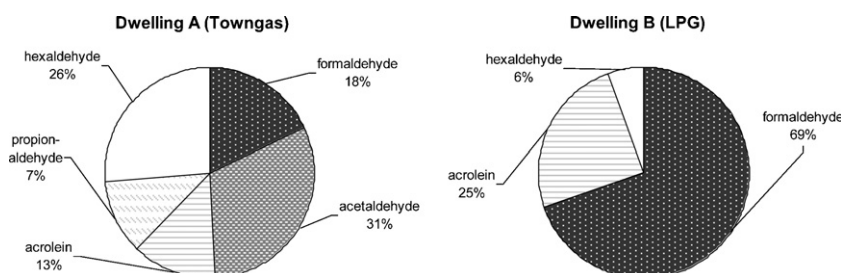
**Fig. 2.** Carbonyls compositions in cooking emissions at two residential dwellings.

Table 5
The estimated chronic dose intake (CDI) and lifetime cancer hazard risk in the two dwellings.

	Chronic dose intake (mg kg ⁻¹ day ⁻¹)		Lifetime cancer hazard risk	
	Dwelling A	Dwelling B	Dwelling A	Dwelling B
Formaldehyde	2.33 × 10 ⁻⁴	3.49 × 10 ⁻⁴	1.05 × 10 ⁻⁵	1.57 × 10 ⁻⁵
Acetaldehyde	3.96 × 10 ⁻⁴	–	3.05 × 10 ⁻⁶	–
Benzene	6.43 × 10 ⁻⁵	5.71 × 10 ⁻⁷	1.86 × 10 ⁻⁶	1.66 × 10 ⁻⁸

discrepancies were found for other carbonyls. Acetaldehyde was the highest emission carbonyl at the dwelling A with a net weight of >1000 µg, but its emission was not found in dwelling B. In addition, the net weights of acrolein and hexaldehyde at the dwelling A were 2 and 18 times, respectively, higher than that of dwelling B. Higher carbonyl emission values for towngas was possibly influenced by the impurities or adducts in the fuels.

3.3. Health risk assessment

Compared with ingestion and dermal absorption, inhalation is a major pathway for intake of VOCs by human. The World Health Organization (WHO) guideline for indoor formaldehyde is a 30-min average of 100 µg m⁻³ (81.8 ppbv) [38]. The formaldehyde levels in dwelling B surpassed the WHO guideline. The WHO guideline for acrolein is a 30-min average of 50 µg m⁻³ (21.7 ppbv). The acrolein levels in both dwelling A and dwelling B were >50% below the WHO guideline. The acetaldehyde levels in either dwelling A or dwelling B were also below the 24-h average tolerable concentration of 2000 µg m⁻³ (1.11 ppmv) set by WHO.

On the contrary, potential health risks for three organic compounds, including formaldehyde, acetaldehyde and benzene, were examined owing to their high abundances in the residential cooking emissions and carcinogenicity classified by U.S. EPA [34]. Housewives and maids, groups of women who work in residential kitchens daily, are thus our targets for the assessment.

Inhalation exposure is always related to exposure frequency, duration, and activity pattern. They are all essential factors in calculations of the chronic daily intake and the lifetime cancer hazard risk. Few assumptions have been taken which suggested by U.S. EPA in the relative carcinogenic assessment. The volume of air inspired per day is 20 m³ day⁻¹ for a woman while the absorption factor of the VOCs is 90%. A housewife spends 4 h every day in her 40 housework-years. In addition, the average body weight of 60 kg and average lifetime of 70 years are assumed for a woman. However, the health risk will be overestimated because no additional ventilation system was turned on and all windows and doors in the kitchens were closed during our sampling. The air exchange rate (AER, *a*) in the kitchen was calculated based on CO₂ decay rates using the equation of [39]:

$$a = \frac{1}{t} \ln \frac{C_t}{C_0}, \quad (4)$$

where *t* is time, *C_t* and *C₀* are concentrations of the CO₂ at times *t* and 0, respectively. The estimated AER for the residential dwelling was 4.13 ± 2.21 h⁻¹ assuming all the windows and door were open and exhaust fan was in operation. The AER factor was taken in the calculation of cancer risk. The chronic daily intake and the lifetime cancer hazard risk for formaldehyde, acetaldehyde and benzene are estimated in Table 5. The risk below one in a million (<1 × 10⁻⁶) is usually considered under a concern level while the risk above 100 in a million (>1 × 10⁻⁴) represent instant actions or interventions are necessary to protect human health [40]. Our results demonstrate that formaldehyde has the highest cancer risk to women who work in the residential kitchens. The lifetime cancer hazard risks associated with formaldehyde in dwelling A and B are 1.05 × 10⁻⁵ and 1.57 × 10⁻⁵, respectively. The risks associated with acetalde-

hyde in dwelling A is 3.05 × 10⁻⁶. Even though the estimated risks of formaldehyde and acetaldehyde from exposure in the residential kitchens do not reach to an extremely danger level, their health impact is not negligible. Benzene imposes less cancer risks as its relatively lower abundances in the cooking emissions. The cancer risk associated with benzene is 1.86 × 10⁻⁶ in dwelling A, which is two orders of magnitude higher than that in dwelling B (1.66 × 10⁻⁸). Formaldehyde contributes most to lifetime cancer hazard risks in the two residential kitchens, accounting for 68% and nearly 100% for dwelling A (towngas) and dwelling B (LPG), respectively. In dwelling A, the contribution ratio of benzene and acetaldehyde to lifetime cancer hazard risks are 12% and 20%, respectively.

4. Conclusion

The concentrations of VOCs and carbonyls were measured at significant levels in the dwellings during the cooking periods. Unsaturated hydrocarbons were the most abundant VOC species accounting for 53% of the total VOCs detected at dwelling A during the cooking processes, followed by saturated and aromatic hydrocarbons. At dwelling B, alkane was the most abundant species accounting for 95% of the total identified VOCs, followed by unsaturated and aromatic hydrocarbons. Direct evaporation losses of cooking fuels were found, which suggests better regulations of household cooking appliances are needed. The contents of cooking fuels either in towngas or LPG harm human health (such as CO) and potentially could react with other VOCs to generate other toxic and reactive chemicals. Incomplete combustion of meat and grease is another source of the C₂ saturated and unsaturated hydrocarbons emitted from the cooking processes. The cooking processes also generated high abundances of aromatic compounds such as benzene and toluene. Different carbonyl emission profiles were determined with using towngas and LPG as the cooking fuels. Carcinogenic compounds such as formaldehyde, acetaldehyde and benzene were significantly produced from the residential cooking activities, which were not measured in the raw fuels. The lifetime cancer hazard risks associated with formaldehyde in dwelling A and B are 1.05 × 10⁻⁵ and 1.57 × 10⁻⁵, respectively. Formaldehyde contributes most to lifetime cancer hazard risks in the two residential kitchens, with the ratio of 68% and nearly 100% for dwelling A (towngas) and dwelling B (LPG), respectively. Even though their emissions from individual household kitchens were much less than that from commercial restaurants or food manufacturers, the potential health risks to housewives and maids who are exposed to the emissions on a daily basis is not negligible. Regulations for the toxic substances emission from the cooking activities, especially for commercial cooking, should be taken in order to protect human health and environment.

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References

- [1] C.P. Weisel, S. Alimokhtari, P.F. Sanders, Indoor air VOC concentrations in suburban and rural New Jersey, *Environ. Sci. Technol.* 42 (2008) 8231–8238.
- [2] S.C. Lee, B. Wang, Characteristics of emissions of air pollutants from burning of incense in a large environmental chamber, *Atmos. Environ.* 38 (2004) 941–951.
- [3] H. Guo, F. Murray, S. Wilkinson, Evaluation of total volatile organic compound emissions from adhesives based on chamber tests, *J. Air Waste Manage. Assoc.* 50 (2000) 199–206.
- [4] L.M. Hildemann, G.R. Markowski, G.R. Cass, Chemical composition of emissions from urban sources of fine organic aerosol, *Environ. Sci. Technol.* 25 (1991) 744–759.
- [5] Y. Chen, K.F. Ho, S.S.H. Ho, W.K. Ho, S.C. Lee, J.Z. Yu, E.H.L. Sit, Gaseous and particulate polycyclic aromatic hydrocarbons (PAHs) emissions from commercial restaurants in Hong Kong, *J. Environ. Monit.* 9 (2007) 1402–1409.
- [6] V. Mugica, E. Vega, J. Chow, E. Reyes, G. Sanchez, J. Arriaga, R. Egami, J. Watson, Speciated non-methane organic compounds emissions from food cooking in Mexico, *Atmos. Environ.* 35 (2001) 1729–1734.
- [7] S.S.H. Ho, J.Z. Yu, K.W. Chu, L.L. Yeung, Carbonyl emissions from commercial cooking sources in Hong Kong, *J. Air Waste Manage. Assoc.* 56 (2006) 1091–1098.
- [8] J.R. Odum, T. Hoffmann, F. Bowman, D. Collins, R.C. Flagan, J.H. Seinfeld, Gas/particle partitioning and secondary organic aerosol yields, *Environ. Sci. Technol.* 30 (1996) 2580–2585.
- [9] D.A. Olson, J.M. Burke, Distributions of PM_{2.5} source strengths for cooking from the Research Triangle Park particulate matter study, *Environ. Sci. Technol.* 40 (2006) 163–169.
- [10] Y.L. Zhao, M. Hu, S. Slanina, Y.H. Zhang, The molecular distribution of fine particulate organic matter emitted from Western-style fast food cooking, *Atmos. Environ.* 41 (2007) 8163–8171.
- [11] Y. Zhao, M. Hu, S. Slanina, Y. Zhang, Chemical compositions of fine particulate organic matter emitted from Chinese cooking, *Environ. Sci. Technol.* 41 (2007) 99–105.
- [12] J.J. Schauer, M.J. Kleeman, G.R. Cass, B.R.T. Simoneit, Measurement of emissions from air pollution sources. 1. C₁ through C₂₉ organic compounds from meat charbroiling, *Environ. Sci. Technol.* 33 (1999) 1566–1577.
- [13] S.C. Lee, W.M. Li, L.Y. Chan, Indoor air quality at restaurants with different styles of cooking in metropolitan Hong Kong, *Sci. Total Environ.* 279 (2001) 181–193.
- [14] E. Kabir, K.-H. Kim, J.-W. Ahn, O.-F. Hong, J.R. Sohn, Barbecue charcoal combustion as a potential source of aromatic volatile organic compounds and carbonyls, *J. Hazard. Mater.* 174 (2010) 492–499.
- [15] S.K. Pandey, K.-H. Kim, C.-H. Kang, M.C. Jung, H. Yoon, BBQ charcoal as an important source of mercury emission, *J. Hazard. Mater.* 162 (2009) 536–538.
- [16] J. Susaya, K.-H. Kim, J.-W. Ahn, M.-C. Jung, C.-H. Kang, BBQ charcoal combustion as an important source of trace metal exposure to humans, *J. Hazard. Mater.* 176 (2010) 932–937.
- [17] A. Ellegard, Cooking fuel smoke and respiratory symptoms among women in low-income areas in Maputo, *Environ. Health Perspect.* 104 (1996) 980–985.
- [18] J.J. Schauer, M.J. Kleeman, G.R. Cass, B.R.T. Simoneit, Measurement of emissions from air pollution sources. 4. C-1-C-27 organic compounds from cooking with seed oils, *Environ. Sci. Technol.* 36 (2000) 567–575.
- [19] A. Fullana, A.A. Carbonell-Barrachina, S. Sidhu, Volatile aldehyde emissions from heated cooking oils, *J. Sci. Food Agric.* 84 (2004) 2015–2021.
- [20] X. Zhu, K. Wang, J. Zhu, M. Koga, Analysis of cooking oil fumes by ultraviolet spectrometry and gas chromatography mass spectrometry, *J. Agric. Food Chem.* 49 (2001) 4790–4794.
- [21] K. Umamo, T. Shibamoto, Analysis of acrolein from heated cooking oils and beef fat, *J. Agric. Food Chem.* 35 (1987) 909–912.
- [22] D.H.W. Li, S.L. Wong, C.L. Tsang, G.H.W. Cheung, A study of the daylighting performance and energy use in heavily obstructed residential buildings via computer simulation techniques, *Build. Environ.* 38 (2006) 1343–1348.
- [23] P.G. Shields, G.X. Xu, W.J. Blot, J.F.J. Fraumeni, G.E. Trivers, E.D. Pellizzari, Y.H. Qu, Y.T. Gao, C.C. Harris, Mutagens from heated Chinese and US cooking oils, *J. Natl. Cancer Inst.* 87 (1995) 836–841.
- [24] A. Seow, W.T. Poh, M. Teh, P. Eng, Y.T. Wang, W.C. Tan, M.C. Yu, H.P. Lee, Fumes from meat cooking and lung cancer risk in Chinese women, *Cancer Epidemiol. Biomarkers Prev.* 9 (2000) 1215–1221.
- [25] L. Zhong, M.S. Goldberg, M. Parent, J.A. Hanley, Risk of developing lung cancer in relation to exposure to fumes from Chinese-style cooking, *Scand. J. Work Environ. Health* 25 (1999) 309–316.
- [26] A.C.K. Lai, Y.W. Ho, Spatial concentration variation of cooking-emitted particles in a residential kitchen, *Build. Environ.* 43 (2008) 871–876.
- [27] U.S. EPA, Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air: Determination of Volatile Organic Compounds (VOCs) in Ambient Air using Specially Prepared Canisters with Subsequent Analysis by Gas Chromatography, second edition, Centre for Environmental Information, Office of Research and Development, U.S. EPA, Cincinnati, OH, 1999.
- [28] J.J. Colman, A.L. Swanson, S. Meinardi, B.C. Sive, D.R. Blake, F.S. Rowland, Description of the analysis of a wide range of volatile organic compounds in whole air samples collected during PEM-Tropics A and B, *Anal. Chem.* 73 (2001) 3723–3731.
- [29] K.F. Ho, S.C. Lee, C.M.Y. Gloria, Characterization of selected volatile organic compounds, polycyclic aromatic hydrocarbons and carbonyl compounds at a roadside monitoring station, *Atmos. Environ.* 36 (2002) 57–65.
- [30] R.R. Arnts, S.B. Tejada, 2,4-Dinitrophenylhydrazine-coated silica gel cartridge method for determination of formaldehyde in air: identification of an ozone interference, *Environ. Sci. Technol.* 23 (1989) 1428–1430.
- [31] T.E. Kleindienst, E.W. Corse, F.T. Blanchard, W.A. Lonneman, Evaluation of the performance of DNPH-Coated silica gel and C18 cartridges in the measurement of formaldehyde in the presence and absence of ozone, *Environ. Sci. Technol.* 32 (1998) 124.
- [32] M. Pires, L.R.F. Carvalho, An artifact in air carbonyls sampling using C-18 DNPH-coated cartridge, *Anal. Chim. Acta* 367 (1998) 223.
- [33] U.S. EPA, Methods for Derivation of Inhalation Reference Concentrations and Application of Inhalation Dosimetry, Office of Health and Environmental Assessment, Environmental Criteria and Assessment Office, Research Triangle Park, NC, 1994, EPA/600/8-90/066F.
- [34] U.S. EPA, Integrated Risk Information System, <http://www.epa.gov/iris>, 1998.
- [35] Hong Kong Towngas Limited, Chemical Compositions of Towngas, Hong Kong Towngas Limited, Hong Kong, 2010, <http://www.towngas.com/tgweb/txtchi/ab.towngas/bus.gas.production.asp>, Hong Kong Towngas Limited.
- [36] U.S. EPA, Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air, Method TO-11A, Center for Environmental Research Information, Office of Research and Development, U.S. EPA, Cincinnati, OH, 1999.
- [37] J.J. Schauer, M.J. Kleeman, G.R. Cass, B.R.T. Simoneit, Measurement of emissions from air pollution sources. 4. C-1-C-27 organic compounds from cooking with seed oils, *Environ. Sci. Technol.* 36 (2002) 567–575.
- [38] World Health Organization (WHO), Guidelines for Air Quality, WHO, Geneva, Switzerland, 2000.
- [39] M.B. Nantka, Air Change Rate and Airtightness in Buildings, ASTM STP 1067, American Society for Testing and Materials, Philadelphia, 1990.
- [40] C.W. Lee, Y.T. Dai, C.H. Chien, D.J. Hsu, Characteristics and health impacts of volatile organic compounds in photocopy centers, *Environ. Res.* 100 (2006) 139–149.