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Indoor air quality at restaurants with different styles of cooking in metropolitan Hong Kong

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Abstract

Indoor air quality (IAQ) of a restaurant has increasingly received a lot of public concerns in Hong Kong. Unfortunately, there is limited data about the IAQ of Hong Kong restaurants. In order to characterize the current IAQ of local restaurants, four restaurants in metropolitan Hong Kong including a Korean barbecue style restaurant, a Chinese hot pot restaurant, a Chinese dim sum restaurant and a Western canteen were selected for this study. The results of this study showed that the mean concentrations of CO_2 at restaurants with gas stoves for food cooking in dining areas exceeded the range from 40 to 60% indoor CO_2 concentrations at restaurants without gas stoves in dining areas. The average levels of PM_{10} and $PM_{2.5}$ at the Korean barbecue style restaurant were as high as 1442 and 1167 $\mu g/m^3$, respectively. At the Korean barbecue and Chinese hot pot restaurants, the levels of $PM_{2.5}$ accounted for 80–93% of their respective PM_{10} concentrations. The 1-h average levels of CO observed at Korean barbecue style and hot pot restaurants were 15100 and 8000 $\mu g/m^3$, respectively. Relatively high concentrations of CO_2, CO, PM_{10}, $PM_{2.5}$ benzene, toluene, methylene chloride and chloroform were measured in the dining areas of the Korean barbecue style and the Chinese hot pot restaurants. The operations of pan-frying food and boiling food with soup in a hot pot could generate considerable quantities of air pollutants. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Indoor air quality (IAQ); Restaurant; Frying food; Hot-pot cooking; Dim sum meal; Volatile organic compounds (VOCs)

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1. Introduction

Hong Kong is one of the most popular food paradises in the world. Different restaurants with different cooking methods such as barbecue cooking, hot pot cooking and dim sum cooking provide customers with a variety of food choices in the metropolitan city. Restaurants can be considered to be 'public' indoor environments where many local and foreign people tend to spend a lot of their time. Indeed, for Hong Kong citizens, a dim sum meal is a fundamental element of Hong Kong society. Therefore, a healthy and comfortable indoor environment of a restaurant is very important. A good indoor air quality in a restaurant not only enhances the enjoyment of the restaurant surroundings, but also protects the health of restaurant workers and customers from exposure to harmful air pollutants.

Many cooking methods involve the use of a wide variety of cooking oils. Unfortunately, a study has documented that heated cooking oils emit a variety of hazardous airborne agents, some of these airborne species are proved to be potential human or laboratory animal carcinogens such as benzene and formaldehyde (Shields et al., 1995; Li et al., 1994). Earlier studies in western countries found that restaurant cooks had an increased risk of lung cancer as they were constantly exposed to cooking stove smoke in kitchens (Coggon et al., 1986; Dubrow and Wegman, 1984). Chinese cooking, which uses a lot of oil, is a major cooking method in many Chinese restaurants. Stir-frying food in a wok is the most common food preparation process in Chinese cooking. A previous study in Italy identified that air pollutants that were harmful to human health could be released by cooking oils heated to the similar temperatures to those found in wok cooking (Benfenati et al., 1998). Compared to other countries, the rate of lung cancer in women is higher than that in men in Asian countries even though Asian women have a lower rate of smoking. One possible answer to this question is that Chinese women are more exposed to cooking fumes that contain a variety of airborne carcinogens (Zhong et al., 1999; Benfenati et al., 1998; Shields et al., 1995). If a restaurant, where Chinese cooking methods are used for food preparation at both dining area and kitchen are inadequately ventilated, the food service workers and customers will be easily exposed to the cooking smoke generated.

Korean barbecued food has become very popular, so there are many Korean barbecue-style restaurants in Hong Kong. The use of steel frying pans on which customers fry their food in hot oil is common in this type of restaurant. Sung-OK et al. (1997) found that elevated indoor levels of respirable suspended particulates (RSP) and carbon monoxide (CO) were obtained at Korean barbecue-cooking restaurants. It was found that the use of charcoal burners degraded indoor air quality and elevated average indoor levels of RSP and CO in these restaurants. The indoor air pollution of these restaurants became serious during the winter when the windows and doors of the restaurants were closed. Although the frying pan is different from the charcoal burner, it can be used to heat food to high temperatures and more indoor pollutants will be released. RSP, CO and VOCs are common air contaminants emitted from frying food on a hot steel pan and broiling food on steel bars above a charcoal burner (Benfenati et al., 1998; Shields et al., 1995; Sung-OK et al., 1997).

In winter, many Chinese hot pot restaurants in Hong Kong are always full. The restaurants use cookstoves, which use liquefied petroleum gas (LPG), on customer's tables for heating pots in which food is boiled in soup. Zhang and Kirk (1999) reported that the LPG cookstoves commonly used in China usually generate more formaldehyde than natural gas and kerosene gas stoves. Some studies reported that elevated formaldehyde concentrations in cooking smoke were measured during cooking hours (Raiyani et al., 1993; Zhang and Kirk, 1999). At Hong Kong Korean barbecue restaurants and hot pot restaurants, the exposure to indoor formaldehyde may be greatly enhanced as their customers cook their own foods on gas cookstoves which are put on customers' tables. Also, total suspended particulate (TSP), carbon monoxide (CO) and formaldehyde (HCHO) were found to be major air pollutants in cooking smoke emitted from the use of

LPG gas stoves in domestic kitchens (Raiyani et al., 1993; Li, 1994).

The indoor air quality in restaurants has become a matter of public concern, as people are more aware that restaurants may contain harmful indoor air pollutants. Unfortunately, there are only few studies intended to characterize and compare indoor levels of air pollutants identified in different cooking styles of restaurants in Hong Kong. Little data are available on the general understanding of indoor air quality at restaurants. Therefore, the objectives of this study are to determine indoor concentrations of selected air pollutants at different types of restaurants in Hong Kong and compare the results with health related Hong Kong indoor air quality objectives (HKIAQO) that are currently used in Hong Kong for IAQ management (EPD, 1999). Also it is intended to evaluate the impact of different cooking methods on the indoor air quality in restaurants.

2. Materials and methods

2.1. Site selection

The study of a total of four restaurants in metropolitan Hong Kong was conducted from April 2000 to July 2000. All these restaurants are different in size and cooking style. They included a Korean barbecuing restaurant (Rest. 1), a Chinese hot-pot restaurant (Rest. 2), a Chinese dim Sum restaurant (Rest. 3) and a Western Canteen (Rest. 4). All of these restaurants are ventilated using central air-conditioning systems. In addition, each of them is located in an urban commercial area with high traffic density. All of the restaurants were occupied during the periods of air sampling. General characteristics of these four restaurants are listed in Tables 1 and 2.

2.2. Sampling and analytical methods

The air pollutants investigated in this study included: carbon dioxide (CO_2); carbon monoxide (CO); volatile organic compounds (VOCs); formaldehyde (HCHO); total hydrocarbon (THC); and respirable particulate matter (PM_{10} and $PM_{2.5}$). Air monitoring works were carried out during the peak hour of each restaurant. Air samples were collected between 19.00 and 21.00 h (dinner) from the Korean barbecue restaurant, Chinese hot pot restaurant and Western Canteen. Air measurement was carried out between 12.00 and 14.00 h (lunch) at the Chinese dim sum restaurant. Air samples were collected on two occasions at each restaurant. Simultaneous indoor and outdoor air sampling occurred at each sampling site. Indoor air samples were collected as near to the central positions of the main dining areas of restaurants as possible. At the same time, outdoor air samples were taken at streets in close proximity to the fresh air intakes. Although there were no restriction in smoking in the monitored restaurants, no smoking activities were observed in the dining areas of these restaurants during air sampling. All air monitors and samplers were placed at 1.5 m above the ground and away from potential sources of air pollutants in each sampling location.

The air bag sampling method was used to sample CO and THC. The sampled air was drawn

Table 1
General comparisons of the four restaurants investigated

Site no.	Type of restaurant	Floor	Average area (m^2) of each floor	Dinning area with or without partition	No. of food service workers	Maximum no. of seats accommodated
Rest1	Korean barbecue	2nd	210	With partition	10	70
Rest2	Chinese hot pot	3rd	590	Without partition	30	120
Rest3	Chinese dim sum	4th	250	Without partition	11	100
Rest4	Western cafeteria	3rd	320	Without partition	14	85

Table 2
General characteristics of the four restaurants investigated

Site no.	Types	Use of cooking oil	Use of gas stove	Way of cooking
Rest. 1	Korean barbecue	Peanut oil	LPG	Frying food in oil on a hot frying pan in its dining area.
Rest. 2	Chinese hot pot	Peanut oil	LPG	Boiling food in soup inside a hot pot in its dining area.
Rest. 3	Chinese dim sum	Peanut oil	Natural gas	Streaming dim sum meal in a fixed food court in its dining area.
Rest. 4	Western cafeteria	Peanut oil	Natural gas	Food prepared in its kitchen and no combustion sources are present in its dining area.

into three 25-l Tedlar bags by a portable air pump (Model HFS-513A, Gilian Ltd.) at a flow rate of 1 l/min for 1 h. After air sampling, the air bags were put into a large black plastic bag to avoid direct exposure to bright light during transportation to the air laboratory for analysis. The air samples were analyzed with a Thermo Electron Gas Filter Correlation CO Ambient Analyzer (Model 48, Thermo Environmental Instruments Inc.). A Methane (MHC) and Non-Methane hydrocarbon (NMHC) analyzer (Model 55, Thermo Environmental Instruments Inc.) analyzed total hydrocarbon (THC). Prior to sampling, the air bags used for sampling were flushed with zero air several times in order to minimize the background contamination.

A TSI portable Q-Trak (Model 8550, TSI Inc.) was used to monitor the indoor and outdoor CO_2 concentrations. The CO_2 analyzer is able to detect CO_2 based on the detection mechanism of non-dispersive infrared. A Dust-Trak air monitor (Model 8520, TSI Inc.) is used to measure PM_{10} and $PM_{2.5}$ concentrations in both indoor and outdoor air, respectively. Basically, the monitor can measure particulate matters with the method of light scattering. The Dust monitor measured PM_{10} and $PM_{2.5}$ at 1-min intervals at a flow-rate of 1.7 l/min. Before sampling, the Q-Trak was calibrated with standard CO_2 gas at a known concentration. Pre- and post-zero checking of the Dust-Trak monitor was carried out. The Dust Trak air monitor had been calibrated against a Hi-Vol sampler (Andersen Instrument Inc.) and Partisol Sampler (Model 2000-H, Rupprecht and Patashnich Co., Inc.), respectively. Each filter used for gravitational sampling was conditioned at approximately 50% relative humidity for 24 h before and after sampling. The blank and sampled filters were weighed at least 3 times using an electronic micro-balance (Model A200 S-D1B, Sartorius Ltd.). Figs. 1 and 2 illustrate that the PM_{10} and $PM_{2.5}$ concentrations measured by a Hi-Vol sampler and a Partisol sampler are well correlated with the corresponding levels measured by the Dust-Trak air monitor. The correlation lines of PM_{10} and $PM_{2.5}$ have R^2 coefficients greater than 0.92, respectively.

Indoor and outdoor formaldehyde samples were

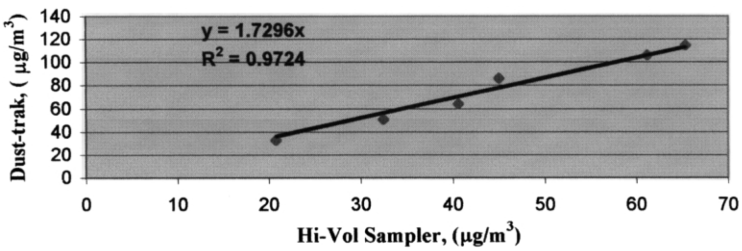

Fig. 1. Measurement of PM_{10} concentrations by Dust-Trak monitor and Hi-Vol sampler.

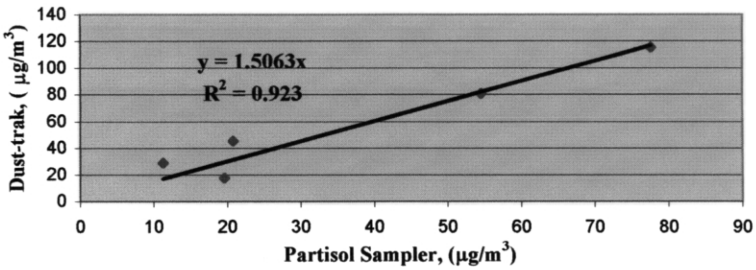

Fig. 2. Measurement of $PM_{2.5}$ concentrations by Dust-Trak monitor and Paritsol sampler.

collected using a SKC formaldehyde monitoring kit at 8-h intervals. Three pairs of bubblers were used for sampling HCHO at both indoor and outdoor sampling locations. A bubbler used as a blank sample remained unopened with a solid cap during transportation and sampling. A second bubbler 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. For indoor air sampling, these blank and sample bubblers were placed in the central position of a main dining area to sample indoor HCHO at each restaurant. For outdoor air sampling, these two bubblers were placed above 1.5 m and approximately 1.2 m away from the exterior walls of the building. After sampling, the screw septum cap of the sample bubbler was removed and replaced by a solid cap and then the actual sample as well as the blank sample were refrigerated and unexposed to sunlight and immediately sent to the laboratory for analysis. HCHO absorbed in both air samples and blank samples were determined by colorimetric analysis and then the measured readings were converted to give average concentrations of indoor and outdoor samples.

For VOC sampling, a batch of clean canisters for sample collection was evacuated before sampling. One-hour average concentrations of VOC air samples were measured during dinner or lunch in the main dining area of each restaurant. The 1-h average samples were obtained using mass flow controllers at a flow rate of 0.035 l/min. Canister samples were collected both indoors and outdoors. After sampling, the canisters were immediately transported to the laboratory for analysis within 4 h. A cryogenic concentrator first concentrated canister samples and then the trapped VOC samples were subsequently separated by gas chromatography (GC) and quantified by a mass selective detector (MS). Before sampling, sequential evacuating and pressurizing with humidified zero air was used to clean SUMMA canisters. Background checks were performed on 25% of the cleaned evacuated canisters to certify that all target compounds were proved to be less than 0.2 ppm. Control sample canisters were also prepared for monitoring losses during sample collection, storage and transportation. The control samples were filled with standard gas containing target organic compounds of known concentrations and they were transported to sampling locations, but remained unopened with the field sample canisters and taken back to the Air laboratory for GC/MS analysis.

2.3. Sampling and analytical precision

The ranges and limits of the detection of analytical methods are summarized in Table 3. In this study, a total of 16 indoor and outdoor air samples were taken for each air pollutant. Duplicated indoor and outdoor samples were collected at these restaurants so as to ensure the consistency and repeatability of sampling data. Sampling precision was evaluated as the percent relative standard deviation (%RSD). The RSD of each air contaminant was shown in Table 4 for each type of restaurant in this study.

Table 3
Detection range and limits of IAQ pollutants

Air parameter	Detectable mechanism	Range	Minimum detection limit
Carbon dioxide (CO_2)	Non-dispersive infra-red (NDIR)	0–5000 ppm	1 ppm
Carbon monoxide (CO)	Non-dispersive infra-red (NDIR)	0–1000 ppm	1 ppm
Formaldehyde (HCHO)	Colorimetric method	0.1–1.5 ppm	0.1 ppm
Respirable suspended particulate (PM_{10})	Light scattering	0.001–100 mg/m^3	1 $\mu g/m^3$
Respirable suspended particulate ($PM_{2.5}$)	Light scattering	0.001–100 mg/m^3	1 $\mu g/m^3$
Total hydrocarbon (THC)	Flame ionization detection	0–200 (non-methane hydrocarbon)	1 ppm
Benzene	VOC air sample trapped by	0.2–5000 $\mu g/m^3$	0.2 $\mu g/m^3$
Toluene	Cryogenic concentrator,	0.2–5000 $\mu g/m^3$	0.2 $\mu g/m^3$
Methylene chloride	analyzed by GC/MS system	0.2–5000 $\mu g/m^3$	0.2 $\mu g/m^3$
Chloroform	using TO-14 method	0.2 – 5000 $\mu g/m^3$	0.2 $\mu g/m^3$

3. Results and discussion

3.1. Indoor and outdoor concentrations of air pollutants

The statistical summaries for the concentrations of the studied air pollutants in indoor and outdoor air are shown in Tables 5 and 6. The average CO_2 concentrations at the occupied restaurants ranged from 636 to 2344 ppm. This is consistent with the study conducted for some restaurant environments (Lee et al., 1999, pp. 443–450). The highest indoor CO_2 level obtained in Rest. 2 was 3051 ppm. The average of outdoor CO_2 level was 537 ppm with a range from 420 to 780 ppm. The outdoor levels of CO_2 were significantly lower than indoors for every sampling period. The use of gas stoves for cooking food are found in the dining areas of rest. 1, 2 and 3; the mean CO_2 levels recorded in ambient air were above 30% of the corresponding indoor concentrations measured in these three restaurants. The average indoor concentration of CO_2 in rest. 4 in which no combustion sources, such as gas stoves, were placed at its dining area exceeded more than 40% of its respective concentration in ambient air. Rest. 1, 2 and 3 had average CO_2 levels above the HKIAQO standard of 1000 ppm; these elevated CO_2 levels indicated that insufficient supply of fresh air occurred in their dining areas when they are occupied (ASHRAE, 1989). Also, considerably high indoor CO_2 levels reflected that the inadequate ventilation easily led to an accumulation of indoor air pollutants inside these three restaurants. Comparatively average indoor CO_2 levels were higher in rest. 1 and rest. 2 than those in rest. 3 and rest. 4. The high CO_2 levels were probably due to the operation of LPG gas stoves for heating frying pans and boiling pots in their dining areas and relatively high occupancy density.

The average concentrations of CO at the surveyed restaurants were found to range from 1280 to 15 730 $\mu g/m^3$ and the corresponding average outdoor CO concentrations varied from 1131 to 1920 $\mu g/m^3$. The highest CO level of approximately 18 743 $\mu g/m^3$ was recorded at rest. 1 with the frying of food in its diner area. The results show that all of the 1-h average indoor and outdoor CO concentrations at these restaurants were below the 1-h average HKIAQO standard of 30 000 $\mu g/m^3$. The results show that the I/O ratios of CO at all of the surveyed restaurants were greater than one when these restaurants

Table 4
Sampling precision for various IAQ pollutants at four restaurants

Target pollutants	Korean barbecue restaurant		Chinese hot pot restaurant	
	Indoor RSD (%)	Outdoor RSD (%)	Indoor RSD (%)	Outdoor RSD (%)
CO_2	12.69	12.13	19.98	13.30
CO	19.37	6.93	10.57	12.09
PM_{10}	20.91	20.57	13.43	19.73
$PM_{2.5}$	14.85	15.16	18.86	19.88
HCHO	18.53	19.77	19.70	16.21
THC	16.19	10.94	17.33	18.58
Benzene	10.60	12.57	20.26	5.37
Toluene	10.06	9.80	10.49	5.34
Methylene chloride	19.53	21.05	14.40	11.54
Chloroform	22.61	15.53	18.46	7.89
	Chinese dim sum restaurant		Western canteen	
CO_2	14.26	14.56	14.38	17.26
CO	6.13	7.39	10.67	6.63
PM_{10}	5.31	19.72	23.98	9.33
$PM_{2.5}$	8.30	19.04	21.91	6.45
HCHO	16.57	20.33	10.45	19.68
THC	9.01	19.32	17.68	14.5
Benzene	5.83	14.08	7.56	4.12
Toluene	4.47	9.89	4.47	7.22
Methylene chloride	14.64	11.05	14.64	4.06
Chloroform	13.83	28.70	13.83	20.63

were operating at meal times, indicating the possibility of dominance of indoor activities such as cooking as a source of indoor CO.

As far as indoor and outdoor concentrations of HCHO are concerned, the average indoor HCHO levels of the surveyed restaurants varied from 18 to 177 $\mu g/m^3$. Except at rest. 2, the mean outdoor HCHO levels usually ranged from ~ 70 to 88% of the corresponding indoor levels at other restaurants. All of these restaurants use peanut oil for cooking. Shields et al. (1995) showed that HCHO could be emitted from heated peanut oil. The mean formaldehyde level observed at rest. 2 was higher outdoors than indoors, the elevated outdoor level was probably related to the close proximity of the outdoor air sampling point (4.3 m) to a traffic road on which there were usually many vehicles idling with running engines. It seems that HCHO was predominantly emitted from indoor sources and cooking activities. Rest. 1 had indoor and outdoor HCHO concentrations exceeding the 1-h average HKIAQO standard of 100 $\mu g/m^3$, the average indoor levels of HCHO could not be attributable to outdoor levels related to heavy traffic conditions. One of the obvious reasons was that the location of the fresh air intake of the commercial building of rest. 1 was approximately 50 m above street level. If the HCHO pollutant is not stable, it immediately reacts with other chemical species such as VOCs when it is directly emitted from its sources such as vehicular emissions or generated by chemical reactions. Furthermore, the opening entrance of rest. 1 was located away from nearby heavily trafficked areas. Therefore, there was less possibility that the increased indoor HCHO levels at rest. 1 were due to air infiltration. As the effects of air infiltration might be a minor factor, the cooking operation of Korean barbecuing in rest. 1 probably became a dominant indoor source of

Table 5
Statistical summary of target air pollutants identified in different types of restaurants

Target pollutants	Indoor Mean	Indoor S.D.	Indoor Range	Outdoor Mean	Outdoor S.D.	Outdoor Range	I/O Ratio
	Korean barbecue restaurant (Rest. 1)						
CO_2	1648	209	1364–1868	512	62.1	461–609	3.2
CO	15703	3041	11543–18743	1920	133.1	1869–1931	8.2
PM_{10}	1442	301	668.9–4052	79	16.3	46–182	18.3
$PM_{2.5}$	1167	173	699–2911	64.8	9.7	35–255	18.2
HCHO	177	32	110–221	132	26.1	88–154	1.3
THC	11.4	1.9	9.7–14.2	6.78	0.7	5.8–7.6	1.7
Benzene	18.4	2	16.9–19.8	11.1	1.4	9.3–12.6	1.7
Toluene	156.1	15.	148.5–171.3	208.3	20.4	186.3–269.6	0.8
Methylene chloride	0.6	0.1	121–139.5	10.8	2.3	5.9–12.9	0.1
Chloroform	14.9	3.4	5.3–18.8	3.7	0.6	2.5–6.6	4.1
	Chinese hot pot restaurant (Rest. 2)						
CO_2	2344	468.3	1301–3051	780	103.7	737–960	3
CO	8114	857.3	7771–8571	1211	146.4	1029–1371	6.7
PM_{10}	105.3	19.9	39.3–129.5	77.3	15.3	49.2–136.5	1.1
$PM_{2.5}$	81.1	10.9	49.1–136.5	66.7	13.3	44.5–106.4	1.6
HCHO	36.7	7.2	28–44	58.7	9.5	40–66	0.6
THC	8.5	1.5	7.9–9	6.5	1.2	4.9–7.8	1.3
Benzene	10.	2	7.4–12.2	3.5	0.2	3.3–3.8	2.8
Toluene	93.8	9.8	86.3–101.5	31.1	1.7	28.9–32.6	3
Methylene chloride	19.5	2.8	3.3–25.6	2.3	0.3	2–2.7	8.3
Chloroform	10.4	1.9	9.55–11.5	3.2	0.3	2.9–3.4	3.3
	Chinese dim sum restaurant (Rest. 3)						
CO_2	1031	147	901–1670	420	61.2	330–523	2.5
CO	2229	136.6	2080–2411	1257	92.8	1131–1337	1.8
PM_{10}	33.9	1.8	31.8–35.9	78.5	15.5	67.8–110.5	0.4
$PM_{2.5}$	28.7	2.4	26.2–31.6	56	10.7	48.3–89.4	0.5
HCHO	21.6	3.6	11–35	15.3	3.1	8–17	1.4
THC	5.6	0.5	4.9–6.1	5.1	1	4.9–5.7	1.1
Benzene	9.3	0.5	8.7–10	8.5	1.2	8.3–8.7	1.1
Toluene	81.6	3.7	78.5–87.3	37.4	3.7	34.4–40.9	2.2
Methylene chloride	7.2	1.1	7.1–9.4	14.3	1.6	13.7–15.1	0.5
Chloroform	2.8	0.4	2.2–3.2	2.2	0.6	1.5–3	1.3
	Western canteen (Rest. 4)						
CO_2	636	91.5	526–750	435	75.1	362–542	1.5
CO	1280	136.6	1169–1291	1131	75	1109–1166	1.1
PM_{10}	38.8	9.3	35.3–55.1	99.8	9.3	78.5–153.3	0.4
$PM_{2.5}$	21.8	4.8	16.6–27	74	4.8	67.2–110.3	0.3
HCHO	17.7	1.9	17–55	15.5	3.1	9–18	1.1
THC	4	0.7	3.1–4.7	4.1	0.6	3.6–4.9	0.9
Benzene	3.7	0.3	3.7–4.3	7.2	0.3	6.5–7.2	0.5
Toluene	17.6	3.7	17.6–29	38.2	2.7	38.2–43.1	0.5
Methylene chloride	1.1	1.1	0.9–1.3	1.3	0.6	1.3–1.5	0.9
Chloroform	1.2	0.4	1–1.4	1.1	0.5	1.1–1.4	1.1

Table 6
Outdoor and indoor air quality objectives currently used in Hong Kong[a]

Air parameters	HKAQO (Hong Kong air quality objective for outdoor air)	HKIAQO (recommended indoor air quality objectives (IAQ) for Hong Kong)
Carbon dioxide (CO_2)	N.A.	1000 ppm (8-h average)
Carbon monoxide (CO)	$< 30\,000$ μg/m^3 (1-h average) $< 10\,000$ μg/m^3 (8-h average)	$< 30\,000$ μg/m^3 (1-h average) $< 10\,000$ μg/m^3 (8-h average)
Respirable particulate (PM_{10})	180 μg/m^3 (24-h average)	180 μg/m^3 (8-h average)
Formaldehyde (HCHO)	N.A.	< 100 μg/m^3 (1-h average) < 50 μg/m^3 (8-h average)
Benzene	N.A.	16.1 μg/m^3 (levels 1 and 2)
Toluene	N.A.	1092 μg/m^3 (levels 1 and 2)
Chloroform	N.A.	163 μg/m^3 (levels 1 and 2)

[a]*Abbreviation:* N.A, not available.

HCHO. This finding could be supported by the fact that the rest. 1 had average I/O ratio higher than 1.

Airborne particulate is one of the major pollutants generated by cooking. In this study, indoor and outdoor mass concentrations of both PM_{10} and $PM_{2.5}$ were measured at selected restaurants during the peak meal time periods. The average 1-h indoor levels of PM_{10} and $PM_{2.5}$ at the investigated restaurants varied from 34 to 1442 μg/m^3 and from 21 to 1167 μg/m^3, respectively. The highest indoor levels of PM_{10} and $PM_{2.5}$ were observed at rest. 1, respectively. The ratios between indoor and outdoor concentrations of PM_{10} and $PM_{2.5}$ at both rest. 1 and rest. 2 exceeded 1. Fig. 3 illustrates that mean indoor concentrations of airborne $PM_{2.5}$ at rest. 1, 2 and 3 were found to range from 80 to 93% of their respective PM_{10} concentrations. This gave rise to an important finding that the PM_{10} emissions resulting from cooking activities were largely composed of fine particulate with aerodynamic diameter less than 2.5 μm. Wolfgang et al. (1991) revealed that the airborne particulate emitted from the operation of charbroiling and frying of meat were usually in a respirable fraction of less than 2 μm in size. Therefore, the relatively high levels of fine particulate matter possibly affected

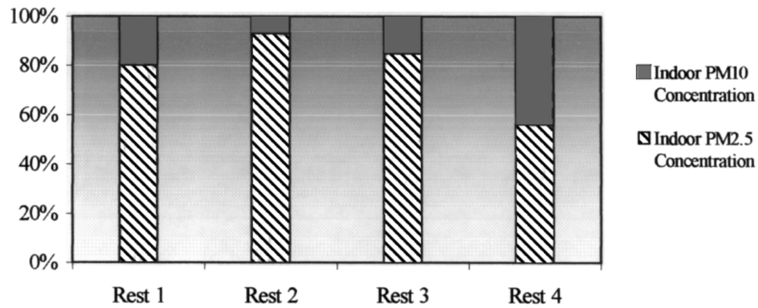

Fig. 3. Proportions of $PM_{2.5}$ to PM_{10} at various types of restaurants in Hong Kong.

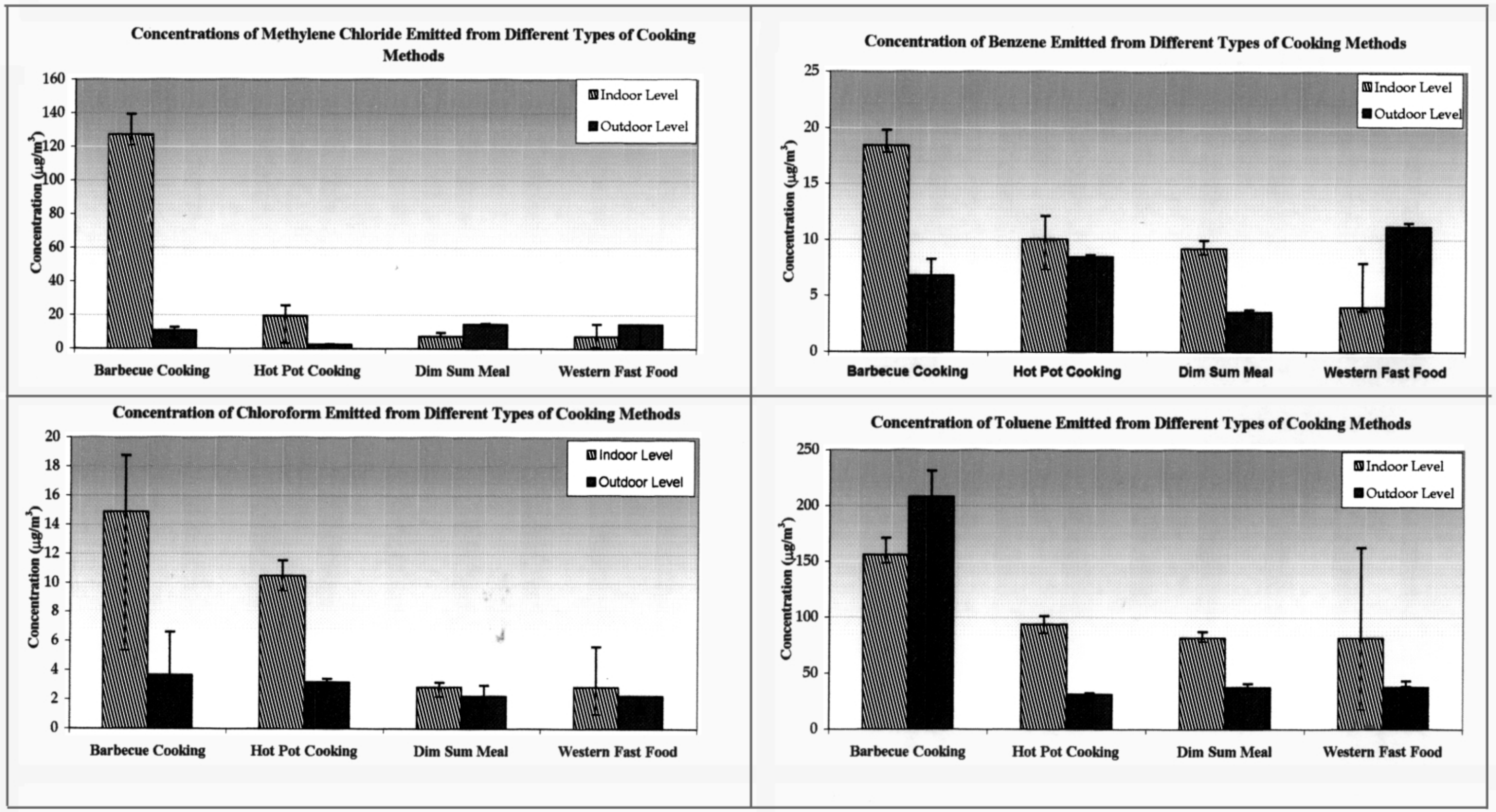

Fig. 4. Comparison of indoor and outdoor levels of targeted VOSs generated from different types of cooking methods.

the restaurants where combustion sources were used in the food preparation processes.

The quality of indoor air at selected restaurants was partially characterized by measuring concentrations of VOCs. The most frequently found VOCs in both indoor and outdoor air samples were benzene, toluene, methylene chloride and chloroform. As shown in Fig. 4, the 1-h average concentrations of individual VOC were relatively higher at rest. 1 and 2 than at the other restaurants. The indoor and outdoor levels of target VOCs were relatively low at rest. 4. The concentrations of the benzene and methylene chloride at rest. 1 and rest. 2 were usually found to be higher indoors than outdoors although the outdoor levels of toluene and chloroform were occasionally elevated due to the infiltration of outdoor air that was probably contaminated by heavy automobile emissions. It seems that the increased levels of these VOCs were attributable to the cooking methods of frying food and hot pot. On the other hand, rest. 1 had 1 h average indoor concentration of benzene above the HKIAQO standard of 16 $\mu g/m^3$. However, the indoor levels of toluene and chloroform were below the corresponding standard limits. Concerning the ratios between indoor and outdoor levels of VOCs, the I/O ratios of benzene and chloroform at selected restaurants were always greater than 1. The ranges of mean I/O ratios of toluene were from 0.5 to 2.8. The mean I/O ratio of methylene chloride was 5.3 with a range from 0.1 to 8.3. Due to the possibility of the influence of heavy vehicular emission at nearby traffic roads and cooking methods, the average I/O ratios of VOCs among different styles of cooking were usually more variable.

3.2. Influence of cooking styles on indoor air quality

From the comparison of the results of indoor and outdoor concentrations of CO_2, three out of the surveyed restaurants were inadequately ventilated as the restaurant environments had indoor CO_2 levels above 1000 ppm. Air pollutants generated by indoor activities such as cooking could possibly build up to the levels that are harmful to human health. The findings of this study showed that indoor CO concentrations were 40–90% higher at rest. 1 and rest. 2 with cooking stoves in dining areas compared to rest. 4 without combustion sources. Rest. 1 and rest. 2 were situated in the same urban area, the traffic conditions at their nearby traffic roads were similar. However, these two restaurants use different cooking methods. Fig. 5 illustrates the comparison of average ratios of air pollutants generated from frying and boiling foods. The operation of frying food appeared to cause more impact on indoor levels of individual air pollutant than that of hot pot cooking. It is particularly associated with an obvious increase in the indoor levels of PM_{10} and $PM_{2.5}$. Both of them are Chinese restaurants in character but differ in cooking styles. Fig. 6 shows that the use of gas stove for cooking at the dining area of the hot pot restaurant had a significant impact on indoor air quality. The elevated CO level was most likely to be associated with the use of gas stove for hot pot cooking.

The result showed that the mean indoor con-

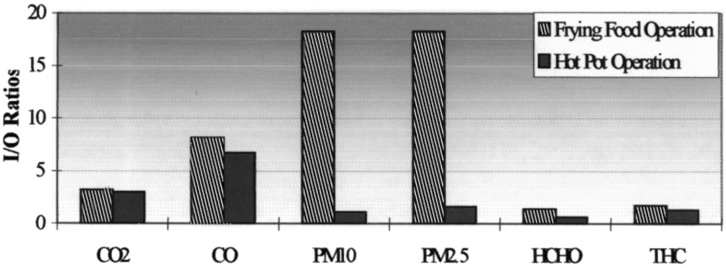

Fig. 5. Comparison of mean ratios of indoor and outdoor levels of target air pollutants due to frying food and boiling food.

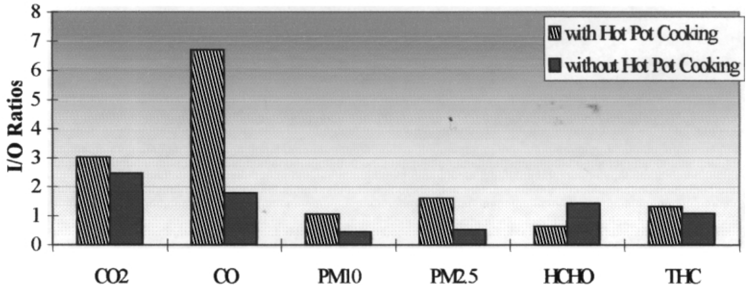

Fig. 6. Comparison of mean ratios of indoor and outdoor levels of target air pollutants in Chinese restaurant with and without operation of hot pot cooking.

centrations of methylene chloride, benzene and toluene due to the emission from Korean barbecue cooking were generally higher than that generated from other styles of cooking. The indoor levels of methylene chloride and toluene at rest. 1 were as high as 140 and 149 $\mu g/m^3$, respectively. The indoor levels of methylene chloride recorded at rest. 1 were approximately 6 times higher than those measured at other restaurants. Furthermore, the indoor levels of toluene observed at rest. 1 were higher than approximately 50% of those observed at rest. 2, 3 and 4. This study found that the process of frying food in cooking oil on a hot pan seemed to increase levels of targeted VOCs in indoor air. Comparing indoor levels of VOCs obtained in the Chinese hot pot restaurant to those measured in the Chinese dim Sum restaurant, the indoor concentrations of toluene and benzene were similar in both types of restaurants.

In addition, the emission from barbecue-style cooking contributed to greater amounts of HCHO in indoor air compared to hot pot cooking, the highest indoor HCHO level at rest. 1 was 221 $\mu g/m^3$. Due to the absence of combustion sources such as cooking and smoking, rest. 4 had the least indoor level of HCHO among the restaurants selected. It is observable that the mean indoor HCHO level generated from gas stoves for boiling food in soups at rest. 2 exceeded 60% of the indoor concentration of HCHO emitted from gas stoves for steaming dim sum at rest. 3. It can be concluded that the average concentration of HCHO at the Chinese hot pot restaurant where LPG gas stoves were utilized for cooking food was comparatively higher than that measured at the Chinese dim sum restaurant where no LPG stoves were put on dining tables for food preparation.

4. Conclusion

The indoor CO_2 concentrations ranged from 636 to 2344 ppm. The restaurants with cooking activities in their dining areas had indoor CO_2 levels exceeding the HKIAQO standard of 1000 ppm. The elevated CO_2 levels within the dining areas of the restaurants were due to high occupancy in crowded indoor environments and operation of combustion sources for cooking without sufficient ventilation. As far as the indoor CO levels were concerned, barbecue style cooking and food boiling can generate considerable amounts of CO. The average indoor CO levels at the Korean barbecue restaurant and the Chinese hot pot restaurant were 4–6 times higher than those concentrations at the Chinese dim sum restaurant and the western canteen in this study.

Extremely high levels of PM_{10} and $PM_{2.5}$ were found at both Korean barbecue-style restaurants and Chinese hot pot restaurants. The average PM_{10} and $PM_{2.5}$ levels at the Korean restaurant were 1442 and 1167 $\mu g/m^3$, respectively. In the Chinese hot pot restaurant, indoor levels of PM_{10} and $PM_{2.5}$ generated by boiling food were 81 and 75 $\mu g/m^3$, respectively. Many Korean restaurants tend to use frying pans for cooking food. This study found that the average indoor levels of PM_{10} and $PM_{2.5}$ measured at the restaurants with operation of gas stoves for cooking in dining areas were tremendously increased compared to those restaurants without combustion sources. The results showed that over 80% of the respirable particulate matters (PM_{10}) measured in the indoor air of the Korean barbecue style, Chinese hot pot and general Chinese restaurants were fine airborne particles ($PM_{2.5}$).

The mean indoor HCHO levels at all of the four restaurants ranged from 20 to 177 $\mu g/m^3$. The average outdoor HCHO levels usually varied from approximately 14 to 85% of the respective indoor concentrations at four restaurants. The Korean barbecue style restaurant had an average indoor and outdoor HCHO concentration above the 1-h average HKIAQO standard of 100 $\mu g/m^3$. The Korean barbecue-style restaurant had a higher indoor average benzene level than the HKIAQO standard of 16.1 $\mu g/m^3$, but it had indoor average levels of toluene and chloroform complied with the HKIAQO standards. Other than the Korean restaurant, the mean concentrations of individual VOCs at other restaurants did not exceed the HKIAQO standards. The average concentration of individual VOC was relatively higher at the Korean barbecue-style and the Chinese hot pot restaurant than at the Chinese dim sum restaurant and Western canteen. The highest indoor levels of all VOCs were obtained at the Korean barbecue-style restaurant associated with the operation of frying food. The indoor air quality of the Chinese restaurant with the presence of gas stoves for hot pot cooking was worse than that of the Chinese restaurant without cooking stoves at its dining area.

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