Contribution of Chinese Hot Pot and Barbecue Restaurants on Indoor Environmental Parameters

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ABSTRACT

The indoor environmental quality of hot pot and barbecue restaurants has caused an increasing amount of public concern. Hence, this study assessed the conditions and ventilation systems in nine such restaurants of Xi'an, China, by performing field measurements focusing on the variations in temperature, relative humidity, and CO and CO₂ concentrations due to cooking style. The results showed that the indoor environmental quality of the test restaurants depended mainly on the cooking fuel, cooking method and ventilation system. Boiling food in soup (hot pot) raised the relative humidity inside the restaurants. However, without sufficient ventilation, cooking with radiation (hot pot/barbecue) resulted in high personal heat exposure and low relative humidity near the heat sources. A substantial rise in the CO level was observed with the burning of charcoal, whereas an increase in the CO₂ concentration was detected with the combustion of natural gas. Furthermore, the operational condition of the kitchen ventilation significantly affected the air quality in the dining area, which was found to be the worst at the restaurant exhibiting the poorest ventilation (i.e., the lowest contaminant removal and heat removal efficiencies). Thus, a more efficient and energy-saving ventilation system for hot pot and barbecue restaurants should be developed.

Keywords: Ventilation; Indoor environmental quality; Restaurant; Hot pot cooking; Barbecue cooking; Field test.

INTRODUCTION

According to the World Health Organization (WHO), approximately millions of people die each year from indoor air pollution (WHO, 2014). Cooking is one of the most important sources of non-smoking air pollution in buildings. Cooking processes generate numerous substances, such as carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxides (NO_x), volatile organic compounds (VOCs), particulate matter (PM), liquid oil droplets and water vapor (Karimatu *et al.*, 2013). The toxic pollutants contained in cooking fumes such as polycyclic aromatic hydrocarbons (PAHs), benzopyrene and others can seriously harm the health of cooks and family members (Chen *et al.*, 2019). Epidemiological studies revealed that exposure to cooking oil fumes increases the morbidity of respiratory tract infections, pneumonia, lung cancer, asthma, kidney disease, cataracts and cardiovascular diseases (Zhang *et al.*, 2017). Oil fumes generated from high-temperature frying are classified as *probable carcinogens* by the International Agency for Research on Cancer (IARC

Working Group on the Evaluation of Carcinogenic Risks to Humans, 2010). Cooks are more likely to develop diseases such as lung cancer, nasopharyngeal cancer and esophageal cancer due to long exposure to cooking fumes (Wang *et al.*, 2017a). In China, traditional cooking activity produces more pollutants. Thus, Chinese women rarely smoke but have a high risk of lung cancer (Wang *et al.*, 2017b; Zhang *et al.*, 2017).

Cooking fumes are generated from both food cooking behavior and fuel combustion. The composition of cooking fumes is highly diverse and depends on factors such as cooking styles, raw materials, cooking temperature, heat sources and cooking fuels (Cheng *et al.*, 2016; de la Sota *et al.*, 2019; Que *et al.*, 2019). Some studies suggest that the cooking methods using oil as heat transfer medium, such as barbecue, deep-frying and stir-frying, produce more pollutants than the cooking methods using water as heat transfer medium (steaming, boiling, etc.) (Zhao *et al.*, 2019; Chen *et al.*, 2020). For example, steel-pan-grilling Chinese-style food is capable of elevating submicron particle concentrations up to 5 times higher than European-style cooking (Levy *et al.*, 2002; He *et al.*, 2004). However, in addition to barbecue restaurants, hot pot restaurants have also been measured for relatively high concentrations of CO, CO₂ and PM (Chen *et al.*, 2007; Lee *et al.*, 2011). At present, limited information

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is available in the published literature. Substantial attention should be paid to the indoor environmental quality of Chinese hot pot and barbecue restaurants.

Cooking with fuels is a main source of air pollution and a leading contributor to disease burden (Ni *et al.*, 2016). Several fuels are used for cooking, including biomass (e.g., charcoal and wood), natural gas, electricity, liquefied petroleum gas and solid alcohol. Natural gas and electricity are the main fuels used in Chinese modern kitchen cooking. Because charcoal and solid alcohol have many advantages, including a higher energy content, the ability to burn evenly for a long time, easier handling, and easily extinguished and reheated, they have been widely used in Chinese barbecue (Susaya *et al.*, 2010). Charcoal combustion is an important source of gaseous (e.g., CO, NO_x and TVOC) and particulate matter emissions (Vicente *et al.*, 2018). Huang *et al.* (2016) investigated ten types of the commercial charcoal that is commonly employed in Taiwan's barbecue restaurants. The results suggested that the adverse effects of the large amounts of air pollutants generated during indoor charcoal combustion on health and indoor air quality must not be disregarded (Huang *et al.*, 2016).

Previous studies primarily focused on the exposure of gaseous pollutants and particulates that occur when eating hot pots and barbecues, with less attention placed on the ventilation systems in restaurants. We should realize that the use of an efficient ventilation system is essential to ensuring a healthy, comfortable, productive and energy-efficient environment in a restaurant (Livchak *et al.*, 2005; Tsai and Hsieh, 2006; Li *et al.*, 2012). The effect of air volume, appliances' position, front overhang, rear seals, side panels, separation plate, baffle plate, mannequin and systematic inspections were investigated and quantified on the performance of kitchen exhaust hood (Keil *et al.*, 2004; Swierczyna *et al.*, 2006; Lim and Lee, 2008; Zhao *et al.*, 2013). Many designers and engineers have the misconception that the bad indoor air quality in kitchens is only related to the exhaust hood and disregard the effects of air distribution on hood performance. Supply air strategies, including ceiling supply, capture jet, air curtain, push-pull and displacement ventilation systems, have a significant influence on the pollutant removal effectiveness in a kitchen environment (Kosonen, 2007; Li *et al.*, 2014; Claeys *et al.*, 2015; Zhou *et al.*, 2016).

In the majority of kitchens, the environment is warm to hot (Simone *et al.*, 2013). In a Chinese commercial kitchen, the air temperatures tend to exceed 40°C. As a result of cooking methods, the relative humidity value in these kitchens significantly varies from 27.5% to 75% (Li *et al.*, 2012). Cooks, whose thermal comfort and working efficiency are affected, generally need to work continuously for more than 4 hours in hot and dry/humid environments. Air temperature, relative humidity, air velocity and average radiant temperature are the main factors that affect thermal comfort. CO is a representative product of incomplete combustion of charcoal. CO₂ was often chosen as the main indicator for evaluating contaminants' distribution characteristics and the performances of ventilation systems because the change in the concentration of CO₂ as a result of cooking was significant, which facilitate

the observation of changes in values (Saha *et al.*, 2012). When the indoor air temperature, relative humidity and CO₂ concentrations are maintained within the standard-recommended range, the indoor air quality can be improved.

Due to a lack of cooking source of pollution in dining areas, evaluation of the ventilation systems in restaurants was often disregarded in the literature. For hot pot or barbecue restaurants, the assessment of a ventilation system in a dining area is essential. None of the existing standards are specially tailored for the ventilation system design in typical Chinese hot pot or barbecue restaurants. In practice, empirical knowledge of existing installations has been employed for ventilation system determination. The actual working condition of the ventilation systems of Chinese hot pot and barbecue restaurants remains unknown. To improve the indoor environmental quality in typical Chinese-style hot pot and barbecue restaurants and assess their ventilation systems while customers are eating hot pot and barbecue, a study was undertaken in nine traditional restaurants, including five hot pot restaurants and four barbecue restaurants, in Xi'an, China.

METHOD

Restaurants

Five Chinese traditional hot pot (H) restaurants and four barbecue (B) restaurants were selected in July, the hottest time of the year. All the restaurants are located in an urban commercial area with high traffic density. No open chimneys or other sources of air pollution were noted nearby. Restaurants H1, H2 and H5 provide the typical Changing *má là* ("numb and spicy") hot pot, which is one of the most popular foods in China. A considerable amount of Sichuan pepper combined with spicy ingredients such as chili is added to the broth. Restaurants H3 and H4 provide fish hot pot, which contains cooked fish. Unlike the Chungking *má là* hot pot, the pot does not contain broth at the beginning of the meal. While the fish is heating, other hot pot dishes and broth can be loaded into the pot. Restaurants B1 and B2 provide Korean-style barbecue. In Restaurants B3 and B4, it is served traditional Chinese-style barbecue. During the process of baking, cooking oil is continuously brushed on a hot steel pan to enhance the flavor of the food.

The scales of the dining areas of the nine restaurants exceed 138 m², and all restaurants have mixed air conditioning systems. The total ventilation rate of all restaurants is designed according to the air change rate (15 h⁻¹). The ventilation rate = the air change rate × the room volume. In Restaurants H2, B1 and B2, a cooking pot or steel pan is sunk into a table with a slot exhaust outlet on the edges of the table. In this case, 80% of the total ventilation rate is used for local ventilation, that is, the local ventilation rate is 12 times h⁻¹ and the general ventilation is 3 times h⁻¹. In other restaurants, the cooking pot or steel pan is placed on a table without local exhaust ventilation. A photograph of the side exhaust outlet on the edges of the table in Restaurant H2 is shown in Fig. 1. The floor plans of the case-study restaurants are shown in Fig. 2.

Fig. 1. A photograph of the side exhaust outlet of the hot pot in Restaurant H2.

Fig. 2. Floor plan of the case-study restaurants (the shaded areas are the kitchens): (a) Restaurant H1, (b) Restaurant H2, (c) Restaurant H3, (d) Restaurant H4, (e) Restaurant H5, (f) Restaurant B1, (g) Restaurant B2, (h) Restaurant B3 and (i) Restaurant B4.

Fig. 2. (continued).

The kitchen areas of the nine restaurants exceed 50 m². In this study, we mainly focused on the environmental quality of the cooking (hot working) area, where a considerable amount of heat and air pollutants are generated. The floor plans of the hot working areas of the case-study kitchens are shown in Fig. 3. H2 is a chain hot pot restaurant. Many ingredients are prepared and shipped to the kitchen for storage, so there is no need for a large number of open-fire operations. Although the kitchen is large, there is no hot cooking area, so the floor plan is not shown in Fig. 3. The cooking ranges of these kitchens are located in a line that backs up to a wall; this setup is a typical arrangement in Chinese commercial kitchens. The cooking ranges are installed under a wall-mounted canopy hood, with the exception of Kitchens H2 and H3. The designed ventilation rate of the exhaust hood is 60 h⁻¹. The front lower edges of the hoods of the seven kitchens are located 1.8 m from the finished floor, as measured vertically. The front edge of the hood is designed to be at an angle of approximately 45°, which is substantially different from American or European methods (Li et al., 2012).

General characteristics of these restaurants are listed in Tables 1–4. Two parameters can be used to characterize the impact of the number of diners on the contribution of indoor CO₂ in dining room, namely, the diner number per unit dining area (*s*) and the heat source number per each diner (*k*).

$$s = \frac{\text{number of diners}}{\text{dining area}} \quad (1)$$

$$k = \frac{\text{number of heat sources}}{\text{number of diners}} \quad (2)$$

Test Parameters

In this study, the designed exhaust air flow rates of the restaurants were determined by the air change rate method, where the air flow rate was calculated by the selected air change rate (15 h⁻¹) and the volume of the restaurants. The capture velocity of the exhaust hood was measured according to the surface air velocity method in AQ/T 4274–2016. We cut a hole in the supply/exhaust air duct above the ceiling and placed the probes through the hole to test the supply/exhaust air parameters. During the tests, the power of the cooking ranges was determined by the consumed quantity of the fuels and the corresponding calorific value. The energy consumption information was provided by the restaurant managers. In this study, the number of heat sources and diners was based on field statistics. The designed cooling load and exhaust air flow rate were provided by the China Northwest Architecture Design and Research Institute.

Sampling Point

Each restaurant was divided into two test sections: the dining area and kitchen. The sampling points were placed at 1.1 m (dining area) and 1.5 m (kitchen) above the floor and far from potential sources of air pollutants in each sampling location. For a single hot pot or steel pan (heat source), the

thermal plume was measured at 0.5 m and 1 m above the table. The sampling numbers and the setup of the sampling points are illustrated in Table 5, Figs. 2, 3 and 4. The measurements were performed during non-meal time (10–11 a.m.) and meal time (1:00–2:00 p.m. or 7:00–8:00 p.m.) to reflect their difference. The sampling time of each restaurant was not more than 1 hour, so as to minimize the impact of changes on the diners. A sample was collected outdoors at a height of 1.5 m in close proximity to the fresh air intake. Simultaneous indoor and outdoor air sampling was performed at each sampling site. No smoking activities were observed in these restaurants during air sampling.

Test Instruments and Error Analysis

Measurements were simultaneously conducted at the sampling points of the dining area, kitchen and outdoors; thus, three sets of test identical instruments were employed in this study. Air velocity, temperature and relative humidity were measured with the calibrated VelociCalc® Plus Multi-Parameter Ventilation Meter (Model 8386A; TSI Inc.). CO₂ and CO concentrations were measured with the IAQ-Calc™ Indoor Air Quality Meter (Model 7545; TSI Inc.) and were tested and calibrated with a calibration gas of known concentration. Pre- and post-zero checking of the monitors was performed. The ranges and limits of the detection of the analytical methods are summarized in Table 6. The data of each sampling point were read with a delay time of 10 seconds to eliminate possible mechanical fluctuations in the probe movement. Instantaneous data measurements were taken every second; these measurements were recorded over a period of at least 1 minute to give the reported value prior to moving to the next sampling point. Each restaurant repeated the test two times on different days. Duplicated indoor and outdoor samples were collected at these restaurants to ensure the repeatability and consistency of the sampling data. The standard deviation (SD) was used to evaluate the sampling precision.

RESULTS AND DISCUSSION

Measurements of Dining Areas

Fig. 5 presents the indoor levels of the targeted parameters generated from the dining areas of the nine restaurants. From Fig. 5, we were able to determine that the indoor environmental quality of the sampled restaurants was related to the fuel of the heat sources and the mechanical exhaust system, especially the local exhaust system. The data in Fig. 5(a) indicates minimal difference between the mean temperatures of the dining areas before and after a meal. Because the supply air temperatures of Restaurants H1, B2 and B3 were reduced to 20°C at dinner time, the indoor average temperatures also decreased. Fig. 5(b) revealed a higher level in the mean values of relative humidity in the dining areas after a meal. The increase in the average relative humidity in hot pot restaurants was larger than 8.2%, whereas it was less than 4.4% in the barbecue restaurants, with the exception of Restaurant B1. This result was primarily related to the catering mode in the hot pot restaurants, during which the broth was maintained in a boiling state for as long as 1–2 hours of the

Fig. 3. Floor plan of the hot working area of case-study kitchens and the layout of the sampling points: (a) Kitchen H1, (b) Kitchen H3, (c) Kitchen H4, (d) Kitchen H5, (e) Kitchen B1, (f) Kitchen B2, (g) Kitchen B3 and (h) Kitchen B4. (The black range indicates that it was burning during the cooking time.)

Table 1. Main background data of dining areas in sampled restaurants.

Dining room	Area (m ²)	Number of diners (# m ⁻¹)	Number of heat sources	k	Power of each pot/steel pan (kW)	Fuel type/chemical composition	Designed cooling (kW)	Designed exhaust air flow rate (m ³ h ⁻¹)
H1	497	220	0.42	54	0.25	3.8	Gas/CH ₄	280
H2	539	250	0.46	61	0.24	3.8	Gas/CH ₄	310
H3	345	182	0.53	57	0.31	1.8	Electricity	150
H4	168	92	0.55	31	0.34	1.5	Electricity	60
H5	257	130	0.51	37	0.28	2.0	Electricity	110
B1	293	144	0.49	29	0.2	0.8	Electricity	180
B2	253	138	0.54	38	0.28	0.8	Electricity	160
B3	286	130	0.45	38	0.29	0.9 ^b	Charcoal/C	132
B4	350	188	0.54	47	0.25	1.25 ^c	Solid alcohol/C ₂ H ₅ OH	150

^a General ventilation/side exhaust ventilation.^b The calorific value of charcoal is 8500 (kcal kg⁻¹).^c The calorific value of alcohol is 30,000 (kJ kg⁻¹).**Table 2.** Main background data of kitchens in sampled restaurants.

Kitchen	Total area (m ²)	Hot working area (m ²)	Power of cooking ranges (kW)	Fuel type/chemical composition	Designed exhaust air flow rate (m ³ h ⁻¹)	Energy use (per meal)	Actual capture velocity of hood (m s ⁻¹)
H1	169	38	20.2	Gas/CH ₄	1,0000	33 m ³	0.1
H2	273	–	–	Electricity	15,000	105 kW h	–
H3	120	13	24.2	Electricity	7200	75 kW h	–
H4	70	16	26.2	Electricity	4200	65 kW h	0.53
H5	71	18	1.65	Gas/CH ₄	5260	25 m ³	0.8
B1	119	15	24.3	Gas/CH ₄	2800	15 m ³	1.5
B2	65	40	31.0	Gas/CH ₄	3900	14 m ³	1.2
B3	60	29	16.5	Gas/CH ₄ charcoal/C	2220	18 m ³ /50 kg	0.79
B4	50	20	25.0	Gas/CH ₄	3000	20 m ³	0.7

Table 3. General comparisons of the ventilation system of sampled restaurants^a.

Restaurant	Dining room	Kitchen
H1	FCU + PAU	LEV + PAU
H2	VRV + PAU + LEV	LEV + PAU + VRV
H3	FCU + PAU	FCU + PAU
H4	FCU + PAU	LEV + PAU
H5	FCU + PAU	LEV
B1	VRV + PAU + LEV	LEV + PAU
B2	FCU + PAU + LEV	LEV + PAU
B3	VRV + PAU	LEV + PAU
B4	FCU + PAU	LEV + PAU

^a VRV: variable refrigerant volume; FCU: fan coil unit; PAU: primary air unit; LEV: local exhaust ventilation; NAS: natural air supply.

dining time. Due to evaporation, the boiled soup needed to be refilled, which enabled a considerable amount of water vapor to evaporate into the surrounding environment and generate a high relative humidity value.

Fig. 5(c) indicates that the CO concentration in the restaurants was primarily related to the fuel used under the hot pot or steel pan. The largest increase in CO concentration was detected in Restaurant B3, where charcoal was employed

as the fuel. Due to the incomplete combustion of charcoal, the local average CO concentration in Restaurant B3 increased to 11.8 ppm, which was 3.8 ppm (47.5%) higher than the acceptable level (8 ppm; GB/T 18883-2002 Indoor Air Quality Standard of China, 2002). The high concentration of CO can cause significant damage to human body health. The second increase in CO concentration occurred in the restaurants that used gas as fuel (Restaurant H1 and H2). Note that the

Table 4. Air parameters of supply and outdoor.

			Restaurant								
			H1	H2	H3	H4	H5	B1	B2	B3	B4
Supply air	Temp. (°C)	Mean	23/20	23	23	23	23	23	23/20	23/20	23
		SD	1.6/0.8	0.6	0.7	1.1	0.8	1.3	1.0/0.9	0.4/0.5	0.6
	RH (%)	Mean	51	48	50	48	48	52	50	51	52
		SD	3.4	2.5	1.9	1.5	0.7	1.8	2.0	1.7	2.1
	CO (ppm)	Mean	2.3	2.1	2.2	2.2	2.4	2.3	2.0	2.1	2.1
		SD	0.22	0.47	0.52	0.39	0.33	0.21	0.41	0.27	0.24
	CO ₂ (ppm)	Mean	382	420	410	397	403	455	453	412	437
		SD	15.4	21.8	19.3	21.6	14.2	12.6	13.4	18.0	22.2
Outdoor	Temp. (°C)	Mean	37	36	36	38	37	37	37	37	33
		SD	3.5	2.9	2.6	3.2	4.7	3.8	4.3	3.5	5.1
	RH (%)	Mean	37	38	34	36	36	43	43	37	38
		SD	2.7	3.9	5.2	4.1	3.8	2.2	3.9	4.5	3.8
	CO (ppm)	Mean	2.1	2.0	2.0	2.1	2.2	2.2	2.1	2.3	2.1
		SD	0.23	0.38	0.31	0.40	0.36	0.52	0.27	0.33	0.26
	CO ₂ (ppm)	Mean	360	379	384	360	395	390	372	399	404
		SD	31.9	28.2	36.7	42.4	30.8	42.5	35.1	46.9	34.2

Table 5. Simple numbers of restaurants.

Restaurant	Dining room	Kitchen	Single hot pot/grill
H1	22	7	–
H2	17	8	14
H3	18	5	–
H4	13	6	–
H5	15	5	–
B1	11	5	14
B2	20	9	14
B3	16	9	–
B4	16	4	–

Fig. 4. The layout of the sampling points for a single hot pot/steel grill.

local exhaust system in Restaurant H2 can effectively exhaust the products of incomplete combustion. Thus, the CO concentration in Restaurant H2 was lower than that in Restaurant H1. Because electricity was used as the fuel, CO

was not produced in the heating process, which enabled lower CO values in the dining area of the restaurants. As shown in Fig. 5(d), the generation of CO₂ was also related to the fuel combustion. The largest increase in CO₂ concentration occurred in the restaurant that used natural gas as fuel (Restaurant H1). The local average CO₂ concentration in Restaurant H1 increased to 1673.2 ppm, which was 673.2 ppm (67.3%) higher than the acceptable level (1000 ppm; GB/T 18883–2002 Indoor Air Quality Standard of China, 2002). The second increase of CO₂ concentration was detected in the restaurants that use charcoal (Restaurant B3) and solid alcohol (Restaurant B4) as fuel. The smallest increase in CO₂ concentration was detected in the restaurants that use electricity as fuel. Lee *et al.* (2001)'s research revealed that the elevated CO₂ levels within the dining areas were attributed to the high occupancy in crowded indoor environments and the operation of combustion sources for cooking without sufficient ventilation. In this study, it can be found that the number of diners in the tested dining rooms per unit area is between 0.44 and 0.55, while the heat source number per each diner of the nine dining rooms is between 0.2 and 0.33. In other words, the number of diners in the tested restaurants is evenly distributed, with a similar density and a similar proportion to the cooking heat source. During the test, the CO₂ values produced by the people measured at a certain point can be considered to be similar. Therefore, the occupancies in all restaurants were almost equal, which suggested that CO₂ is primarily derived from the combustion of fuel. However, with the exception of Restaurant H1, the CO₂ concentrations in the other restaurants did not exceed the Chinese indoor air quality standard. From the available data, the environmental quality in Restaurant H1 was the worst.

To further analyze the poor indoor environmental quality in Restaurant H1, a single heat source (hot pot or steel pan) was selected in Restaurants H1, H2 and B1 to investigate the effect on the local exhaust ventilation system. As shown in Fig. 6, because the cooking pot or steel pan in Restaurants H2 and B1 was sunk into the table with a local exhaust

Table 6. Detection range and limits of tested air parameters.

Air parameter	Range	Accuracy	Resolution
Temperature (°C)	–10 to 60	±0.3	0.1
Relative humidity (%)	0–95	±3	0.1
Velocity (m s ^{–1})	0–50	±3% of reading or ±0.15 m s ^{–1}	0.01 m s ^{–1}
CCO ₂ (ppm)	0–5000	±3% of reading or ±3 ppm, whichever is greater	1
CCO (ppm)	0–500	±3% of reading or ±50 ppm, whichever is greater	0.1

Fig. 5. Comparison of indoor levels of targeted parameters generated from different dining areas: (a) temperature, (b) relative humidity, (c) CO concentration and (d) CO₂ concentration.

ventilation system, the temperature and contaminant levels above the hot pot (heat source) were relatively low and underwent minimal change during meal time. Conversely, the measurement values in Restaurant H1 were extremely high because the cooking pot was placed on the table without local exhaust ventilation. Note the air outlet installed on the roof of the private room in Restaurant H1. Thus, the peak values did not appear in the middle of the heat source. In Restaurant H1, the maximum values of temperature, CO and CO₂ above the hot pot during meal time were 40.9°C, 9.8 ppm and 3340 ppm at 0.5 m above the table. The distribution of

relative humidity was different than other parameters. In Restaurants H2 and B1, the values of relative humidity above the hot pot or steel pan underwent minimal change, which ranged from 60.2% to 68.8%. In Restaurant H1, the change in relative humidity was significant: The maximum value of 95% was achieved 0.5 m above the heat source, whereas the lowest value of only 35.4% was achieved at the personnel breathing zone beside the table. As a result, during meal time, people were in an environment with hot, dry air and a high concentration of pollutants, and achieving satisfactory thermal comfort and air quality in Restaurant H1 was difficult.

Measurements of Kitchens

Fig. 7 presents the indoor levels of targeted parameters that were generated from the hot working areas of nine

restaurants. From Fig. 7, we were able to determine that the indoor environmental quality of the sampled kitchens was related to the fuel, cooking method and the exhaust hood

Fig. 6. Comparison of targeted parameters generated from a single hot pot/steel grill among Restaurants H1, H2 and B1: (a) temperature, (b) relative humidity, (c) CO concentration, (d) CO₂ concentration and (e) velocity.

Fig. 7. Comparison of indoor levels of the targeted parameters generated from different dining kitchens: (a) temperature, (b) relative humidity, (c) CO concentration and (d) CO₂ concentration.

system. As shown in Fig. 7(a), a significant difference was observed between the mean temperatures of the hot working areas before and after cooking. In Kitchen H2, no heavy load cooking operations were employed; thus, the temperature increase was the minimum. The largest increase in temperature of Kitchen H1 was related to the boiling of hot pot broth with four gas stores, where the peak temperature was 45.9°C. For the California Energy Commission (CEC) study, a thermally neutral temperature is 23.9°C. If the temperature in the space increases by 5.5°C above the comfort level, the productivity may decrease as much as 30% (Chen *et al.*, 2001). Thus, the bad thermal environment in Kitchen H1 can cause high labor costs. Fig. 7(b) revealed that the mean relative humidity of cooking mode differed from the idle mode in hot working areas. This difference was primarily related to the cooking method. In Kitchen H5, small fire was used to boil the broth. Due to evaporation, the relative humidity value was increased. However, in Kitchen H1, a large fire was used to boil the broth with a gas stove. The relative humidity was reduced due to high temperature and high radiation.

From Fig. 7(c), we were able to determine that the CO concentration in restaurants was primarily related to the fuel used in the kitchen. The largest increase in CO concentration was detected in the kitchen that used charcoal as the fuel (Restaurant B3). Due to the incomplete combustion of charcoal, in the hot working area of Kitchen B3, the local CO concentration increased to 17.6 ppm, which is 9.6 ppm (120%) higher than the acceptable level (8 ppm). The mean CO concentrations in Kitchens H1 and B4 also exceeded the acceptable level by 4.9 ppm and 0.4 ppm, respectively. The data shown in Fig. 7(d) revealed that the average CO₂ concentrations in all kitchens did not exceed the indoor standard values, with the exception of Kitchen H1. The actual capture velocity of the hood in Kitchen H1 was only 0.1 m s⁻¹, which could not satisfy the design requirements and produces an excessive CO₂ concentration. The ventilation system of H3 in the restaurant failed to turn on in time during non-meal time, and the meal was prepared in kitchen, so the concentration of pollutants in the kitchen during non-dining time was higher than the value of dining time. In addition,

since there is no local exhaust system in Kitchen H3, it can only rely on general ventilation to remove pollutants, so it is difficult to form the air flow direction from the dining room to the kitchen and form an effective “negative pressure area.” So the concentration of pollutants in the dining area during non-dining time was also higher than the value of dining time.

The specific situations of the hot working area in the nine kitchens is described in Fig. 3 to further analyze the characteristics of the indoor environmental quality in these areas. As shown in Fig. 8, the temperature, humidity, and CO and CO₂ concentrations substantially changed due to different positions in Kitchen H1, which differed from other kitchens. We also determined that the variation in relative humidity was contrary to the trend of temperature, CO and CO₂ concentrations. In this case, the upper body of a chef would be subjected to hot and dry air. Combined with the floor plan, we determined that the steamer at Point A4 in Kitchen H1 was not burning. For this reason, the values of

temperature, CO and CO₂ concentrations should not exceed the values of the sampling points for the cooking range that was burning. The results indicated that the air impurities had spread throughout the kitchen, and the capture and containment efficiency of the exhaust hood were questioned. In the Chinese standards, the capture velocity of the hood opening should not be less than 0.5 m s⁻¹. In Kitchen H1, the actual capture velocity of the hood was only 0.1 m s⁻¹, which explains the poor indoor environmental quality in Kitchen H1. An extremely high value of CO concentration appeared in the hot working area in Kitchen B3, which ranged from 41.2 ppm (Point D4) to 14.1 ppm (Point D1 and D2) among the sampling points. Combined with the floor plan, we observed a charcoal burner range near Point D4, where 50 kg of charcoal were burned every meal to prepare the steel-pan-grilled fish. These situations contributed to the poor indoor air quality.

In these case-study restaurants, the designed exhaust air flow rates were larger than the supply air flow rate, which

Fig. 8. Comparison of targeted parameters generated from the different hot working areas: (a) temperature, (b) relative humidity, (c) CO concentration and (d) CO₂ concentration.

produced a negative pressure in the restaurants. In the kitchen, the make-up air primarily infiltrated the interior door between the dining area and the kitchen because the windows were closed. Thus, the indoor thermal environment in the kitchen was related to the indoor environmental quality in the dining area. The kitchen ventilation system had an important effect on the environmental quality in the dining area. When the exhaust ventilation in the kitchen is not sufficient, contaminants will overflow from the kitchen and enter the dining area through the interior door. By dimensionless analysis, a correlation for the contaminants in the restaurants is obtained in Fig. 9. This correlation indicates a similar trend in the CO and CO₂ concentrations between the dining area and the hot working area in the kitchen. Some differences were observed between the CO and CO₂ concentrations, especially for Restaurant B3. The deviations can be attributed to the fuel used in restaurants. Charcoal was the main fuel in Restaurant B3, where the incomplete combustion of charcoal produced a substantially high concentration of CO. For other restaurants that use gas, electricity or solid alcohol as fuel, the range of change of CO and CO₂ concentrations were almost consistent. In the following study, CO₂ was chosen as the main contaminant for evaluating the performance of the kitchen ventilation systems because the changes in concentration were considerable.

Assessment of Ventilation Mode

In the following section, we discuss our attempts to evaluate the ventilation mode and poor air distribution through the measurement parameters. We employed two evaluation indicators: contaminant removal efficiency (CRE) and efficiency of heat removal (EHR):

Contaminant Removal Efficiency (Yaglou and Witheridge 1937)

One of the first indicators that actually define a perceived air quality is the contaminant removal effectiveness:

$$\varepsilon = \frac{C_e - C_s}{C - C_s} \quad (3)$$

This indicator is based on the room average contaminant concentration, $\bar{C}$, the contaminant concentration at supply, C_s , and the contaminant concentration at exhaust, C_e . As an indoor air quality indicator, ε provides more informative results for the removal of contaminants with known position (Atila and Jelena, 2003).

Efficiency of Heat Removal (Awbi and Gan, 1993)

When waste heat is regarded as a contaminant, we can obtain the efficiency of heat removal, which is also known as the *energy utilization coefficient*. This coefficient is defined by temperature, which is used to examine the ventilation effectiveness for the heat removal:

$$\eta_t = \frac{t_e - t_s}{\bar{t} - t_s} \quad (4)$$

This indicator is based on the room average temperature

Fig. 9. Comparison of CO and CO₂ concentrations in the sampled restaurants during meal time.

$\bar{t}$, the temperature at supply t_s , and the temperature at exhaust t_e . When $\bar{t} < t_e$, $\eta_t > 1$; otherwise, $\eta_t < 1$. The larger is η_t , the higher is the energy utilization of this air distribution.

As shown in Table 7, the highest contaminant removal efficiency of the dining areas was 1.16 in Restaurant B1, whereas the lowest contaminant removal efficiency of the dining areas was 0.46 in Restaurant H1. Due to the side exhaust system on edges in Restaurants H2, B1 and B2, all contaminant removal efficiencies exceeded 0.83. The energy utilization coefficient of the dining areas ranged from 0.87 (H1) to 1.22 (B1). In the dining area, even the air conditioning system can provide adequate cooling capacity, and the ability to eliminate contaminants was questioned.

The data in Table 7 showed that the highest contaminant removal efficiency of the hot working area in Kitchen B1 was 1.07. The lowest contaminant removal efficiency in Kitchen H1 was 0.50. Kitchens H2 and H3 did not have a local exhaust system; thus, the contaminant removal efficiency was representative of the general ventilation system. For other kitchens, the contaminant removal efficiency had a significant correlation to the capture efficiency of the exhaust hood. One of the important factors that affect the capture efficiency of the exhaust hood is the surface air velocity. In Kitchen H1, the main reason for low contaminant removal efficiency was that the surface air velocity of the exhaust hood was only 0.1 m s^{-1} , which did not meet the design requirement of 0.5 m s^{-1} . The highest energy utilization coefficient of the kitchens of 1.03 was achieved in Restaurant B1, whereas the lowest energy utilization coefficient of 0.57 was achieved in Restaurant H1.

DISCUSSION

In contrast from the general-style restaurants, in Chinese hot pot and barbecue restaurants, the dining process and cooking process are simultaneously performed. The dining area is equivalent to the kitchen, and the diner is equivalent to the chef. Air pollutants, waste heat, water vapor, and odors that were generated during the eating process were

Table 7. Comprehensive assessment of the dining areas in sampled restaurants.

		H1	H2	H3	H4	H5	B1	B2	B3	B4
Dining area	$\bar{C}$ (ppm)	1672.9	682.2	785.9	861.8	762.2	496.2	844.3	803.2	908.5
	C_s (ppm)	382	420	410	397	403	455	453	412	437
	C_e (ppm)	981	637	750	803	724	503	825	776	843
	ε	0.46	0.83	0.90	0.87	0.89	1.16	0.95	0.93	0.86
	$\bar{t}$ (°C)	25.4	27.7	26.0	25.5	26.0	28.7	24.8	24.7	27.1
	t_s (°C)	23.0	23.0	23.0	23.0	23.0	23.0	20.0	20.0	23.0
	t_e (°C)	25.1	27.2	26.0	25.4	25.8	30.0	24.9	25.3	26.9
	η_t	0.87	0.89	1.00	0.96	0.93	1.22	1.02	1.12	0.95
Kitchen	$\bar{C}$ (ppm)	1691.2	595.4	726.8	979.3	610.8	560.0	747.8	654.2	960.2
	C_s (ppm)	382	420	410	397	403	455	453	412	437
	C_e (ppm)	1040	550	684	830	648	567	738	625	834
	ε	0.50	0.74	0.86	0.74	0.93	1.07	0.97	0.88	0.76
	$\bar{t}$ (°C)	40.3	27.3	26.8	28.2	31.0	29.3	28.2	28.3	30.0
	t_s (°C)	23.0	23.0	23.0	23.0	23.0	23.0	20.0	20.0	23.0
	t_e (°C)	33.5	27.2	26.4	28.0	30.5	29.5	27.7	27.7	29.3
	η_t	0.57	0.98	0.89	0.96	0.94	1.03	0.94	0.93	0.9

released into the indoor air. Heat exposure and pollution exposure to personnel are extremely serious because people sit around the cooking sources throughout meal time. This type of restaurant often arranged dozens of cooking sources in the dining area. Hundreds of people eat together.

The results indicated that the CO concentration fueled with charcoal was the highest in the dining area, whereas the CO₂ concentration fueled with gas was the highest. This finding is consistent with the study conducted by Lee *et al.* (2001) and Chen *et al.* (2007) for some restaurant environments. When the local exhaust system was present, the indoor pollutants in the dining area could be effectively reduced. However, the premise was that the kitchen's local ventilation system would operate well because the local exhaust hood creates negative pressure in the kitchen and the make-up air predominantly originated in the dining area through a pass-through window or door. The ventilation rate of all the restaurants is based on the same air change rate; however, in actuality, the ventilation system is difficult to meet the design requirements, especially the local exhaust system in the kitchen. Due to improper operation adjustment (some kitchens only open the exhaust system during peak dining time), grease blockage and unreasonable pipeline design, the local exhaust ventilation rate may exceed or fall below the design value. If the actual local exhaust ventilation rate is too low, it will lead to positive pressure in the kitchen, making cooking pollutants escape the kitchen and affect the indoor air quality in the dining room. On the contrary, if the actual exhaust air is too high, it will lead to higher operating energy consumption. The connection between the ventilation systems in the kitchen and the dining area of the hot pot and barbecue restaurants had been neglected.

During a meal, the temperature change in the dining area was small, and the relative humidity significantly increased. The air conditioning system was able to provide sufficient cooling capacity in the hot pot and barbecue restaurants. However, the system lacked the ability to eliminate moisture and pollutants. The traditional mixed ventilation system that is based on the dilution principle aims to satisfy people's

thermal comfort and hygiene requirements. Regardless of the location of indoor pollution sources and the personnel distribution, the importance of the occupied zone, which requires a large amount of ventilation, applies to all restaurants. In many cases, not only the problem of poor indoor air quality but also the initial investment and operating costs of the entire ventilation system are increased, which causes unnecessary economic waste (Gao *et al.*, 2014). In previous studies, we discussed the reasons for poor thermal environments in kitchens and unsuitable mixed ventilation systems (Li *et al.*, 2012). In this research, we determined that a mixed ventilation system is not suitable for the dining areas of hot pot and barbecue restaurants for the following reasons.

1. The unwanted air movement and cross-drafts created by the high discharge velocity from mixing diffusers generates pollution that gathers at the top of a restaurant (dining area or kitchen) and extends to the breathing zone. Human exposure to pollutants is increased due to the poor air distribution.
2. All heat and pollutants from multiple heat sources in the restaurant (dining area or kitchen) are mixed within a space, which hinder the capture of the plumes from cooking sources with an exhaust air flow or hood.

Compared to a kitchen, the indoor environment in a dining area deserves more attention due to the highly intensive cooking sources. The actual distribution of the cooking sources in the dining area must be considered to ensure that contaminants can be effectively eliminated during meal time and fresh air can be efficiently delivered to the sitting area. In this study, the side exhaust system that is placed on the edge of a table can effectively reduce the exposure to pollutants; however, the energy consumption was immense. The air volume used for the side exhaust system exceeded 80% of the total exhaust air volume of the dining area. A more suitable ventilation mode for hot pot and barbecue restaurants is needed. Similar to the kitchen, the thermal plumes and cooking fumes that are generated during eating hot pot and barbecue flow upward. As a reference for kitchen ventilation, the displacement ventilation combined with a

local exhaust system, which warrant further investigation, may be a suitable system for this type of restaurant (Li et al., 2012).

CONCLUSIONS

The indoor environmental quality of hot pot and barbecue restaurants, where cooking and dining simultaneously occur, has attracted growing public concern. Thus, this paper presents an integrated evaluation of the conditions and ventilation systems in five commercial hot pot restaurants and four barbecue restaurants in China. The environment in the dining area was influenced by the cooking fuel and the mechanical exhaust systems, especially the local one. Although the relative humidity in the dining areas significantly increased following a meal, the mean temperature showed minimal difference. Restaurant B3, which used charcoal as the cooking fuel, and Restaurant H1, which used natural gas, exhibited the highest mean CO (11.8 ppm) and CO₂ (1673.2 ppm) concentrations, respectively. In restaurants that had installed a local exhaust ventilation system beneath the dining table (where the heat source was located), the temperature and contaminant levels above the table remained relatively low and consistent throughout the meal. On the other hand, the environment in the cooking area of the kitchen depended on the fuel, cooking method and hood exhaust system.

In general, as with other types of restaurants, charcoal burning and natural gas combustion were associated with increases in CO and CO₂, respectively. Various cooking patterns caused different heat and humidity loads. Owing to the low contaminant removal and heat removal efficiencies of the ventilation system, the average temperature, and CO and CO₂ concentrations in the cooking area of Restaurant H1 were 40.3°C, and 12.9 ppm and 1691.2 ppm, respectively. Additionally, the relative humidity was 47.0%, and the capture and containment efficiencies of the exhaust hood were found to fall short of the standard.

Overall, the use of charcoal in indoor restaurants should be reduced, and a clean alternative, such as electricity, should be employed. To ensure that the kitchens exhaust a sufficient volume of air, local exhaust systems should be installed. However, determining the most suitable air distribution system requires further investigation.

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