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Indoor thermal environment and air quality in Chinese-style residential kitchens

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ABSTRACT

This paper reviews the published literature on indoor thermal environment and air quality in Chinese-style residential kitchens (CRKs). The paper first discusses typical characteristics of CRKs, including kitchen layout, cooking methods and ventilation systems used. Next, the paper describes the current state of the indoor thermal environment and air quality in CRKs. Finally, this paper summarizes measures to control and improve the environment inside CRKs. The results indicate that the indoor environment of CRKs is too hot in summer and exhibits a large vertical temperature difference. No appropriate model was available for accurately evaluating the thermal environment in CRKs. At the same time, CRKs are highly polluted by COx, NOx, TVOC and particulate matter (PM). Although existing exhaust hoods could improve the indoor environment to some extent, the use of a combined exhaust, make-up air and air-conditioning system should be considered to provide a comfortable and healthy environment in CRKs.

Keywords: Thermal comfort, Indoor air quality, Exhaust, Air-conditioning, Range Hood, Experiment

Practical Implications

This study reviews the characteristics of Chinese-style residential kitchens (CRKs), the current status of thermal comfort and indoor air quality in CRKs and measures to improve thermal comfort and indoor air quality for CRKs. The result can be used to provide a better understanding of the effects of the indoor environment of CRKs on human comfort and health as well as ways to improve the indoor environment.

1. Introduction

A kitchen is an important place in a Chinese home, where considerable time is spent on meal preparation for the family. A 2017 survey [1] showed that 66% of Chinese families used their kitchens more than five days per week, while 40% used them at least once per day. Therefore, residential kitchens should provide a healthy and thermally comfortable indoor environment. However, the actual environment inside Chinese residential kitchens (CRKs) is not satisfactory. Epidemiologic evidence has confirmed an association between exposure to cooking fumes and lung cancer risk among never-smoking women in China, especially in poorly ventilated settings [2]. The above-mentioned survey [1] indicated that only 4.62% of the respondents were very satisfied with the existing kitchen environment, and another survey [3] showed that 89% of respondents were negatively affected by kitchen fumes.

There were two main reasons for survey respondents' dissatisfaction with the kitchen environment. First, Chinese-style cooking includes frying, stir-frying, stewing, etc., which generate large amounts of heat and moisture during [4]. These processes lead to a high indoor air temperature in summer, when CRKs are ventilated inefficiently, or not ventilated at all. The high air temperature and humidity would cause thermal discomfort. Furthermore, the high-power gas stoves commonly used in CRKs [5] generate large amounts of heat in small kitchens, which would further worsen the thermal environment [6]. Zhao et al. [7] measured the air temperature inside residential kitchen at 10.3K higher than that outdoors during cooking. Even with a high ventilation rate, an exhaust hood cannot effectively remove excess heat from the kitchen [8]. The second reason for dissatisfaction is that cooking fumes in Chinese kitchens contain a mixture of pollutants, including particulate matter (PM), polycyclic aromatic hydrocarbons (PAHs), and gaseous pollutants, such as volatile organic compounds (VOCs), oxides of carbon (COx), and oxides of nitrogen (NOx) [5]. Many studies [9,10] have shown that these air pollutants are harmful to human health, exhibiting lung toxicity, immune-toxicity, genotoxicity and potential carcinogenicity. Chinese cooking releases more particulate and gaseous pollutants than Western cooking [5, 11]. Therefore, it is especially important to improve the thermal environment and indoor air quality (IAQ) in CRKs.

Exhaust hood was commonly used to exhaust cooking heat and pollutants for improving thermal environment and IAQ in CRKs. To increase the flow rate through hood can improve IAQ [12,13] but may increase energy consumption. The reduction of the distance between stove and hood can also increase the capture efficiency [14] but there was a limit. Some used air curtains [15,16] around stove to control fume diffusion or to optimize hood design by adding baffle plate [17], separation plate [18] and side plate [19], etc. These measures can improve IAQ in kitchens. In addition, commercial kitchens used air conditioning for creating a thermally comfortable environment [20] that could also be used in CRKs. In order to have a better understanding of the performance of different measures, it is important conducted a critical review on the above mentioned measures for improving indoor environment in CRKs.

Many review studies have been conducted on CRKs. For example, Wang et al. [21] reviewed the impact of Chinese cooking emissions on the atmospheric environment and human health. Zhao et al. [22] reviewed the characteristics of air pollutant emissions from Chinese cooking. Han et al. [23] reviewed the hood performance and capture efficiency of Chinese commercial kitchen ventilation systems. These studies focused on commercial and industrial kitchens or cooking pollutant emissions from Chinese cooking. Our literature search did not find any reviews of efforts to improve the thermal environment and indoor air quality in CRKs. Such literature would provide a better understanding of the effects of the indoor environment of CRKs on human comfort and health as well as ways to improve the indoor environment. Our aim in this paper is to provide such an overview. This paper first introduces various features of CRKs, including kitchen layout, cooking methods, and ventilation systems. We then discuss the thermal environment and indoor air quality in CRKs. Finally, we summarized several strategies for improving the environment inside CRKs.

2. Chinese Residential Kitchens Features

The environment inside a CRK can be affected by the layout of the kitchen, the cooking method used, and the ventilation system. This section discusses these factors.

2.1 Kitchen layout

CRKs are relatively small in size. The Chinese design code for residential buildings [24] stipulates a residential kitchen not be smaller than 4.0 m^2 for an apartment with a living room, a bed room, and a bath room, or smaller than 3.5 m^2 for an apartment without a living room. However, according to a survey in 2017 [25], 14.9% of residential kitchens in Chinese first- and second-tier cities had an area smaller than 4.0 m^2, 25.6% were in the range of 4.0 to 6.0 m^2, and 47.7% ranged from 7.0 to 12.0 m^2. The median size of CRKs was 6.0 to 7.0 m^2. By contrast, in the United States, the average area of new residential kitchens was far greater, reaching 28.0 m^2 in 2013. This is also reflected in the sizes of CRKs used in previous studies, as summarized in Table 1.

Table 1 Sizes of CRKs used in previous studies

No.	Reference	Year	Type of kitchen	Size (L×W×H) (m)
1	Nong [26]	1996	Actual kitchen	1.9×2.5×2.8 1.5×2.2×2.7 1.5×2.1×2.8 1.6×2.2×2.7
2	Chiang [8]	2000	Mock-up kitchen	2.7×2.1×2.4
3	Lai [27]	2005	Mock-up kitchen	3.0×1.6×2.1
4	Gao et al [28]	2013	Mock-up kitchen	3.5×1.8×2.4
5	Poon [29]	2013	Mock-up kitchen	4.6×2.3×2.3
6	Zhao et al. [7]	2014	Actual kitchen	3.0×2.5×2.8
7	Liu et al. [30]	2014	Mock-up kitchen	3.2×2.4×2.8
8	Yu [31]	2015	Actual kitchen	7.0×7.7×4.0 2.2×3.4×3.0 1.9×3.8×3.0 2.2×4.0×3.0 3.8×4.4×4.0
9	Zhou [32]	2016	Mock-up kitchen	2.3×1.5×2.4
10	Li et al [33]	2016	Mock-up kitchen	4.5×4.0×3.0
11	Cao [3]	2017	Mock-up kitchen	3.5×1.8×2.4
12	Wei et al. [34]	2016	Mock-up kitchen	2.3×1.5×2.4
13	Chen [35]	2018	Mock-up kitchen	2.7×2.0×2.3
14	Zhou [36]	2019	Mock-up kitchen	3.0×1.9×2.4
15	Zhou et al [37]	2019	Actual kitchen	2.9×1.9×2.3

Fig. 1 shows the layout of a typical Chinese apartment with two bedrooms for a three-person family. The apartment was located in Changsha, China. It was newly built in 2018. The total area of the apartment is 90 m^2 with a 5.4 m^2 kitchen. Unlike Western kitchens, which are large and mostly open without partition walls, the CRK is small and enclosed.

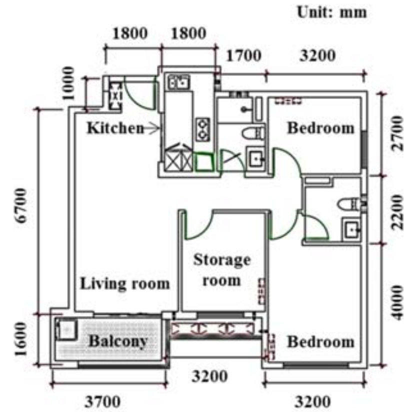


Fig. 1. Layout of a typical Chinese apartment

Fig. 2 provides a schematic of a typical CRK. It has an exterior window, an interior door, a range hood, and a gas stove. Unlike commercial kitchens, the CRK has only a simple exhaust hood and does not have air conditioning or a make-up air system. The make-up air for the range hood comes from the exterior window or adjacent living room, through an opened window/door and cracks. Depending on the local climate, some residents may close the exterior window to prevent the flow of exhausted air back into kitchen during cooking or when the outdoor air temperature is too high or too low. Cao [3] collected 1,176 questionnaires between 2012 and 2015, and the results indicate that 32% of the residents closed their windows during cooking because outdoor conditions were not acceptable. The interior door of the kitchen was also usually closed because of high concentrations of fumes and PM, and noise generated during cooking [32]. Similar behavior was observed in South Korea [38], where only 28.3% of respondents turned on the range hood and opened windows at the same time.

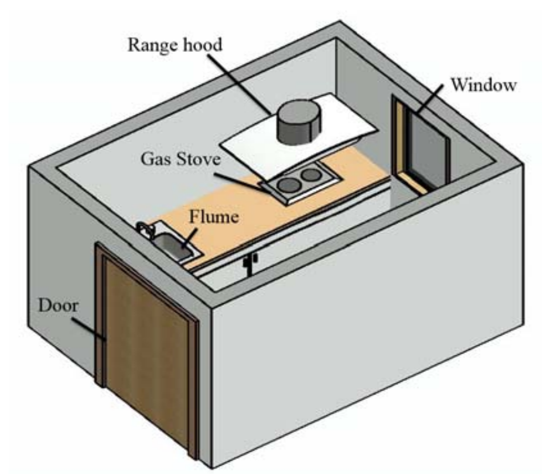


Fig. 2. Schematic of a typical residential kitchen in China

In summary, CRKs are generally small in size with a median floor area of around 6.0 to 7.0 m^2. Typical CRKs have a hood but no make-up air system. Many people close the window or door in the kitchen during cooking.

2.2 Cooking methods

China has different cuisines with a variety of cooking methods, such as stir-frying, boiling, steaming, stewing, pan-frying, and deep-frying. Cooking method, cooking fuel, cooking oil, food ingredients, cooking duration, and so on, affect cooking emissions [21]. In order to identify the most important factor, Chen et al. [5] measured the emission rates of $PM_{2.5}$, ultrafine particles, and VOCs generated in CRKs. They designed five-level orthogonal tests for cooking method, ingredient weight, meat type, oil type, and meat/vegetable ratio. According to the results, cooking method was the most important factor for cooking emissions, and stir-frying released the greatest number of cooking pollutants. As shown in Table 2 [5], 84.6% of Chinese people prefer stir-frying when they are cooking at home. People usually remain in the kitchen when they are engaged in various types of frying. Fig. 3 shows an example of stir-frying, which generates many different pollutants.

Table 2. Cooking method preferences and remaining in the kitchen during cooking in CRKs [5]

Cooking method	Percentage who prefer the method	Percentage who remain in Kitchen
Stir-frying	84.6%	96.9%
Boiling	9.4%	24.5%
Steaming	2.7%	14.4%
Stewing	2.0%	8.8%
Pan-frying	1.0%	83.1%
Deep-frying	0.3%	82.9%

Fig. 3. Stir-frying of Chinese food

Thus, the results in the literature show that cooking method is the most important factor in pollutant generation, and stir-frying generated many different pollutants.

2.3 Ventilation systems

As mentioned above, in contrast with commercial kitchens, the CRKs described in the literature had only a simple exhaust hood and did not have air conditioning or make-up air systems. During cooking, the hood exhausted cooking fumes to the outdoor environment, and negative pressure was maintained in the kitchen. Chen et al. [5] reviewed the top 165 best-selling range hoods, which accounted for 90% of sales in China. The nominal airflow rate of these hoods ranged from 780 to 1,080 m^3/h and could reach 1,320 m^3/h. However, the measured airflow rates in various studies ranged from 120.5 to 774.3 m^3/h, as shown in Table 3, and were much lower than the nominal values. The main reason for the difference was the lack of sufficient make-up air in the kitchen when the exterior window or interior door was closed. According to airtightness tests for buildings constructed in cold regions in 2013 and

2014, the air change rate varied from 1.89 h^{-1} to 0.84 h^{-1} with a mean value of 1.42 h^{-1} under a pressure difference of 50 Pa between indoor and outdoor air [39]. Similarly, in 2016, Liu [40] monitored the room infiltration rate in the residences of 224 Chinese families for a period of one year, in a study that covered all of the five Chinese climate zones. The results showed that the median infiltration rate was only 0.37 h^{-1} in northern China and 0.42 h^{-1} in southern China. Under such airtightness, and even if the kitchen door was open, the airflow from the living room would be too low to provide make-up air. In addition, the exhaust system was often shared by several families in the same building. The shared chimney and operation of the exhaust hood by those families may complicate the exhaust system and significantly increase the flow resistance. The use of a range hood with uncontrolled natural ventilation may not be sufficient for removal of cooking pollutants. According to a survey in 2019 [41], the actual exhaust airflow rate of range hoods was only 30% to 40% of the nominal airflow rate. Thus, range hoods cannot effectively remove excess heat or indoor pollutants from CRKs [42].

Table 3. Actual airflow rates of range hoods

Reference	Year	Airflow rate (m^3/h)
Chiang [8]	2000	530
Lai [27]	2005	444
Man [29]	2013	483.6 682.8 774.3
Zhou [32]	2016	583.2
Cao [3]	2017	120.5 563.6

In summary, the above review found that CRKs did not have adequate make-up air. The actual ventilation rate was much lower than the nominal ventilation rate indicated on the hood.

3. Thermal Environment in Chinese Residential Kitchens

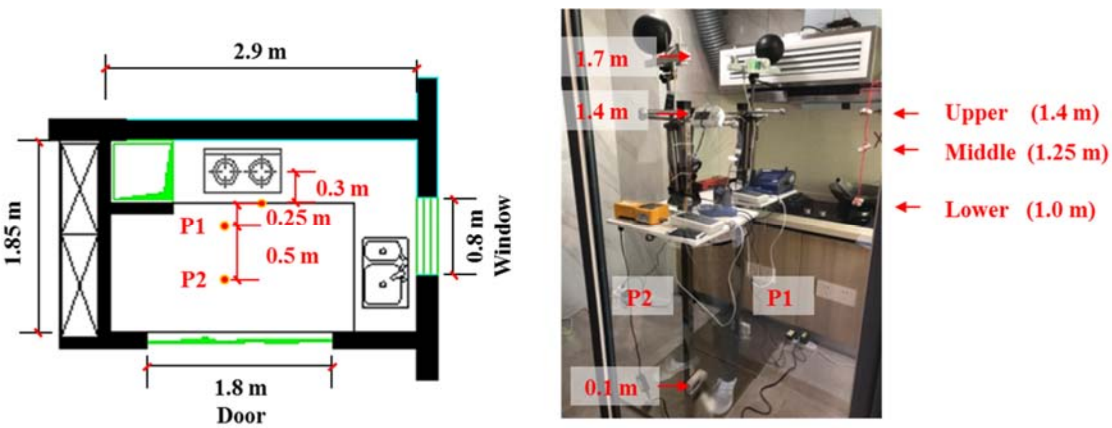
This section addresses the thermal environment in CRKs in terms of air temperature, relative humidity, and vertical air temperature difference. We also discuss the thermal comfort of cooks and the evaluation method for thermal comfort in CRKs.

3.1 Thermal environment in CRKs

Zhao [7] measured air temperature and humidity in an actual kitchen during the cooking of eight traditional Chinese dishes. The air temperature in the kitchen was found to increase by about 4.0 to 11.5 K, depending on the cooking method. The heat generated in the kitchen should have reduced the relative humidity. However, the relative humidity actually increased by 15-30% as a large amount of water vapor from cooking entered in the space. When the range hood was turned off, the temperature and relative humidity were found to increase dramatically [43]. Even with sufficient make-up air at 25°C from an exterior window and with a range hood operating, the air temperature could still increase by about 6.0 to 8.5 K during frying [32,36]. The maximum vertical temperature difference between ankle level (0.1

m) and head level (1.7 m) could reach 6.3 K, which exceeds the maximum difference of 3.0 K accepted for thermal comfort [34].

In order to better understand the thermal environment inside CRKs, we conducted experimental tests in a CRK on a late summer day (September 12, 2018) in Changsha, China, which belongs to the subtropical monsoon climate. As shown in Fig. 4, the kitchen dimensions were 2.9 m (L) × 1.85 m (W) × 2.3 m (H). Subjects were asked to cook two dishes (one capsicum-fried meat and the other stir-fried vegetables) in the kitchen during the experiment. Nine HOBO loggers were used to record the temperature and relative humidity of the indoor air, at heights of 0.1, 1.4, and 1.7 m above the floor at positions P1 and P2 in the occupied zone of the kitchen, and at three locations (upper, middle, and lower) between the stove and the hood as shown in Fig 4. We also used one HOBO logger to measure outdoor air temperature and humidity outside the kitchen. The HOBO loggers had a measuring accuracy of ±0.2 K for air temperature and ±2% for relative humidity.



(a) (b)

Fig. 4. Experimental setup in a kitchen for indoor air temperature and relative humidity measurements. (a) Schematic of kitchen layout, and (b) Photo of experimental setup. HOBO data loggers were hung on poles P1 and P2 at heights of 0.1, 1.4, and 1.7 m above the floor in the occupied zone of the kitchen.

Fig. 5 portrays the air temperature and relative humidity distributions in the kitchen as well as outdoor air temperature and relative humidity. The indoor air temperature began to rise when the subject turned on the stove for cooking at 11:15 am, and it continued to rise during cooking. The highest air temperature rise, 6.3 K, was observed at the "stove-lower" position, which was closest to the stove. The maximum vertical air temperature difference was 4.0 K between P1-0.1m and P1-1.7m, and 3.0 K between P2-0.1m and P2-1.7m. The air temperature around the subject was highly non-uniform. Meanwhile, the relative humidity did not change significantly in the kitchen because of the counter-reaction between temperature increase and moisture generation. In contrast, the relative humidity above the stove (upper, middle, lower) decreased greatly because of significant heat generation by the stove.

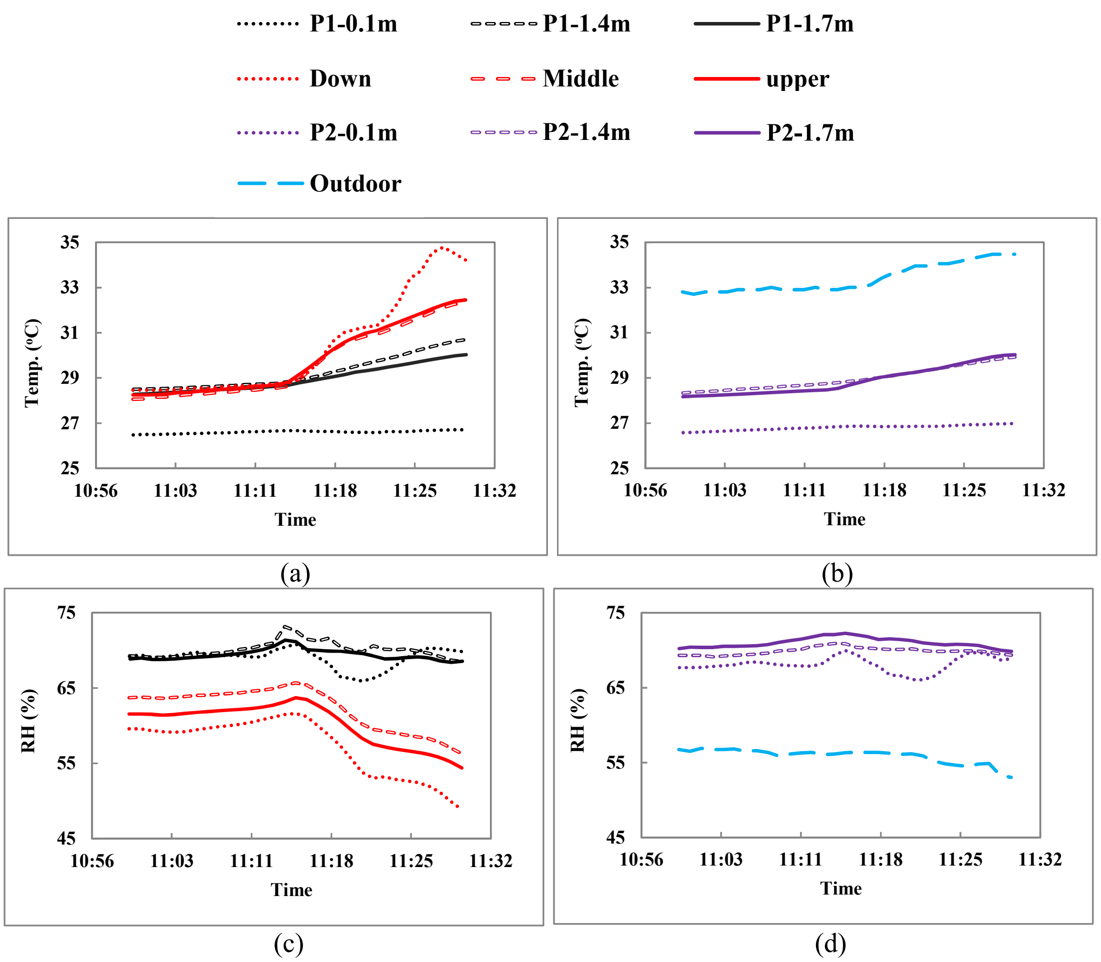


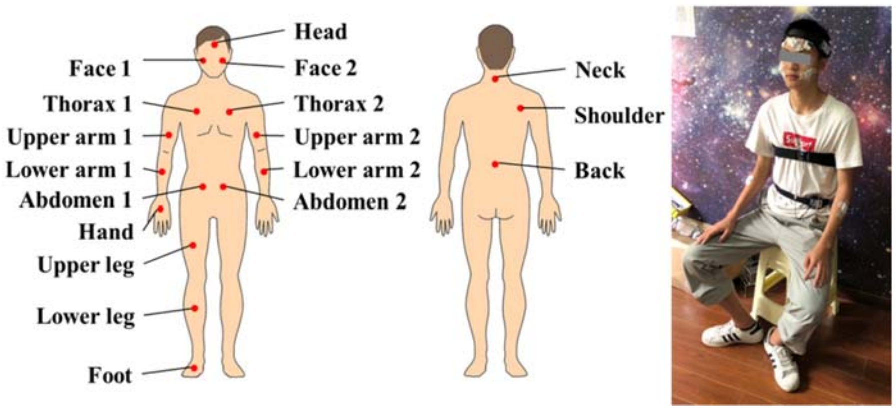
Fig. 5. Air temperature and relative humidity changes during cooking in the CRK: (a) Air temperature changes at P1, Upper, Middle and Lower, (b) Air temperature changes at P2 and Outdoor, (c) Relative humidity changes at P1, Upper, Middle and Lower, and (d) Relative humidity changes at P2 and Outdoor.

The results in the literature and from our measurements demonstrate that air temperature increased dramatically in CRKs during cooking, often creating an excessively hot thermal environment. In addition, the vertical temperature difference between head and ankle level was often too large to be acceptable to the occupants.

3.2 Thermal Comfort in CRKs

The transient and non-uniform thermal environment in CRKs would affect cooks' skin temperature as well as thermal sensation and comfort. Wei et al. [34] and Zhou et al. [36] conducted thermal comfort measurements in a CRK under winter conditions. They measured the subjects' skin temperatures on different body parts and recorded the subjects' thermal sensation votes (TSV) during cooking. They found that the thermal comfort of the chest, abdomen, and right lower arm would increase because of the heat generated during cooking. In winter, the cooking heat was beneficial to the cook's thermal comfort. In the summer, however, thermal comfort would decline. Zhou et al. [37] conducted human subject tests for 20 cooks as they prepared dishes in a CRK under summer conditions. The researchers found that the subjects' TSV increased by 0.5 units when the stove was turned on. After 15 minutes, the median TSV reached the highest level of +3 (very hot).

We also conducted thermal comfort measurements in the CRK shown in Fig. 4. Sixteen subjects, nine males and seven females with an average age of 22 (standard deviation = 4) from a cooking school, participated in the tests. While the subjects were cooking, a subjective questionnaire survey recorded their thermal sensation votes, and objective on-site measurements of their skin temperatures (T_{sk}) were conducted. We asked the subjects to vote their thermal sensations every minute during cooking. The skin temperature on 18 body parts of the subjects was measured with the use of wireless button thermometers, which had been employed in previous studies [34]. Fig. 6 depicts the skin temperature measurement locations.



(a) (b)

Fig. 6. Measurement positions for skin temperature: (a) schematic view and (b) photograph of a subject wearing wireless button thermometers.

The experimental process was as follows: Before each test, the external window and interior door were opened. A portable vertical fan in the kitchen and the exhaust hood were turned on about 20 minutes and then the window and door of the kitchen were closed for 10 minutes. The effort was to ensure the kitchen started with a non-conditioned status as most CRKs. At the same time, we asked the subject to stay at a preparation room with an ambient temperature close to 26^{o}C for 30 minutes to achieve a neutral thermal state. During their stay in the room, all the subjects were briefed on the experimental procedure and taped the wireless button thermometers on their skin. After they reached the thermal neutral status at t = 30 minutes, they went to the kitchen and the exhaust hood and the stove were switched on. The airflow rate of the exhaust hood was 700 m^3/h with make-up air and 225 m^3/h without make-up air. The external window and door were closed during cooking. The total cooking period lasted around 20 to 30 minutes. During this time, we asked the subjects to vote their thermal sensations every minute. When the cooking was finished, the subject left the kitchen. Each test took 50 to 60 minutes depending on the cooking speed.

Figures 7(a) and (b) show the skin temperatures on the forehead and face versus the TSV during cooking for a typical subject. TSV is thermal sensation vote. The TSV rose with the skin temperature. The maximum increases in skin temperature on these two body parts during cooking were 2.5 K and 3.0 K, respectively. All the cooks complained that the hottest body parts were the head, face and thorax areas. This occurred because the three regions were highly exposed to the elevated air and radiant temperatures. Figure 7(c) depicts the maximum skin temperature increase on different body parts during cooking, for the 16 subjects. The skin temperature increase was highest at the head region with a median of 3.4 K. The lower body parts and the back were less affected by the stove. The high radiation asymmetry may have distorted the TSV of the subjects. Both the results from the literature and our results seem to indicate that the thermal environment in CRKs was too hot in summer.

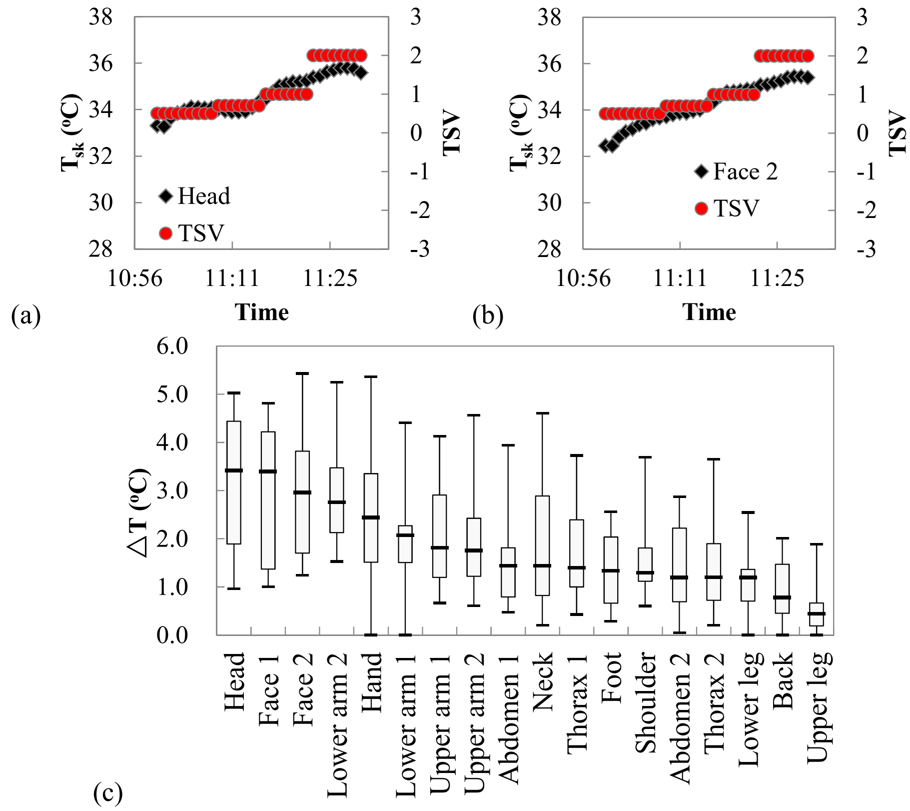


Fig. 7. (a) Head and (b) face temperature and the corresponding TSV during cooking for a typical subject, and (c) skin temperature increase on different body parts of the 16 subjects.

3.3 Thermal comfort evaluation models

To evaluate thermal comfort in kitchens, some investigations have used the PMV-PPD index [44]. This index was intended for buildings where the thermal environment is steady and uniform with sedentary or near-sedentary activity levels. It may not be suitable for kitchens, where the thermal environment is transient and non-uniform. Several other thermal comfort models have been developed for transient and non-uniform situations. For example, the dynamic thermal sensation model (DTS) from Fiala [45] was based on regression analysis of thermal sensation votes from an experiment in a climate chamber and human physiological responses (skin temperature, hypothalamus temperature, rate of change in skin temperature) calculated with the use of a multi-segment human heat transfer model. The University of California at Berkeley (UCB) model [46] was based on large-scale experimental tests of local and overall thermal sensations and thermal comfort. The dynamic outdoor thermal comfort model from Lai et al. [47] used thermal load, mean skin temperature, and the change rate of mean skin temperature as the predictor variables for thermal sensation. Here we discuss whether these four models (PMV, DTS, UCB, and Lai's) could be used to predict thermal comfort in CRKs.

Using our TSV data from the CRK in Changsha, China, Fig. 8 compares the actual individual thermal sensation with the sensation predicted by the above four models [37]. The results show that 39.2%, 28.9%, 21.3% and 16.1% of the votes predicted by the PMV, UCB, Lai and DTS models, respectively, differed by more than one unit from the actual votes. None of the models seem to provide acceptable results. Given the performance assessment of the above models, a transient and non-uniform thermal comfort model should be developed for the Chinese residential kitchen.

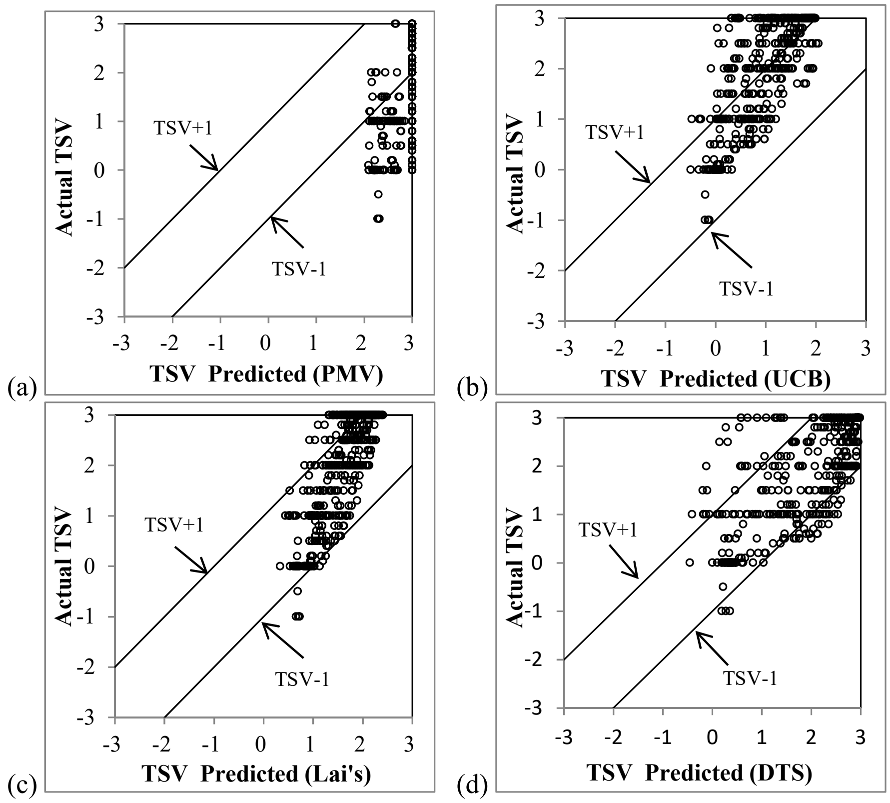


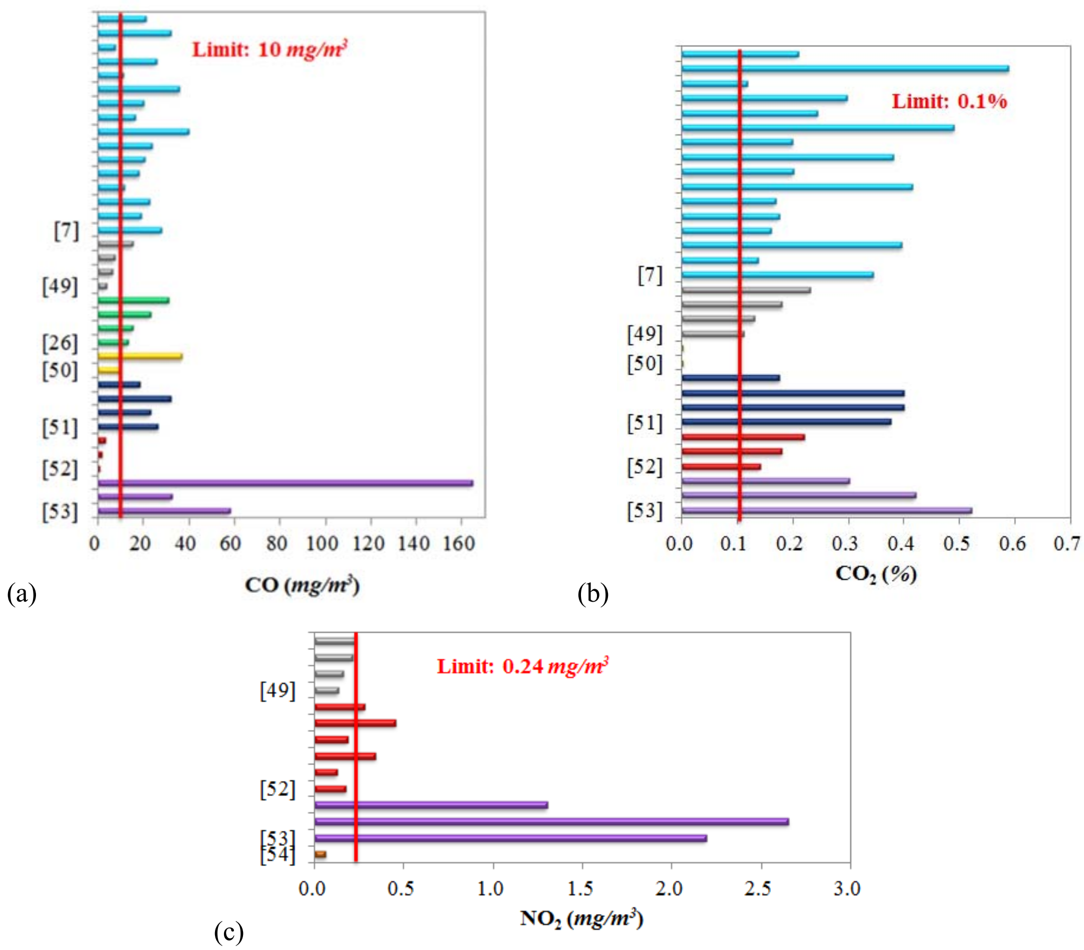
Fig. 8. Comparison of the actual individual thermal sensation with the predicted sensation by the (a) PMV, (b) UCB, (c) Lai, and (d) DTS models. ″TSV+1″ and ″TSV−1″ are the lines at winch predictions are one unit higher or lower than the actual value.

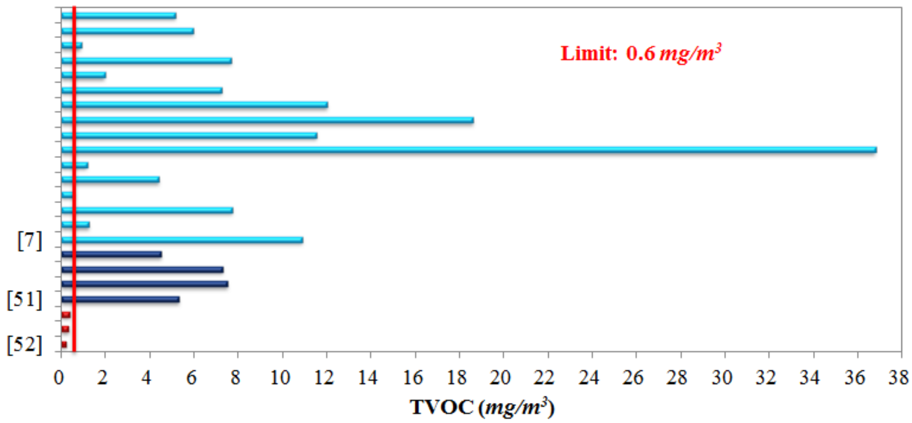
4. Indoor Air Quality in CRKs

Pollutants in CRKs consist of gaseous contaminants and PM. This section discusses indoor air quality in CRKs.

4.1 Gaseous pollutants in CRKs

The limits for TVOCs, CO, CO_2 and NO_2 in residential buildings in Chinese standard GB/T 18883-2002 [48] are 0.60 mg/m^3, 10 mg/m^3, 0.10%, 0.50 mg/m^3 and 0.24 mg/m^3, respectively. The limit for TVOCs is an eight-hour average, for CO and NO_2 an hourly average, and for CO_2 a daily average. Zhao et al. [7] measured CO, CO_2 and TVOC concentrations in the breathing zone of a CRK during the cooking of traditional Chinese dishes. The maximum increase in the concentrations of CO, CO_2, and TVOCs was from 1% to 240.8%, from 16.5% to 143.5%, and from 50% to 1900% of the limits in the national standard, respectively. Liu [49] investigated 400 residential kitchens and found that only 4.8% of them contained gaseous pollutants at levels below the stipulated limits. Similarly, Nong et al. [26] measured CO and NO_2 concentrations in four flats in Beijing and found that the CO concentration exceeded the national standard limits by 31.7% to 211.6%, and NO_2 by 315.5% to 1342.4%. Meanwhile, Huang et al. [50] measured CO and CO_2 concentrations in two dwellings in Hong Kong. They discovered that although CO_2 concentration met the standard requirement, CO concentration exceeded the standard by 3.0% and 268.4%, respectively, in the two dwellings. Zhou and Zhao [51] measured CO_2, CO and TVOC concentrations during the cooking of four different dishes in a typical CRK. The concentrations of CO and TVOC exceeded the standard limits by 83.3% to 220.8% and 650.0% to 1150.0%, respectively. Wang et al. [52] measured gaseous pollutants in kitchens in northeastern China during winter. Their results showed that although other pollutant concentrations met the standard, the CO_2 concentration exceeded the standard limit by 10% to 130%, and NO_2 exceeded the limit by over 40%. Guo et al. [53] studied CRKs with three types of domestic fuel (natural gas, liquefied petroleum gas and coal briquettes) and found that the gaseous pollutants (NO_2, CO, CO_2) all exceeded the national standard limits. Chao and Law [54] found that the average NO_2 level in CRKs without cooking activities was 38.6 ug/m^3, and with cooking activities it was 68.4 ug/m^3. The presence of a gas stove was the main factor associated with a significant increase in CO_2, CO, and NO_2 [43,55], especially with poor ventilation [56,57]. Fig. 9 compares the CO, CO_2, NO_2, and TVOC concentrations in CRKs reported in the above-mentioned studies. The red lines indicate the limits of the Chinese national standard. The results demonstrate that most of the CRKs had poor IAQ.

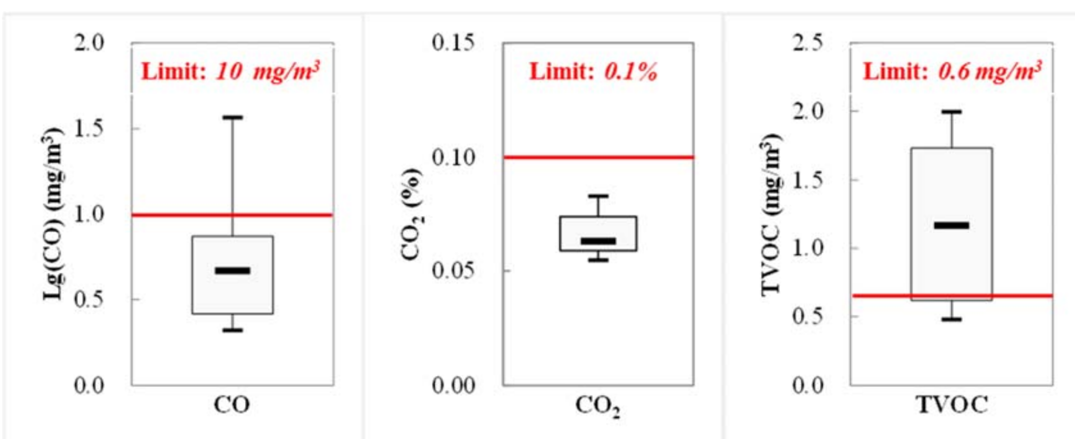




(d)

Fig. 9. Gaseous pollutant concentrations in CRKs according to various studies: (a) CO, (b) CO_2, (c) NO_2, and (d) TVOCs.

We also conducted gaseous pollutants measurements in the CRK shown in Fig. 4. We used one HOBO MX1102 logger to measure CO_2 concentration in the kitchen. The HOBO logger had a measuring accuracy of ±50 ppm. We also used one TSI IAQ CALCTM 7574 to measure CO concentration in the kitchen. Its measuring accuracy was ±3.0%. Measuring frequency for CO and CO_2 was every minute. The measured data was averaged for the whole cooking period. In order to measure TVOC concentration, Tenax TA tubes after aging treatment were used for sampling at 0.4 L/min for 5 min. Each sampling started when the subject added cooking material into the pan and started to stir-fry. The analysis of TVOCs used thermal desorption gas chromatography mass spectrometry (TD-GCMS). All measuring instruments were placed on a table at 1.4 m above the floor in position P1. Fig. 10 shows the CO, CO_2, and TVOC concentrations in the kitchen for the 16 tests. The red lines indicate the limits of the Chinese national standard. Although median value of CO and CO_2 concentrations met the standard, the TOVC concentration exceeded the limit specified by the standard.



(a) (b) (c)

Fig. 10. (a) Gaseous pollutant concentrations measured during cooking for the 16 tests: (a) CO, (b) CO_2, and (c) TVOCs.

Thus, the data from the literature and from our measurements indicates that most CRKs contained gaseous air pollutants, such as CO, CO_2, NO_2, and TVOCs, that exceeded the limits set by the Chinese national standard. Some kitchens had excessively high pollutant concentrations.

4.2 Particulate matter in CRKs

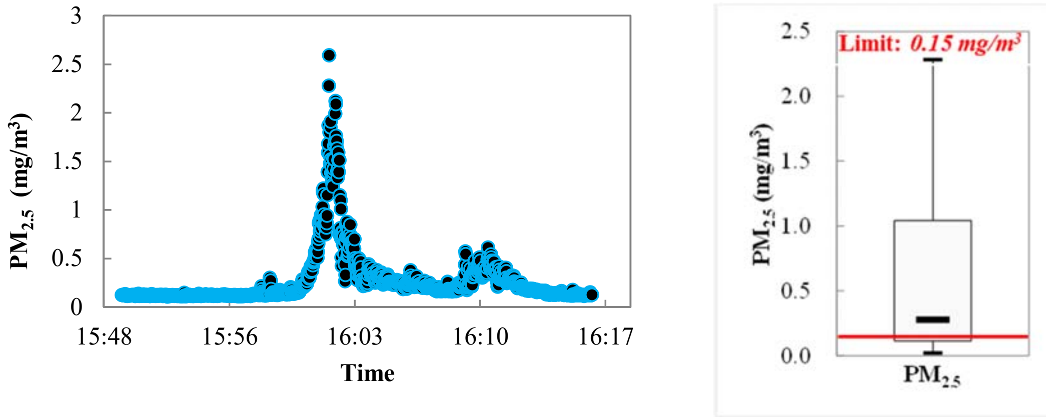
Cooking-generated particle matter (PM) is another important indoor pollutant. The limit for PM concentration in residential buildings is 0.15 mg/m^3 as a daily average, according to Chinese standard GB/T 18883-2002 [48]. The acceptable level for the 24-h average $PM_{2.5}$ is 25 ug/m^3, according to the World Health Organization (WHO) [58]. Yu [31] measured PM concentrations in five CRKs using gas stoves. Their results show that the 24-h mean PM number concentration in the breathing zone was 1,220–6,200 particles/cm^3 during non-cooking hours. However, the number concentration increased rapidly to 1.4×10^6 particles/cm^3 during cooking. Wan [59] measured the $PM_{2.5}$ concentration in 12 non-smoking homes and found that the average $PM_{2.5}$ concentration in the kitchen was 20 to 40 times that in the outdoor air when the hood was on. Similarly, Cao [3] measured $PM_{2.5}$ concentration in the breathing zone with an open exterior window and closed interior door. Even with the range hood on, the highest $PM_{2.5}$ concentration could range from 2.6 to 59.9 times the upper limit in the standard [60]. The highest concentration exceeded 10 mg/m^3. Du et al. [61] measured the particle exposure level generated by domestic Chinese cooking. They found that $PM_{2.5}$ mass concentration in the breathing zone during cooking far exceeded the acceptable level for the 24-h average recommended by the WHO. Meanwhile, To and Yeung [62] measured PM_{10} mass concentration in the breathing zone of the cook during the preparation of three kinds of cuisine. The PM_{10} concentrations ranged from 520 to 1330 ug/m^3; in other words, they were 3.5 to 8.9 times higher than the limit in the Chinese standard. Guo et al. [53] studied CRKs with three types of domestic fuel and found that the $PM_{2.5}$ and PM_{10} concentrations all exceeded the national standard by 28.3 to 117.0 times and 28.7 to 145.5 times, respectively. Table 4 summarizes the PM concentrations in CRKs reported in the above-mentioned studies. The data indicate that most of the CRKs had very poor IAQ, and the PM concentration could exceed the standard limit by 100 times or more.

Table 4. Variation in PM concentration in residential kitchens (P - peak value, A - average value)

Ref.	Particle size	Mass concentration (ug/m^3)	Number concentration (10^3/cm^3)	Stove	Cooking method
[31]	$PM_{1.8}$	15 (24-h A)	--	Gas	Daily cooking
	$PM_{1.8}$	111 (24-h A)	--	Gas	Daily cooking
	$PM_{1.8}$	19 (24-h A)	--	Gas	Daily cooking
	$PM_{1.8}$	18 (24-h A)	--	Gas	Daily cooking
	$PM_{1.8}$	5 (24-h A)	--	Gas	Daily cooking
	$PM_{3.2}$	17 (24-h A)	--	Gas	Daily cooking
	$PM_{3.2}$	156 (24-h A)	--	Gas	Daily cooking
	$PM_{3.2}$	35 (24-h A)	--	Gas	Daily cooking
	$PM_{3.2}$	37 (24-h A)	--	Gas	Daily cooking
	$PM_{3.2}$	7 (24-h A)	--	Gas	Daily cooking
	PM_{10}	22 (24-h A)	--	Gas	Daily cooking
	PM_{10}	227 (24-h A)	--	Gas	Daily cooking
	PM_{10}	101 (24-h A)	--	Gas	Daily cooking
	PM_{10}	80 (24-h A)	--	Gas	Daily cooking
	PM_{10}	10 (24-h A)	--	Gas	Daily cooking
[59]	$PM_{2.5}$	160 (A)	--	Gas	Daily cooking
[3]	$PM_{2.5}$	4491 (P)	--	Electric	Heating oil
	$PM_{2.5}$	198 (P)	--	Electric	Heating oil
	$PM_{2.5}$	679 (P)	--	Electric	Heating oil

	$PM_{2.5}$	1647 (P)	--	Electric	Heating oil
	$PM_{2.5}$	4008 (P)	--	Electric	Heating oil
	$PM_{2.5}$	210 (P)	--	Electric	Heating oil
	$PM_{2.5}$	1925 (P)	--	Electric	Heating oil
	$PM_{2.5}$	2152 (P)	--	Electric	Heating oil
	PM_{10}	8299 (P)	--	Electric	Heating oil
	PM_{10}	450 (P)	--	Electric	Heating oil
	PM_{10}	1938 (P)	--	Electric	Heating oil
	PM_{10}	4436 (P)	--	Electric	Heating oil
	PM_{10}	7259 (P)	--	Electric	Heating oil
	PM_{10}	622 (P)	--	Electric	Heating oil
	PM_{10}	5088 (P)	--	Electric	Heating oil
	PM_{10}	5102 (P)	--	Electric	Heating oil
[61]	$PM_{2.5}$	15530 ± 11270 (A)	--	Electric	Stir-frying of pork with peppers
	$PM_{2.5}$	8320 ± 7790 (A)	--	Electric	Scrambling of eggs with tomatoes
	$PM_{2.5}$	6950 ± 3250 (A)	--	Electric	Stir-frying of green vegetables
	PM	--	30.64 ± 20.68 (A)	Electric	Stir-frying pork with peppers
	PM	--	20.96 ± 17.24 (A)	Electric	Scrambling of eggs with tomatoes
	PM	--	13.33 ± 5.23 (A)	Electric	Stir-frying of green vegetables
[62]	PM_{10}	1330 (A)	--	Gas	Frying of vermicelli with beef
	PM_{10}	1020 (A)	--	Gas	Pan frying of meat
	PM_{10}	890 (A)	--	Gas	Deep frying of chicken wings
	PM_{10}	1030 (A)	--	Electric	Frying of vermicelli with beef
	PM_{10}	520 (A)	--	Electric	Pan frying of meat
	PM_{10}	680 (A)	--	Electric	Deep frying of chicken wings
[53]	$PM_{2.5}$	7024 ± 3951 (A)	--	Natural gas	Daily cooking
	$PM_{2.5}$	5176 ± 1767 (A)	--	Liquefied gas	Daily cooking
	$PM_{2.5}$	1697 ± 375 (A)	--	Coal	Daily cooking
	PM_{10}	21818 ± 10239 (A)	--	Natural gas	Daily cooking
	PM_{10}	13417 ± 5960 (A)	--	Liquefied gas	Daily cooking
	PM_{10}	4302 ± 1884 (A)	--	Coal	Daily cooking

We also measured $PM_{2.5}$ concentration in the CRK shown in Fig. 4. We used one TSI DustTrak 8530 to measure $PM_{2.5}$ concentration in the kitchen. It was placed on the table at 1.4 m above the floor in position P1. The frequency of the measured data was collected 60 Hz. The measuring accuracy was 1 $\mu g/m^3$. Fig. 11(a) shows the $PM_{2.5}$ concentration during cooking for a typical subject. The $PM_{2.5}$ concentration started to rise when the subject added cooking materials into the pan for cooking. The $PM_{2.5}$ concentration had two peaks because each subject was asked to cook two dishes (one capsicum-fried meat and the other stir-fried vegetables) in the kitchen during the experiment. In order to compare with the standard limit, the measured data was averaged for the whole cooking period for each test. Fig. 11(b) summarizes the $PM_{2.5}$ concentrations in the kitchen for the 16 tests. The median $PM_{2.5}$ concentration exceeded the standard limit after considering the background concentration.



(a) (b)

Fig. 11. $PM_{2.5}$ concentrations measured during cooking in the kitchen: (a) for a typical test, and (b) for the 16 test

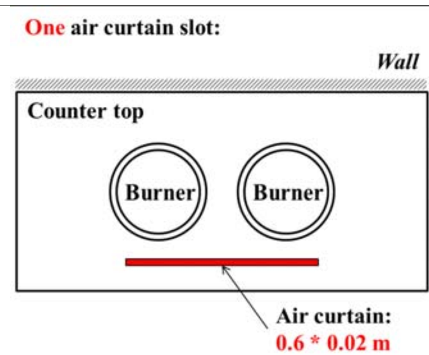
5. Improvement Measures for Kitchen Ventilation

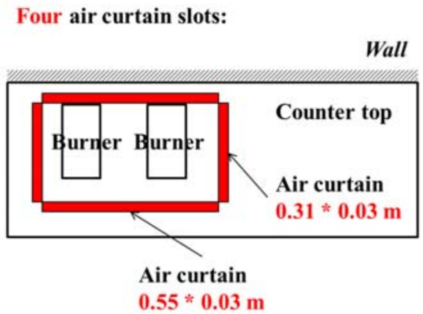
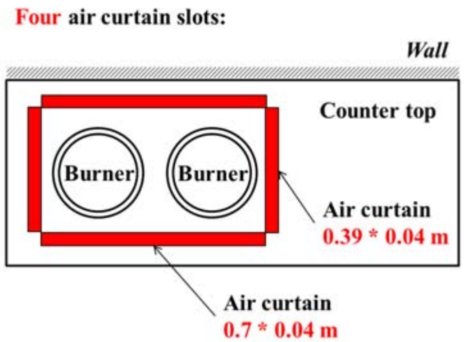
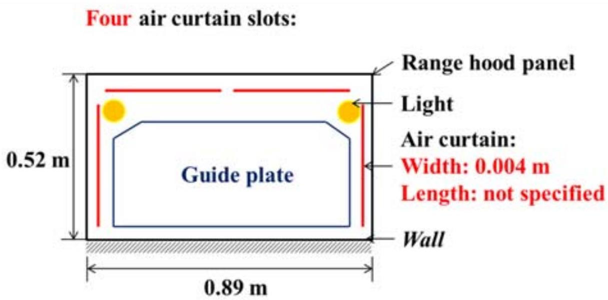
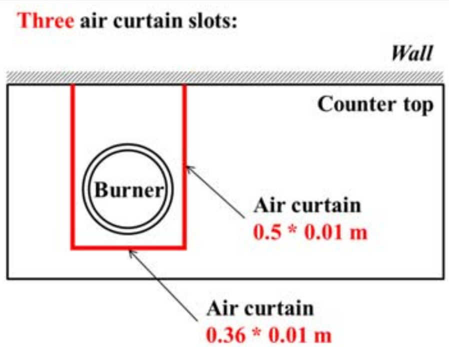
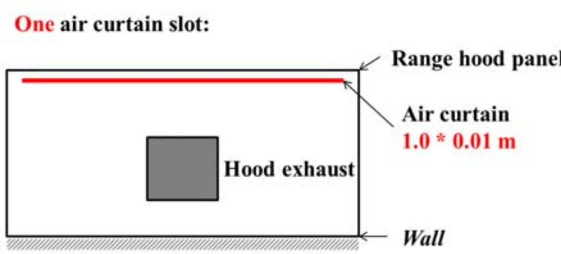
Previous investigations have suggested various measures to improve the thermal environment and IAQ in CRKs, such as controlling fume diffusion with air curtains, improving range hood design and installing air conditioners. This section aims to provide a critical review of these measures.

5.1 Controlling fume diffusion with air curtains

Controlling the diffusion of cooking fumes above the stove would be a straightforward way to improve the thermal environment and IAQ in CRKs. Many investigations have used air jets around the stove to form air curtain that restrain the spread of cooking fumes. In addition, the airflow from this curtain can provide make-up air to improve hood performance. Two major types of air curtain can be found in the literature, as shown in Table 5: upward and downward air curtains.

Table 5. Proposed air curtain design for improving thermal comfort and IAQ in CRKs

Ref.	Air curtain schematic	Air curtain details
Huang et al. [15,16]	 	• Upward air curtain • Velocity: 1.0 m/s • Angle: 15° • Flow rate: 41.7 m^3/h

<table>
<tr><td>Zhou et al. [32]</td><td>
</td><td>• Upward air curtain
• Velocity: 0.5 m/s
• Angle: 90º
• Flow rate: 92.9 m^3/h</td></tr>
<tr><td>Zhou et al. [36]</td><td>
</td><td>• Upward air curtain
• Velocity: 0.5 m/s
• Angle: 90º
• Flow rate: 92.9 to 157.0 m^3/h</td></tr>
<tr><td>Liu et al. [30]</td><td>
</td><td>• Downward air curtain
• Velocity: 1.5 m/s
• Angle: -5º
• Flow rate unspecified</td></tr>
<tr><td rowspan="2">Cao et al. [3]</td><td>
</td><td>• Upward air curtain
• Velocity: 1.0 ~1.5 m/s
• Angle: 90º
• Flow rate: 49.0 to 73.5 m^3/h</td></tr>
<tr><td>
</td><td>• Downward air curtain
• Velocity: 1.8 to 2.5 m/s
• Angle: 90º
• Flow rate: 64.8 to 90.1 m^3/h</td></tr>
</table>

As shown in the second row of Table 5, Huang et al. [15,16] used one slot at the front of the cooking range to form an air curtain that was directed upward. They found that, in comparison with a conventional hood, the air curtain dramatically reduced the spread of fumes and was much more “robust” in resisting the influence of walk-by motion. Using SF_6 as a tracer gas, the researchers observed that the concentration level in the breathing zone with the air curtain was 100 times lower than with a conventional hood.

Zhou et al. [32,36] used four slots around a gas stove to create upward air curtains as shown in the third and fourth rows of the table. The air curtains reduced the air temperature in the occupied region by 2.1 K and CO_2 concentration by 311 ppm [32]. The investigators also found that the air curtains increased the capture efficiency by around 5.6%, while the maximum vertical air temperature difference decreased by 0.5 K, in comparison to the case without the curtains [36].

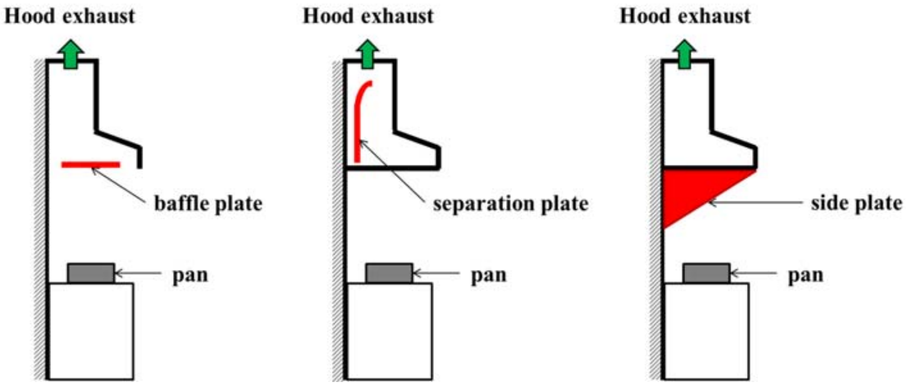
Liu et al. [30] used four slots located along the front and side edges of the range hood to generate downward air curtains, as shown in the fifth row of Table 5. In addition, there was a guide plate under the suction inlet of the hood where oil fumes were discharged. They found that with the air curtain, the air temperature in the breathing zone was 7.4 K lower than without the curtain. The concentration of oil fumes in the breathing zone of the case without the air curtain was $5.5x10^5$ times that in the case with the air curtain.

The last two rows of Table 5 show layouts used to compare the effectiveness of upward and downward air curtains in reducing an individual’s exposure to contaminants during cooking [3]. Cao et al. used three slots located in the front and on both sides of the stove to form an upward air curtain, and one slot in the front edge of the range hood to form a downward air curtain. When the upward air curtain was used, the pollutant mass inhaled by the cook was about two orders of magnitude smaller than in the case with all make-up air from an open window. Similar results were obtained with the downward air curtain.

In the above studies, no conclusion was reached about which kind of air curtain would be better. The airflow rate supplied from the curtains accounted for less than 30% of the range hood airflow rate, and the majority of the make-up air would still have to come from the window, door or leakages. Thus, the use of air curtains will improve thermal comfort in CRKs but cannot provide full satisfaction.

5.2 Improving range hood design

Another way to improve the thermal environment and IAQ in CRKs is to enhance range hood performance. Past investigations have used a baffle plate, separation plate, or side plates, as shown in Fig. 12. The plates reduce the suction area so that the sucking air velocity at the bottom of the hood increases, thus raising the likelihood that cooking fumes will be captured. As a result, the effort may reduce the spread of cooking fumes throughout the kitchen.



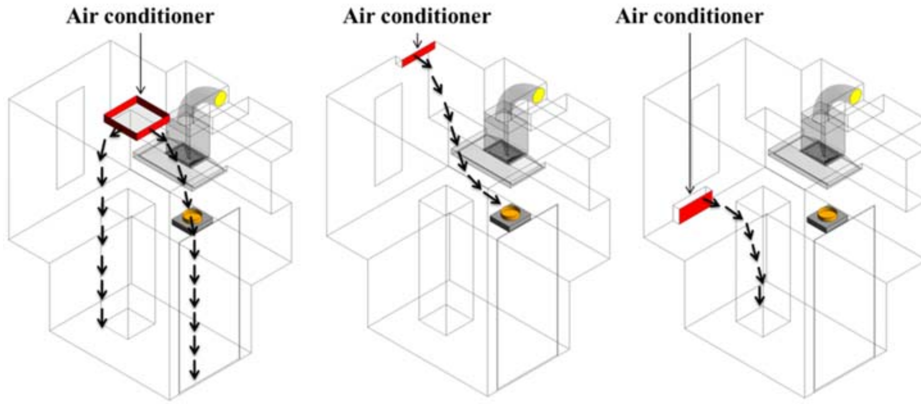
(a) (b) (c)

Fig. 12. Schematic for the use of various plates with a range hood: (a) baffle plate, (b) separation plate, and (c) side plates.

Kotani et al. [17] explored the influence of a baffle plate on the capture efficiency of a hood and found that a divided baffle plate with a 50% opening ratio could increase the capture efficiency by more than 5%. Lim and Lee [18] added separation plates in different shapes underneath a range hood and found that the effort removed 10% more CO_2. Zhao et al. [19] explored the performance of different hood shapes and side panels along with various exhaust duct arrangements. Their results showed that adding side plates improved the capture efficiency by 20%. Meanwhile, Huang et al. [63, 64] installed two side plates at the lateral ends of a hood to increase containment removal efficiency and reduce energy consumption. The relative leakage of contaminant from the hood into the occupied zone became virtually non-existent. The above studies show that incorporating different plates into the hood design would help to reduce the spread of fumes.

5.3 Installing an air conditioner

The installation of an air conditioner in a CRK could effectively improve the thermal environment, as this approach is widely used in commercial kitchens [20]. Many air-conditioner manufacturers have pushed very hard by advertising the use of air conditioning in CRKs, and many products are already available on the market. However, our literature search did not identify many studies on the subject. Three types of air conditioners could be used in CRKs in summer, as shown in Fig. 13: ceiling-mounted air conditioners [65], wall-mounted air conditioners [66], and movable air conditioners [67]. As illustrated in the figure, conditioned air may interact with an air curtain and the airflow to a range hood. Note that the tracks of the flow may not reflect actual situations but possible scenarios. Huang et al. found that range hood performance was very sensitive to drafts in the environment [68]. Cooking fumes in the return air of an air conditioner can deposit on the heat exchanger inside the device and reduce the heat exchange efficiency [69]. It would be preferable to supply 100% outdoor air to the air conditioner, but doing so could increase system costs and energy use [70]. Bu [71] suggested the use of a personalized air conditioner, which is very similar to a movable air conditioner, to improve a cook's local thermal comfort.



(a) (b) (c)

Fig. 13. Schematic of various types of air conditioners to improve the effectiveness of range hoods: (a) ceiling-mounted, (b) wall-mounted, and (c) movable.

The use of air conditioners in CRKs seems like a good idea. However, the idea needs systematic study for identification of the best air conditioner with optimal air supply parameters under both summer and winter conditions.

6. Discussion

There may be other methods for improving the kitchen environment. Here are a few examples:

- Yi et al. [72] proposed a concurrent supply and exhaust kitchen ventilation system to block contaminated air from entering other indoor spaces. A ceiling supply and ceiling exhaust could be used in the kitchen. The researchers found that the heat capture efficiency was more than 100% higher than that for a conventional range hood alone, and contaminant capture efficiency was at least 58% higher.
- Lai [27] proposed a novel side-exhaust system to improve on the traditional range hood. The exhaust outlet was installed on the side wall next to the stove. The system maintained indoor air quality in the kitchen at an acceptable level.
- Jeong [73] introduced a new airflow-inducing local exhaust ventilation system, which combined general ventilation with a local exhaust ventilation system and a separate exhaust outlet. The results indicated that the air temperature in the kitchen could be 0.5-1.8 K lower than with the existing exhaust ventilation system.
- Dobbin et al. [74] found that running an exhaust fan for 15 min after cooking reduced the $PM_{2.5}$ concentration to that achieved by a 50 L/s increase in ventilation.
- It is also possible to increase the cook's thermal comfort with the use of phase-change-material clothing [75]. A vest of this type could effectively suppress rapid changes in temperature and reduce the physiological heat stress experienced by the cook.
- Zhou et al. [36] found that an open window could improve the capture efficiency of a range hood. However, natural ventilation depends very much on outdoor air temperature. It would be better to use mixed ventilation: When the outdoor environment is favorable, one would use natural ventilation and the range hood. Otherwise, a make-up air system, an air conditioner and a hood would be used simultaneously to provide a comfortable and healthy kitchen environment.

7. Conclusions

This paper presented a comprehensive and critical review of literature on the indoor environment in CRKs with a focus on several aspects: Chinese residential kitchen features, indoor thermal environment, indoor air quality, and measures for improving the residential kitchen environment. The study led to the following conclusions:

CRKs were generally reported to be small in size with a median floor area of around 6.0 to 7.0 m^2. CRKs usually had a hood but no make-up air system. Many people closed the window or door in the kitchen during cooking. Since CRKs did not have adequate make-up air, the actual ventilation rate was much lower than the nominal rate indicated on the hood. Cooking method was the most important factor in pollutant generation, and stir-frying generated the most cooking pollutants.

According to the results from the literature and from our measurements, the air temperature increased dramatically in CRKs during cooking, which often created an excessively hot thermal environment in summer. In addition, the vertical temperature difference between head and ankle level was often too large to be acceptable to the occupants. This investigation identified four thermal comfort models, but none of them could predict thermal comfort accurately.

CRKs were found to contain gaseous air pollutants, such as CO, CO_2, NO_2, TVOCs and particulate matter that exceeded the limits set by the Chinese national standard. The poor indoor air quality in CRKs is not acceptable.

It is possible to improve the thermal environment and IAQ in CRKs by controlling fume diffusion with air curtains, improving range hood design, installing air conditioners, etc. Some of these measures seem very effective, whereas others require further study.

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References

[1] http://www.chinachugui.com/news/2017/0722/170722177481.shtml

[2] Kim C, Gao Y T, Xiang Y B, et al. Home kitchen ventilation, cooking fuels, and lung cancer risk in a prospective cohort of never smoking women in Shanghai, China. International Journal of Cancer, 2015, 136(3): 632-638.

[3] Cao C, Gao J, Wu L, et al. Ventilation improvement for reducing individual exposure to cooking-generated particles in Chinese residential kitchen. Indoor and Built Environment. 2017, 26(2): 226-237.

[4] Yik F W H, Sat P S K, Niu J. Moisture generation through Chinese household activities. Indoor and Built Environment. 2004, 13(2), 115-131.

[5] Chen C, Zhao Y, Zhao B. Emission rates of multiple air pollutants generated from Chinese residential cooking. Environmental Science & Technology. 2018, 52(3): 1081-1087.

[6] Wang H, Hu J, Huang C, et al. The research of fume pollution and optimization control in typical Chinese residential kitchen. The 6th International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Buildings. IAQVEC Oct. 2007: 28-31.

[7] Zhao Y, Li A, Gao R, et al. Measurement of temperature, relative humidity and concentrations of CO, CO_2 and TVOC during cooking typical Chinese dishes. Energy and Buildings, 2014, 69: 544-561.

[8] Chiang C, Lai C, Chou P, et al. The influence of an architectural design alternative (transoms) on indoor air environment in conventional kitchens in Taiwan. Building and Environment, 2000, 35(7): 579-585.
[9] See SW, Balasubramanian R. Physical characteristics of ultrafine particles emitted from different gas cooking methods. Aerosol and Air Quality Research, 2006, 6(1): 82-92.
[10] Zhao Y, Hu M, Slanina S, et al. Chemical compositions of fine particulate organic matter emitted from Chinese cooking. Environmental Science & Technology, 2007, 41(1): 99-105.
[11] Balasubramanian R, Lee S S. Characteristics of indoor aerosols in residential homes in urban locations: A case study in Singapore. Journal of the Air & Waste Management Association, 2007, 57(8): 981-990.
[12] Rim D, Wallace L, Nabinger S, et al. Reduction of exposure to ultrafine particles by kitchen exhaust hoods: the effects of exhaust flow rates, particle size, and burner position. Science of the Total Environment, 2012, 432: 350-356.
[13] Singer B C. Experimental evaluation of installed cooking exhaust fan performance. 2011.
[14] Yik F W H, Au P W. Flow rate and capture efficiency of domestic kitchen exhaust hoods for Chinese households. International Journal in Architectural Science, 2002, 3: 125-134.
[15] Huang R F, Nian Y C, Chen J K. Static condition differences in conventional and inclined air-curtain range hood flow and spillage characteristics. Environmental Engineering Science, 2010, 27(6): 513-522.
[16] Huang R F, Nian Y C, Chen J K, et al. Improving flow and spillage characteristics of range hoods by using an inclined air-curtain technique. Annals of Occupational Hygiene, 2010, 55(2): 164-179.
[17] Kotani H, Yamanaka T, Sagara K, et al. High efficiency exhaust hood with baffle plate for commercial kitchen. 9th International Conference on Industrial Ventilation, Japan. 2009.
[18] Lim K, Lee C. A numerical study on the characteristics of flow field, temperature and concentration distribution according to changing the shape of separation plate of kitchen hood system. Energy and Buildings, 2008, 40(2):175-184.
[19] Zhao Y, Li A, Tao P, et al. The impact of various hood shapes, and side panel and exhaust duct arrangements, on the performance of typical Chinese style cooking hoods. Building Simulation. Tsinghua Press, 2013, 6(2): 139-149.
[20] Livchak A, Schrock D, Sun Z. The effect of supply air systems on kitchen thermal environment. ASHRAE Transactions, 2005, 111(1): 748-754.
[21] Wang L, Xiang Z, Stevanovic S, et al. Role of Chinese cooking emissions on ambient air quality and human health. Science of the Total Environment, 2017, 589: 173-181.
[22] Zhao Y, Zhao B. Emissions of air pollutants from Chinese cooking: A literature review. Building Simulation. Tsinghua University Press, 2018, 11(5): 977-995.
[23] Han O, Li A, Kosonen R. Hood performance and capture efficiency of kitchens: A review. Building and Environment, 2019: 106221.
[24] GB50096-2011. Design code for residential buildings. Beijing: Standardization Administration of China, 2011.
[25] China's overall kitchen market operation situation and strategic consulting research report from 2019 to 2025. 2019. http://www.ibaogao.com/baogao/0Z42Z9532019.html.
[26] Nong G, Shen S, Chen T. Evaluation of ventilation effectiveness in the kitchens of Beijing flats. Indoor and Built Environment, 1996, 5: 358-363.
[27] Lai C. assessment of side exhaust systems for residential kitchens in Taiwan. Building Service Engineering Research and Technology. 2005, 26(2): 1587-166.
[28] Gao J, Cao C, Zhang X, et al. Volume-based size distribution of accumulation and coarse particles (PM0. 1–10) from cooking fume during oil heating. Building and Environment, 2013, 59: 575-580.
[29] Poon K M. A study of exposure to ultrafine particles generated from cooking with a domestic kitchen range hood. City University of Hong Kong, 2013.
[30] Liu X, Wang X, Xi G. Orthogonal design on range hood with air curtain and its effects on kitchen environment. Journal of Occupational and Environmental Hygiene, 2014, 11(3): 186-199.
[31] Yu K, Yang K, Chen Y, et al. Indoor air pollution from gas cooking in five Taiwanese families. Building and Environment, 2015, 93: 258-266.
[32] Zhou B, Chen F, Dong Z, et al. Study on pollution control in residential kitchen based on the push-pull ventilation system. Building and Environment, 2016, 107: 99-112.

[33] Li S, Gao J, He Y, et al. Determination of time-and size-dependent fine particle emission with varied oil heating in an experimental kitchen. Journal of Environmental Sciences, 2017, 51: 157-164.
[34] Wei P, Zhou B, Tan M, et al. Study on thermal comfort under non-uniform thermal environment condition in domestic kitchen. Procedia Engineering, 2017, 205: 2041-2048.
[35] Chen W, Li J, Wang C, et al. 2D-PIV measurement of range hood-driven flow in a domestic kitchen, Energy and Buildings, 2018, 177: 64-76.
[36] Zhou B, Wei P, Tan M, et al. Capture efficiency and thermal comfort in Chinese residential kitchen with push-pull ventilation system in winter-a field study. Building and Environment, 2019, 149: 182-195.
[37] Zhou X., Liu S. Liu X, et al. Evaluation of four models for predicting thermal sensation in Chinese residential kitchen. CLIMA 2019, May 26-29, 2019, Bucharest, Romania.
[38] Lee H, Lee Y J, Park S Y, et al. The improvement of ventilation behaviors in kitchens of residential buildings. Indoor and Built Environment, 2012, 21(1): 48-61.
[39] Ji Y, Duanmu L. Airtightness field tests of residential buildings in Dalian, China. Building and Environment, 2017,119: 20-30.
[40] Liu J, Dai X, Li X, et al. Indoor air quality and occupants' ventilation habits in China: Seasonal measurement and long-term monitoring. Building and Environment, 2018, 142: 119-129.
[41] Liu J. Final Scientific and Technical Report for investigation of window-opening behavior, air purifier usage mode and indoor air quality. 2016YFC0700501. Tianjin University. Tianjin. 2019.
[42] Li A, Zhao Y, Jiang D, et al. Measurement of temperature, relative humidity, concentration distribution and flow field in four typical Chinese commercial kitchens. Building and Environment, 2012, 56: 139-150.
[43] Zhao Y, Li A, Gao R, et al. Measurement of the pollutants from cooking Chinese dishes. Proceedings of the 8th International Symposium on Heating, Ventilation and Air Conditioning. 2013, 193-201.
[44] ASHRAE ANSI. Standard 55-2010: Thermal environmental conditions for human occupancy. ASHRAE, Atlanta USA, 2010.
[45] Fiala D, Havenith G, Bröde P, et al. UTCI-Fiala multi-node model of human heat transfer and temperature regulation. International Journal of Biometeorology, 2012, 56(3): 429-441.
[46] Zhang H, Arens E, Huizenga C, et al. Thermal sensation and comfort models for non-uniform and transient environments, Part III: Whole-body sensation and comfort. Building and Environment, 2010, 45(2): 399-410.
[47] Lai D, Zhou X, Chen Q. Modelling dynamic thermal sensation of human subjects in outdoor environments. Energy and Buildings, 2017, 149: 16-25.
[48] GB/T 18883-2002. Indoor air quality standard. Beijing: Standardization Administration of China, 2002.
[49] Liu L. 2007. Detection and evaluation of air pollution in kitchen. Gas & Heat 2007, 5.
[50] Huang Y, Ho S S H, Ho K F, et al. Characteristics and health impacts of VOCs and carbonyls associated with residential cooking activities in Hong Kong. Journal of Hazardous Materials, 2011, 186(1): 344-351.
[51] Zhou J, Zhao Y. Residential kitchen smoke pollution field tests and numerical simulation. Contamination Control & Air-conditioning Technology. 2015, 2.
[52] Wang Y, Song J, Tang A. Experimental study on pollutant dispersion of residential kitchen. Journal of Shenyang Jianzhu University Natural Science 2010, 26(6): 1177 -1181.
[53] Guo D, Cao J, Wang Y, et al. Detection and analysis of harmful composition of cooking oil fume in the kitchen. Chinese Journal of Disease Control & Prevention, 2010, 14(2): 142-145.
[54] Chao C Y H, Law A. A study of personal exposure to nitrogen dioxide using passive samplers. Building and Environment, 2000, 35(6): 545-553.
[55] Melia R J W, Chinn S, Rona R J. Indoor levels of NO_2 associated with gas cookers and kerosene heaters in inner city areas of England. Atmospheric Environment. Part B. Urban Atmosphere, 1990, 24(1): 177-180.
[56] Cibella F, Cuttitta G, Della Maggiore R, et al. Effect of indoor nitrogen dioxide on lung function in urban environment. Environmental Research, 2015, 138: 8-16.
[57] Bellander T, Berglind N, Gustavsson P, et al. Using geographic information systems to assess individual historical exposure to air pollution from traffic and house heating in Stockholm. Environmental Health Perspectives, 2001, 109(6): 633-639.

[58] World Health Organization. Air quality guidelines: global update 2005: Particulate matter, ozone, nitrogen dioxide and sulfur dioxide. World Health Organization, 2006.
[59] Wan M, Wu C, To G N S, et al. Ultrafine particles, and PM2.5 generated from cooking in homes. Atmospheric Environment, 2011, 45: 6141-6148.
[60] GB 3095-2012. Ambient air quality standards. Beijing: Standardization Administration of China, 2012.
[61] Du B, Gao J, Chen J, et al. Particle exposure level and potential health risks of domestic Chinese cooking. Building and Environment, 2017, 123: 564-574.
[62] To W M, Yeung L L. Effect of fuels on cooking fume emissions. Indoor and Built Environment, 2011, 20(5): 555-563.
[63] Huang R F, Chen J K, Lee J H. Development and characterization of an inclined quad-vortex range hood. Annals of Occupational Hygiene, 2013, 57(9): 1189-1199.
[64] Chen J K, Huang R F. Flow characteristics and robustness of an inclined quad-vortex range hood. Industrial Health, 2014: 2013-0138.
[65] Kim Y J. Ceiling-mounted air conditioner: U.S. Patent 8,715,047. 2014-5-6.
[66] Lim S Y. Wall-mounted air conditioner: U.S. Patent Application 29/287,245. 2008-5-13.
[67] Dong R F, Lao B Q, Cao X R, et al. Movable air-conditioner: U.S. Patent Application 29/067,771. 1999-11-23.
[68] Huang R F, Dai G Z, Chen J K. Effects of mannequin and walk-by motion on flow and spillage characteristics of wall-mounted and jet-isolated range hoods. Annals of Occupational Hygiene, 2010, 54(6): 625-639.
[69] Wei H. Design of miniature kitchen air conditioner. Proceedings of the 14th National Academic Conference on Refrigerators (Cabinets), Air Conditioners and Compressors. China Refrigeration Society Small Refrigerator Low Temperature Biomedical Professional Committee, 2018: 3.
[70] Qiu C. Research on the design of kitchen air conditioning system. Home Appliance Technology, 2017 (12): 58-59.
[71] Bu Z. Application of local air supply air conditioner in public kitchen operation room. HV&AC, 1997, 1: 73-74.
[72] Yi K W, Kim Y I, Bae G N. Effect of air flow rates on concurrent supply and exhaust kitchen ventilation system. Indoor and Built Environment, 2016, 25(1): 180-190.
[73] Jeong S H, Kwon H M, Ahn S J, et al. A study on the improvement of ventilation rate using air-flow inducing local exhaust ventilation system. Journal of Asian Architecture and Building Engineering, 2016, 15(1): 119-126.
[74] Dobbin N A, Sun L, Wallace L, et al. The benefit of kitchen exhaust fan use after cooking - an experimental assessment. Building and Environment, 2018, 135: 286-296.
[75] Reinertsen R E, Færevik H, Holbø K, et al. Optimizing the performance of phase-change materials in personal protective clothing systems. International Journal of Occupational Safety and Ergonomics, 2008, 14(1): 43-53.