processes

MDPI

Article

An Experimental Study on Temperature, Relative Humidity, and Concentrations of CO and CO_2 during Different Cooking Procedures

Xi Chen *, Yahui Gao, Liu Yang, Yang Liu, Miaomiao Qin, Jialing Xia and Peng Wang

School of Civil Engineering and Architecture, Henan University of Technology, Zhengzhou 450001, China
* Correspondence: chenxi2014@haut.edu.cn; Tel.: +86-18623719927

Abstract: In order to explore the indoor air quality during different cooking procedures, a very common kitchen in China is selected for experimental research. An indoor air quality meter is used to measure the temperature, relative humidity, and CO and CO_2 concentrations of the indoor air above the stove when people cook four different dishes under different ventilation patterns in the kitchen. The results indicate that the heat and gas consumed during cooking are closely related to the temperature and concentrations of CO and CO_2. Some cooking procedures such as boiling water are related to the indoor air temperature and relative humidity in the kitchen. In addition, in kitchens without mechanical ventilation, natural ventilation shows a more significant positive effect on controlling temperature, relative humidity, and concentrations of CO and CO_2 during cooking procedures.

Keywords: temperature; relative humidity; CO concentration; CO_2 concentration; cooking procedure

check for updates

Citation: Chen, X.; Gao, Y.; Yang, L.; Liu, Y.; Qin, M.; Xia, J.; Wang, P. An Experimental Study on Temperature, Relative Humidity, and Concentrations of CO and CO_2 during Different Cooking Procedures. *Processes* **2023**, *11*, 2648. https://doi.org/10.3390/pr11092648

Academic Editors: Yabin Guo, João M. M. Gomes, Zhanwei Wang and Yunpeng Hu

Received: 8 August 2023
Revised: 2 September 2023
Accepted: 3 September 2023
Published: 4 September 2023

1. Introduction

In recent years, indoor air quality (IAQ) has received increasing attention as people recognize the importance of air quality to health and comfort. Great interest has been directed towards indoor obnoxious gases such as CO and CO_2. Kitchens are environments wherein multiple pollutants and airflow combine with the emissions from cooking operations to create considerable indoor air pollution. Cooking plays an important role in people's lives, especially in China with a population of 1.4 billion. The statistics show that Chinese housewives spend an average of 3.4–4 h in kitchens every day [1]. However, the cooking process produces a large amount of particles, which are inhaled by the human body and deposited in the lungs, thereby affecting human health [2]. Therefore, indoor air pollution from the cooking process deserves more attention.

Many investigators have explored the air quality of kitchen environments during cooking. For example, Chiang et al. [3] found that the accumulation location of air contaminants was highly correlated with the location of gas fires. Furthermore, Ryhl Svendsen et al. [4] found through experimental measurements that people in rural areas of Denmark were exposed to a certain level of indoor air pollution. In addition, Singh et al. [5] found that the concentration of pollutants in the kitchen after cooking was higher than the recommended guidelines. Following this work, another study found that kitchen type, fuel type, and kitchen location were also important factors affecting the concentration of pollutants in the kitchen [6]. Torkmahalleh et al. [7] studied the neurological responses caused by human exposure to pollutants from indoor gas ovens by recording electroencephalograms before, during (14 min), and 30 min after cooking. The study suggested that Alzheimer's disease might develop in people chronically exposed to high levels of cooking pollutants. Zhao et al. [8] reported the air temperature, air relative humidity, and generations of CO and CO_2 during the cooking of Eight Cuisines of China as a case study. They pointed out that cooking techniques were not responsible for the serious pollution. The air temperature and humidity were the main factors affecting thermal comfort [9]. Zhou et al. [10] found that the area between the gas stove and the exhaust fan observed the highest temperature when cooking. The results of other researchers indicated that the indoor environment of Chinese-style residential kitchens was too hot in summer [11,12]. Moreover, the questionnaire survey on the Tianjin campus showed that 83.33% of chefs felt hot in summer, but most chefs had neutral wet sensations in four seasons [13]. Liu et al. [14] found that heat diffused significantly after the oil was heated for 30 s. The air temperature around the cook increased by about 10.0 °C throughout the cooking process. Moreover, during the cooking process, high levels of indoor air pollution including CO and CO_2 often accumulate in the kitchen. Exposure to high levels of CO could affect the cardiovascular system, lungs, blood, and central nervous system as well as lead to various health problems [15,16]. Increased levels of CO_2 in the atmosphere stimulated respiration and caused all sorts of systemic confusion [17]. Although many articles have studied the generation of pollutants in the cooking process and the impact of related pollutants on the human body, there are few studies on the temperature, relative humidity, and CO and CO_2 concentrations in the cooking process of different cooking procedures.

Ventilation systems are commonly used in kitchens to remove secure contaminants and provide a comfortable and healthy environment. Related studies have shown that the closer the exhaust outlet of the kitchen range hood is to the pollution source, the higher the efficiency of pollutant removal [18]. Li et al. [19] evaluated the impact of typical ventilation systems of four commercial kitchens in China on their indoor thermal environment and found that the ventilation systems of typical commercial kitchens in China were unable to effectively remove waste heat and impurities. The impact of increased air exchange rates in the test kitchen was discussed by Grabow et al. [20]. Their results indicated that opening the door and window in the test kitchen lowered particulate matter and CO. Afterwards, another research showed that the push–pull ventilation system could provide scientific support for reducing the indoor pollutant concentration in the kitchen [21]. Nejat et al. [22] improved the performance of a two-sided windcatcher under low wind speed conditions by installing anti-short-circuit devices on them. Recently, Lu et al. [23] explored a new way of obtaining make-up air based on a push–pull ventilation system in the kitchen. The experimental results showed that it could be used to create more efficient air distribution and a good environment in the kitchen. Although a lot of work has been conducted on kitchen ventilation, few researchers have studied the air quality during different cooking processes in the kitchen with different ventilation patterns.

This study reports the results of an experimental investigation of the air quality during cooking in a Chinese residential kitchen. Four cooking procedures (boiling, steaming, sautéing, and frying) and different ventilation patterns generate 24 different case scenarios. A TSI 7545 IAQ-Calc Indoor Air Quality Meter is used to monitor the air temperature, relative humidity, and concentrations of CO and CO_2 above the stove.

2. Materials and Methods

2.1. Site Description

The characteristics of Chinese cooking result in the production of large amounts of pollutants. Most Chinese people are exposed to the environment with CO and CO_2 when they are cooking in residential kitchens [24]. This experiment was carried out in May, 2023 in a typical Chinese residential kitchen located on the sixth floor of a 6-floor building, which is far from the streets and in a community of Zhengzhou city. The kitchen is part of a 90 m^2 family apartment with a length of 4440 mm, a width of 1700 mm, and a height of 2600 mm, as shown in Figure 1. The kitchen has an exterior window on the north wall, and the dimension of the window is width × height = 1700 mm × 1550 mm. Opposite the exterior window, there is an interior door on the south wall, and the size of the door is 650 mm × 2000 mm (width × height). In addition to this, the kitchen also has a two-head natural gas stove, which is placed on the hearth. Above the stove, there is an exhaust hood used in the present study. The locations as well as parameters of the stove and the exhaust hood are presented in Figure 2 and Table 1, respectively. In this research, only the left head of the stove is adopted for cooking.

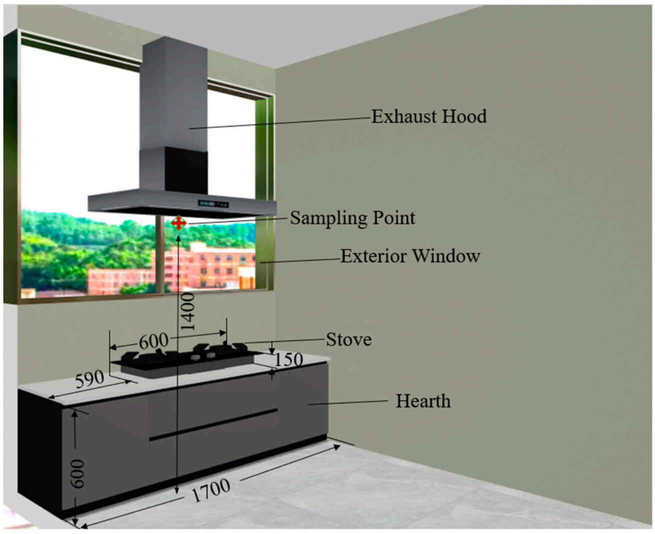


Figure 1. Schematic of the kitchen.

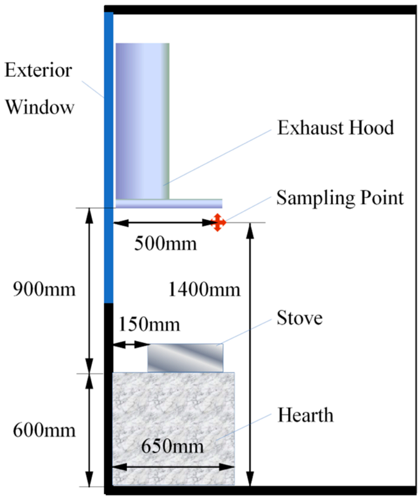


Figure 2. Schematic of the Sampling Point.

Table 1. Parameters of the stove and the exhaust hood.

Name	Model	Size (mm)	Parameters
Two-head natural gas stove	JZT-Q30A (12T)	710 × 400 × 150	Rated pressure: 2000 Pa
			Weight: 8.1 kg
			Rated heat load: 4.1 kW × 2
Exhaust hood	CXW-219-JT30 (SN)	900 × 520 × 880	Maximum pressure: ≥300 Pa
			Weight: 30 kg
			Volume flow rate: 0.25 m^3/s

2.2. Studied Cases

The apartment residents involved in this study suffered from variations in the temperature, humidity, and concentrations of CO and CO_2 during the cooking process, which made the residents uncomfortable. At the same time, the apartment residents were affected differently by different cooking processes. A significant contribution to indoor air pollution is made by different styles of cooking operations. Therefore, boiling, steaming, sautéing, and frying, which are very common cooking procedures and have different characteristics, are considered in this work to detect the air quality during different cooking procedures. Four dishes, namely boiled eggs, steamed perch, sautéed mungbean sprouts, and fried chicken middle wings, are chosen to represent the four cooking procedures. The details of these four dishes are listed in Table 2. Exhaust hoods are often used in residential kitchens to ensure the provision of a healthy environment. Opening windows and doors in kitchens is another choice for some people to make improvements to indoor environments during cooking. For a better understanding of the effects of ventilation on the indoor quality in kitchens, various on–off patterns of the interior door, exterior window, and exhaust hood are set in different cases. This study is performed under 24 cases with different cooking procedures as well as ventilation patterns, and the cases are listed in Table 3.

Table 2. The information on the four dishes.

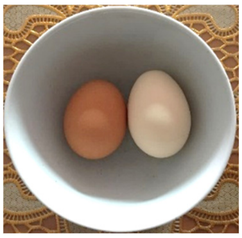
Names	Pictures	Average Consumed Gas (m^3)	Cooking Procedures
Boiled eggs		0.020	Preparation: Put 2 eggs into 425 g water and soaked for 10 min.
			Step 1: Turned on the stove to medium-high and brought to the water boil.
			Step 2: Turned the heat to low and boiled the eggs for 6 min.
			Step 3: Turned off the stove and dished out the eggs.
Steamed perch		0.096	Preparation: Rinsed the perch (450 g) and marinated with salt, scallion, ginger, and light soy sauce for 30 min.
			Step 1: Turned on the stove to high and brought 1200 g of water to a boil.
			Step 2: Put the perch above the water and steamed for 8 min.
			Step 3: Turned off the stove and left the perch in the steamer for a period of time.
Sautéed mungbean sprout		0.023	Step 1: Turned on the stove to medium-high and made the wok hot.
			Step 2: Added 10 g cooking oil, 2 chili peppers, and some scallion into the wok.
			Step 3: When the oil smoked, added 375 g of mungbean sprout. Turned the heat up to high and performed a few quick stirs.
			Step 4: Added some salt as well as light soy sauce and kept on stirring.
			Step 5: Turned off the stove. Added some vinegar and dished out the mungbean sprout.

Table 2. *Cont.*

Names	Pictures	Average Consumed Gas (m^3)	Cooking Procedures
Fried chicken middle wings		0.060	Preparation: Rinsed 15 chicken middle wings (550 g) and marinated with salt, scallion, ginger, garlic, white pepper, and light soy sauce for 30 min.
			Step 1: Turned on the stove to medium-high and made the wok hot.
			Step 2: Added some cooking oil, Sichuan pepper, and star aniseed.
			Step 3: When the oil was heat, turned the heat to low and put in 4 chicken middle wings. Fried the chicken middle wings until golden brown and dished out. (Repeated 3 times.)
			Step 4: Put in 3 chicken middle wings. Fried the chicken middle wings until golden brown and dished out.
			Step 5: Turned off the stove. Added some cumin powder and coriander to the chicken middle wings.

Table 3. Parameters in different cases.

Cases	Dishes	Interior Door	Exterior Window	Exhaust Hood
1	Boiled eggs	off *	off	off
2	Boiled eggs	off	off	on ***
3	Boiled eggs	off	on **	off
4	Boiled eggs	on	on	off
5	Boiled eggs	on	off	on
6	Boiled eggs	off	on	on
7	Steamed perch	off	off	off
8	Steamed perch	off	off	on
9	Steamed perch	off	on	off
10	Steamed perch	on	on	off
11	Steamed perch	on	off	on
12	Steamed perch	off	on	on
13	Sautéed mungbean sprout	off	off	off
14	Sautéed mungbean sprout	off	off	on
15	Sautéed mungbean sprout	off	on	off
16	Sautéed mungbean sprout	on	on	off
17	Sautéed mungbean sprout	on	off	on
18	Sautéed mungbean sprout	off	on	on
19	Fried chicken middle wings	off	off	off
20	Fried chicken middle wings	off	off	on
21	Fried chicken middle wings	off	on	off
22	Fried chicken middle wings	on	on	off
23	Fried chicken middle wings	on	off	on
24	Fried chicken middle wings	off	on	on

* The interior door is closed completely, and there is a crack with a height of 6mm under the door. ** The exterior window is opened to the maximum. *** The exhaust hood is turned on to the high-speed level when the stove is switched on. And 5 min after the stove is turned off, the exhaust hood is switched off.

2.3. Apparatus and Parameters Measured

In the present study, a TSI 7545 IAQ-Calc Indoor Air Quality Meter is selected for monitoring the air temperature, relative humidity, and concentrations of CO and CO_2 at the sampling point above the stove during the cooking procedures. The TSI 7545 IAQ-Calc Indoor Air Quality Meter is widely accepted and has been used in the field of indoor measurements by several authors [25,26]. More information about the TSI 7545 IAQ-Calc Indoor Air Quality Meter can be seen in Table 4 [27]. The sampling point is set in the breathing zone, which is 1400 mm above the ground, in the middle of the two heads of the stove, and 500 mm away from the exterior window, as shown in Figure 2.

Table 4. Specifications of the Indoor Air Quality Meter.

Parameters	Range	Accuracy	Resolution
Temperature	0–60 °C	±0.6 °C	0.1 °C
Relative humidity	5–95% RH	±3% RH	0.1% RH
CO concentration	0–500 ppm	±3% of reading or ±3 ppm, whichever is greater	0.1 ppm
CO_2 concentration	0–5000 ppm	±3% of reading or ±50 ppm, whichever is greater	1 ppm

2.4. Procedure

In this work, the interior door and the exterior window are opened at least 2 h before each measurement to keep the air fresh in the kitchen [28]. The doors of other rooms are closed during the experiment to minimize the impact of other rooms on the kitchen's air quality. When preparations are completed, the TSI 7545 IAQ-Calc Indoor Air Quality Meter starts running, and the operator leaves the kitchen. The Indoor Air Quality Meter tests the initial background levels of the air temperature, relative humidity, and concentrations of CO and CO_2 for 10 min before the stove is turned on. Then, these parameters at the sampling point are continuously measured for 50 min. During the measurements, the data are automatically recorded every 1 s. There are no other people except the cook in the kitchen during the cooking. The cook should stay as far away from the sampling point as possible. The distance of the cook from the sampling point is about 0.5–1 m in different cases. Meanwhile, the cook is asked to wear a mask. In order to reduce errors, the experiments are repeated twice for each case. The purpose of the second test is to verify the trend and correctness of the data in the first test. If the law of the data in the two tests is close, the values presented in this paper use the data obtained from the first test; otherwise, the tests are carried out for the third time or even more.

3. Results and Discussion

3.1. Temperature

In order to reduce the effect of the airflow on the results, the cases with a closed door and window and an idle exhaust hood are chosen to compare the data during the cooking with different procedures. Figure 3 depicts the air temperatures versus time at the sampling point in Cases 1, 7, 13, and 19 with a closed interior door, exterior window, and exhaust hood. The steps in these cases are also marked in Figure 3. We can observe that the air temperatures increase initially and then decrease in all cases. During cooking, the temperatures are obviously above the comfort level without ventilation measures, and productivity will drop according to the research of Wyon [29]. The maximum temperatures in Cases 1, 7, 13, and 19 all appear at 600–1500 s. However, the specific moments and steps with the maximum temperatures are different. The case with the maximum peak temperature is not the one with the highest initial background temperature, which mostly has to do with the cooking process. And the gaps between the maximum and the initial background temperatures increase with an increase in the average consumed gas. It follows that the temperature increment is in connection with the consumed gas during the cooking. It can also be demonstrated that the temperatures dramatically increase after the stove is turned on and decrease as soon as the stove is turned off. This agrees with the result of a previous study in which cooking makes the air temperature increase in commercial kitchens [19]. Thus, the increase in temperatures during the cooking is mainly due to the burning fire. At 60 min (3600 s), the air temperatures are still greater than the initial background values, which is mainly related to the absence of ventilation measures. In addition, it can be seen the temperature is turned to be low after reaching the peak value of 39.7 °C in Case 1. Also, the temperature decreases obviously after Step 2 is carried out. The air temperature in Case 7 continuously rises until the stove is turned off. The comparison of Cases 1 and 7 shows that reducing heat can lower the temperature in the kitchen. In Case 13, a sharp increase in the temperature appears after the stove is turned on. Then, the temperature keeps rising until the stove is turned off. The slope of the temperature curve between Step 1 and Step 3 is observed to be slightly larger than that between Step 3 and Step 5. A possible reason is that the procedures of making the wok hot and oil smoked contribute to the increase in the temperature. The temperature in Case 19 sharply increases between Step 1 and Step 3. When the heat is turned to be low, the temperature initially decreases and then increases slightly till the stove is turned off. This phenomenon indicates that the change in temperature is directly affected by the heat of the stove. A comparison of the data in different cases shows that the temperatures in Cases 1 and 7 increase slowly before the values reach the maximum, whereas the temperatures in Cases 13 and 19 rise sharply. The difference between the cooking procedures (such as boiling water and making the wok hot and oil smoked) is possibly sufficient to trigger this result.

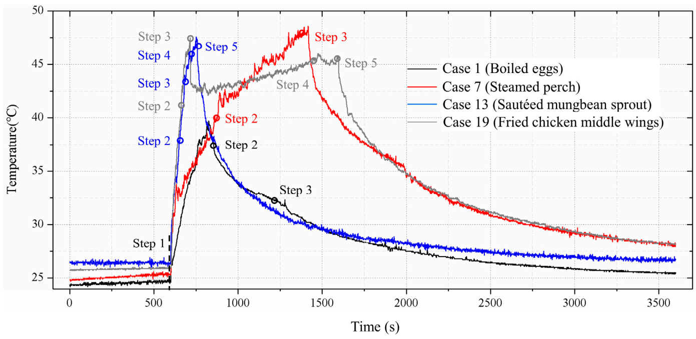


Figure 3. Variations in air temperatures in Cases 1, 7, 13, and 19.

In Figure 4, the temperatures at the sampling point against time in cases with the dish of sautéed mungbean sprout are presented. As it is seen, the air temperatures all increase as soon as the fire is lighted and decline when the stove is turned off. The temperatures come up to the maximum value before Step 5 is performed. This may be caused by a habit of putting the lid on the wok before the stove is turned off. Putting the lid on the wok and turning off the stove happen almost simultaneously. The gaps between the peak and the initial background temperatures are ordered from high to low, starting with Case 15 then Case 13 and Case 16. There is little difference between Cases 13 and 15. The reason may be that only opening the exterior window has a lesser impact on the airflow and temperature control. The interior door and exterior window opened simultaneously, which could promote the airflow in the kitchen and may have lowered the peak temperature to some degree. The maximum temperatures in cases with an idle exhaust hood all exceed 42 °C, while the peak values of temperatures in cases with the working exhaust hood fall below 33 °C. This implies that the working exhaust hood can effectively reduce the temperature in the kitchen during cooking. The gaps between the maximum and the initial background temperatures in cases with the working exhaust hood ordered from high to low are Case 17, then Case 18, and Case 14. This means that the open door or window has little effect on the temperature drop when the exhaust hood keeps working. And the open window shows a better effect on the cooling of heated air than the open door. The larger distance between the interior door and the stove as well as the greater air velocity outdoors possibly leads to this result. It can also be concluded that the temperatures in cases with an idle exhaust hood increase firstly, reach the peak values, and then decrease when the time is increased. However, temperatures in cases with the working exhaust hood present a different trend and increase a bit after the exhaust hood is switched off. One of the possible causes is that the heated air above the stove can be taken away effectively by the exhaust hood.

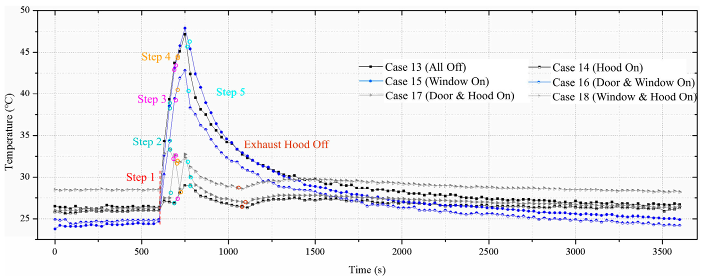


Figure 4. Variations in air temperatures while cooking sautéed mungbean sprout.

3.2. Relative Humidity

The variation in the relative humidity in Cases 1, 7, 13, and 19 with a closed interior door, exterior window, and exhaust hood is plotted in Figure 5. As soon as the stove is turned on, the relative humidity rises in all of these cases. A similar result was obtained in the study by Giwa et al. [30]. The relative humidity has a similar trend to the temperature. We also find that the relative humidity is comparatively volatile during the cooking procedures. In Case 1, after turning on the stove, the relative humidity increases first and then decreases. The relative humidity comes up to a small peak value before the heat is turned to low, which is related to the large amount of steam from the boiling water. While the eggs are being boiled, the relative humidity stays at a higher level. After the stove is turned off, the relative humidity gradually decreases and then tends to be stable. It proves that the relative humidity above the stove is related to the water status in the saucepan. The relative humidity in Case 7 has a similar tendency to that in Case 1. One reason for this could be that Cases 1 and 7 both have the process of boiling water and keep some water in the vessels throughout the cooking time. The difference is that the ascensional range of relative humidity in Case 7 is higher than that in Case 1 after the stove is turned off, which may be due to the lag of dishing out the perch. For Case 13, the relative humidity rises initially and then declines with fluctuations after the fire is lighted. After the stove is turned off, the relative humidity rises a bit and keeps steady later. The relative humidity in Case 19 fluctuates regularly from Step 3 to Step 5, and a reduction in relative humidity appears after every time the chicken middle wings are dished out. It is also shown that the gaps between the maximum and the initial relative humidity in Cases 1 and 7 are greater than those in Cases 13 and 19. One of the possible causes is that Cases 1 and 7 have the same procedure of boiling water, while Cases 13 and 19 do not have this step. By comparing the values in Figure 5 and Table 2, it can be concluded that the average consumed gas has little influence on the relative humidity.

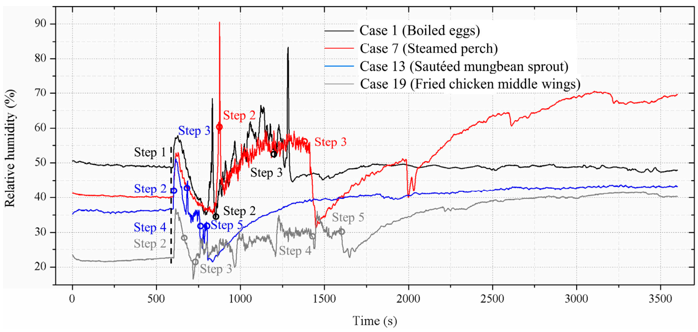


Figure 5. Variations in the relative humidity in Cases 1, 7, 13, and 19.

Figure 6 illustrates the relative humidity versus time at the sampling point in cases with the dish of boiled eggs. The relative humidity in these cases with the maximum peak value of 65.6% increases rarely. After the 1500 s, the relative humidity tends to be stable and is close to the initial background level. In cases with an idle exhaust hood, the relative humidity increases as soon as the stove is switched on and goes down after the stove is turned off. The relative humidity in cases with the working exhaust hood declines when the stove is turned on and has no obvious changes as soon as the stove is turned off. Also, Li et al. [19] found that the relative humidity was reduced due to the use of exhaust hoods during the cooking process in commercial kitchens. The relative humidity in Cases 1, 3, and 4 exhibits a larger fluctuation than that in Cases 2, 5, and 6 during cooking. It seems that the differences in the relative humidity curves between the cases with an idle and working exhaust hood are caused by the vapor, which can be exhausted in a timely manner by the hood. The comparison in Figure 6 also shows that the gaps between the maximum and the initial background relative humidity in Case 1 are the highest, followed by Case 3, with Case 4 the lowest among the cases with an idle exhaust hood. This result indicates that appropriate natural ventilation is beneficial to control the increase in relative humidity during cooking. For the cases with a working exhaust hood, the minimum values of the relative humidity during cooking are lower than the corresponding initial background relative humidity. The gaps between the initial background and the minimum relative humidity among cases with the working exhaust hood appear from large to small in the following order: Case 5, Case 6, and Case 2. This order implies that an open door or window can make the relative humidity change more dramatically during cooking when the exhaust hood keeps working.

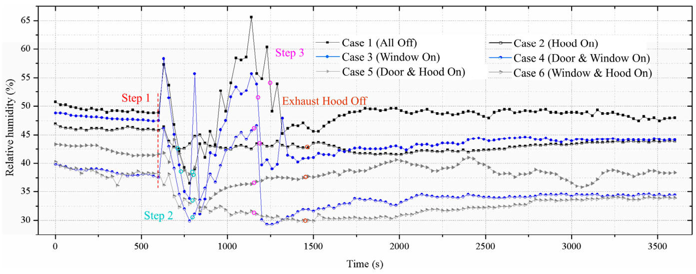


Figure 6. Variations in the relative humidity while cooking boiled eggs.

3.3. Concentration of Carbon Monoxide

Figure 7 displays the variation in the concentrations of CO in Cases 1, 7, 13, and 19 with a closed interior door, exterior window, and exhaust hood. According to the results, the concentrations of CO in all cases exhibit a sharp increase after the fire is lit and stay at a high level during the cooking, which is in consonance with some previous research [31]. The CO concentrations decrease with a delay when the stove is turned off. The acceptable value of the Indoor Air Quality Standard in China is 10 ppm for the CO concentration, and the concentrations of CO in all of these four cases are always below this value [32]. In Case 1, the CO concentration increases quickly between Step 1 and Step 2 and fluctuates smoothly after the heat is turned to low. When the stove is switched off, the concentration of CO shows a rapid decrease with a lag. An obvious increasing trend of CO concentration in Case 7 is observed after the stove is turned on. The value of the CO concentration achieves a peak value of 8.4 ppm and then decreases. Though the process of boiling water exists both in Cases 1 and 7, the continuous increase in the CO concentration shown in Case 7 is absent in Case 1. A possible cause is that there is a step to lowering the heat in Case 1. With a similar trend of CO concentration in Case 7, the concentration of CO in Case 13 shows a shorter rising process and a smaller maximum value. These results can be explained by assuming that there is no step of heat regulation in both cases and that the time between turning on and off the stove is longer in Case 7 than that in Case 13. The variation trend of CO concentration in Case 19 is similar to that in Case 1, which can be attributed to the step to lowering the heat in both cases. This series of observations suggests that the emission of CO is mainly related to the burning of the gas, and the CO concentration presents a smooth fluctuation when the heat is turned to low. In Figure 7, it is also recognized that the

CO concentration in Case 7 has the maximum peak value and is about double the initial background level at 3600 s. Part of the reason might be due to the largest consumed gas volume used in Case 7. At 3600 s, the CO concentration in Case 1 is the only one that approaches the corresponding initial background value. One reason for this could be that the average consumed gas of boiled eggs is the lowest, and the accumulative CO in the kitchen can be exhausted in a timely manner after the stove is turned off.

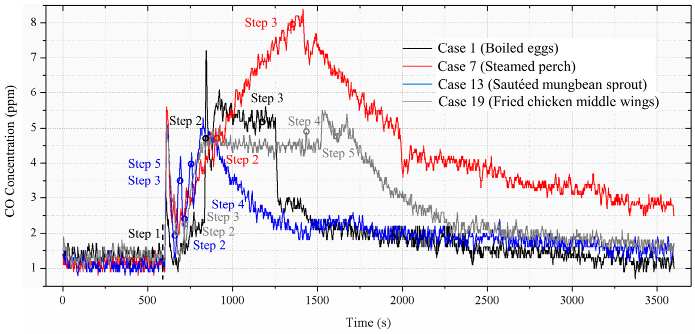


Figure 7. Variations in the concentrations of CO in Cases 1, 7, 13, and 19.

The concentrations of CO at the sampling point against time in cases with the dish of steamed perch are illustrated in Figure 8. It can be seen that CO concentrations are all lower than the acceptable value of 10 ppm. During the cooking procedures, the CO concentrations in cases with an idle exhaust hood are apparently higher than those in cases with a working exhaust hood. It appears that the working exhaust hood plays an important role in reducing indoor CO concentration. By comparing the data in cases with an idle exhaust hood, the CO concentrations in Cases 7 and 9 both increase first and then decrease, while those in Case 10 have a greater fluctuation and no obvious regularity, which bears similarity to the study of the fluctuation indices in chemistry [33,34]. This may be attributed to the stronger convection when the door and window are opened simultaneously. At 3600 s, the concentrations of CO in Cases 7 and 9 are higher and close to the initial background values, whereas those in Case 10 are lower than the initial background CO concentrations. This could mean that natural ventilation can promote a decrease in CO concentration and that cross-ventilation is more effective. The dramatic impact of increasing ventilation by opening the window and door on lowering the level of CO can also be seen in the study by Grabow et al. [20]. Moreover, the above results suggest that the effect of controlling CO concentration is more susceptible to the weather outside when the exterior window is opened. For the cases with a working exhaust hood, CO concentrations increase slightly during cooking and are even lower than the initial background values when the exhaust hood is turned off. After the exhaust hood stops working, the CO concentrations increase rarely and then reach stable values. The CO concentrations at 3600 s are nearly equal to the initial background level. The peak values of the CO concentrations from highest to lowest order the cases with a working exhaust hood in the sequence of Case 11, Case 12, and Case 8, which has a similar condition with the temperature pattern. It may be that natural ventilation has little contribution to reducing CO concentration when the exhaust hood keeps working.

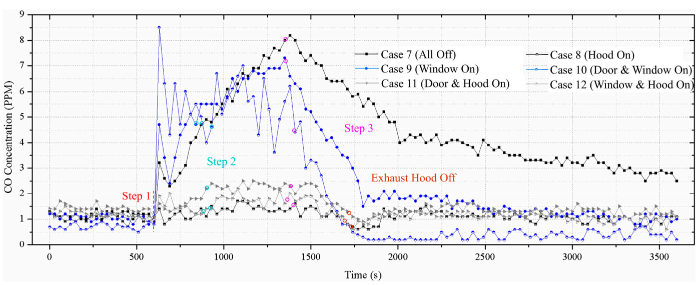


Figure 8. Variations in concentrations of CO while cooking the steamed perch.

3.4. Concentration of Carbon Dioxide

Figure 9 shows the concentrations of CO_2 versus time in Cases 1, 7, 13, and 19 with a closed interior door, exterior window, and exhaust hood. From Figure 9, it can be observed that the CO_2 concentration rises sharply once the fire is lit, which is similar to the findings of Zhao et al. [8]. Subsequently, the CO_2 concentrations gradually decline after the stove is turned off. Different from the results of the CO concentration, the CO_2 concentrations in these four cases rapidly exceed the acceptable value of the Indoor Air Quality Standard in China (1000 ppm) [32] when the stove is turned on and always higher than 1000ppm during cooking. These data imply that CO_2 concentrations have an adverse impact on the air quality in the kitchen during cooking without ventilation. The CO_2 concentration in Case 1 presents a decrease as soon as the stove is turned to low and shows a stationary fluctuation until the stove is turned off. This suggests that the magnitude of the heat is closely associated with the change in the CO_2 concentration. In Case 7, the CO_2 concentration strikes the peak value of 5000 ppm many times and drops slowly after the stove is turned off. The CO_2 concentration in Case 13 grows rapidly before the stove is turned off and decreases sharply later. The CO_2 concentration in Case 19 exhibits an obvious decrease after the heat is turned to be low and then rises gradually. When the stove is turned off, the CO_2 concentration declines. A comparison of the data for different cases shows that the CO_2 concentration with the maximum value of 5000 ppm in Case 7, which uses the most gas, stays at a high level for the longest time among these cases and that the CO_2 concentration in Case 1 with the least consumed gas has the lowest peak value. After 3600 s, the CO_2 concentration in Case 1 is the only one that is lower than the acceptable level. These results suggest that the emission of CO_2 has a positive association with the consumed gas.

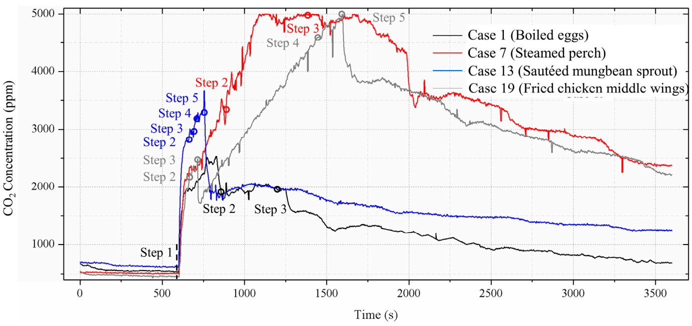


Figure 9. Variations in concentrations of CO_2 in Cases 1, 7, 13, and 19.

The concentrations of CO_2 at the sampling point against time in cases with the dish of fried chicken middle wings are presented graphically in Figure 10. The CO_2 concentrations in cases with a working exhaust hood are significantly lower than those in cases with an idle exhaust hood during cooking. This finding is consistent with the results reported by Zhao et al. [8]. Also, the CO_2 concentrations in cases with an idle exhaust hood all exceed the acceptable value of 1000 ppm when the cooking is carried out in the kitchen, whereas most of the CO_2 concentrations in cases with a working exhaust hood are below the acceptable level. The CO_2 concentrations in cases with a working exhaust hood fluctuate around a constant level during the cooking procedures and drop to the initial background values before the exhaust hood is turned off. These indicate that the exhaust hood is a valid tool for reducing the CO_2 generated from cooking and that the CO_2 concentration is basically lower than the acceptable level when the exhaust hood is working. For cases with an idle exhaust hood, the maximum CO_2 concentrations from large to small order the cases by ventilation patterns: Case 19, Case 21, and Case 22. The CO_2 concentration in Case 19 is still higher than 2000 ppm at 3600 s. Until about 3000 s from the beginning, the CO_2 concentration in Case 21 dips below 1000 ppm. The CO_2 concentration in Case 22 is relatively stable between Step 3 and Step 5, lower than 1000ppm at about 1650 s, and close to the initial background concentration at about 1700 s from the beginning. These data suggest that natural ventilation measures contribute to the elimination of CO_2 during cooking and that the effect is limited. If the exhaust hood keeps working, the case dependence of the gap between the maximum CO_2 concentration and the initial background value appears from large to small in the following order: Case 23, Case 24, and Case 20. It seems that the measure of opening the door or window merely cannot make the effectiveness of the CO_2 elimination better when the exhaust hood is turned on.

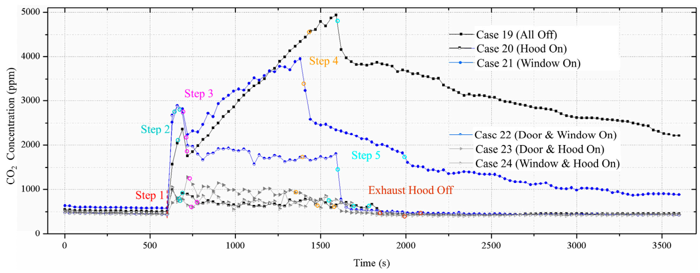


Figure 10. Variations in concentrations of CO_2 while cooking the fried chicken middle wings.

Based on the above discussions, we suggest that chefs should be aware of the impact of the kitchen environment on their own health during the cooking process and keep ventilation devices (such as an exhaust hood) working to maintain good indoor air quality. In addition, wearing a mask during cooking activities is also a way to protect people's health.

4. Conclusions

In the present work, the air temperature, relative humidity, and concentrations of CO and CO_2 during cooking procedures are measured in a Chinese residential kitchen. The influences of four cooking procedures and different ventilation patterns in the kitchen on these parameters are discussed. According to the data generated from the experiment and the above analysis, the main conclusions are as follows:

(1) When the stove is on, the temperature and CO and CO_2 emissions increase, and when the stove is turned off, the temperature and CO and CO_2 emissions decrease. The heat used in the cooking is closely related to the temperature and concentrations of CO and CO_2.

(2) With the reduction in gas consumption, the temperature and CO and CO_2 emissions during the cooking are reduced, and the relative humidity varies irregularly.

(3) Some cooking procedures, such as boiling water, are related to changes in the air temperature and relative humidity in the kitchen.

(4) The temperature and concentrations of CO and CO_2 are maintained at a high level in the kitchen without ventilation measures, and the working exhaust hood can effectively reduce the temperature and concentrations of CO and CO_2 during cooking.

(5) Natural ventilation, especially cross-ventilation, has a positive effect on controlling the air temperature, relative humidity, and concentrations of CO and CO_2 in kitchens with idle exhaust hoods.

(6) Opening the interior door or the exterior window only has no significant impact on the control of air temperature, relative humidity, and concentrations of CO and CO_2 during cooking in kitchens with working exhaust hoods.

The current research has some limitations. This paper does not discuss all cooking methods and dishes and only selects four dishes. Furthermore, other pollutants such as COF produced during different cooking procedures have not been studied. In the future, we will upgrade related instruments to measure other pollutants in the kitchen. In addition, the indoor air quality during some other cooking procedures is also well worth investigating.

Author Contributions: Conceptualization, X.C.; methodology, X.C. and Y.G.; formal analysis, Y.G., L.Y. and Y.L.; writing—original draft preparation, X.C., Y.G. and M.Q.; writing—review and editing, X.C., J.X. and P.W.; funding acquisition, X.C. and L.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (no. 51708180); the Key Scientific Research Project for Universities in Henan, China (no. 23A560010); the Youth Backbone Teacher Training Program of Henan University of Technology (no. 21420099); and the funding support from The Department of Science and Technology of Henan Province, China (no. 222103810076 and no. 232102111126).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lai, C. Assessment of side exhaust system for residential kitchens in Taiwan. *Build. Serv. Eng. Res. Technol.* **2005**, *26*, 157–166. [CrossRef]
2. Vu, T.V.; Ondracek, J.; Zdímal, V.; Schwarz, J.; Delgado-Saborit, J.M.; Harrison, R.M. Physical properties and lung deposition of particles emitted from five major indoor sources. *Air Qual. Atmos. Health* **2016**, *10*, 1–14. [CrossRef]
3. Chiang, C.; Lai, C.; Chou, P.; Li, Y. The influence of an architectural design alternative (transoms) on indoor air environment in conventional kitchens in Taiwan. *Build. Environ.* **2000**, *35*, 579–585. [CrossRef]
4. Ryhl-Svendsen, M.; Clausen, G.; Chowdhury, Z.; Smith, K.R. Fine particles and carbon monoxide from wood burning in 17th–19th century Danish kitchens: Measurements at two reconstructed farm houses at the Lejre Historical–Archaeological Experimental Center. *Atmos. Environ.* **2010**, *44*, 735–744. [CrossRef]
5. Singh, A.; Chandrasekharan Nair, K.; Kamal, R.; Bihari, V.; Gupta, M.K.; Mudiam, M.K.R.; Satyanarayana, G.N.V.; Raj, A.; Haq, I.; Shukla, N.K.; et al. Assessing hazardous risks of indoor airborne polycyclic aromatic hydrocarbons in the kitchen and its association with lung functions and urinary PAH metabolites in kitchen workers. *Clin. Chim. Acta* **2016**, *452*, 204–213. [CrossRef]
6. Sidhu, M.K.; Ravindra, K.; Mor, S.; John, S. Household air pollution from various types of rural kitchens and its exposure assessment. *Sci. Total Environ.* **2017**, *586*, 419–429. [CrossRef] [PubMed]
7. Amouei Torkmahalleh, M.; Naseri, M.; Nurzhan, S.; Gabdrashova, R.; Bekezhankyzy, Z.; Gimnkhan, A.; Malekipirbazari, M.; Jouzizadeh, M.; Tabesh, M.; Farrokhi, H.; et al. Human exposure to aerosol from indoor gas stove cooking and the resulting nervous system responses. *Indoor Air* **2022**, *32*, e12983. [CrossRef] [PubMed]
8. Zhao, Y.; Li, A.; Gao, R.; Tao, P.; Shen, J. Measurement of temperature, relative humidity and concentrations of CO, CO_2 and TVOC during cooking typical Chinese dishes. *Energy Build.* **2014**, *69*, 544–561. [CrossRef]
9. Andrey, L. The Effect of Supply Air Systems on Kitchen Thermal Environment. Available online: https://www.researchgate.net/publication/242516657_The_Effect_of_Supply_Air_Systems_on_Kitchen_Thermal_Environment (accessed on 1 July 2023).
10. Zhou, J.; Kim, C.N. Numerical Investigation of Indoor CO_2 Concentration Distribution in an Apartment. *Indoor Built Environ.* **2010**, *20*, 91–100. [CrossRef]
11. Liu, S.; Cao, Q.; Zhao, X.; Lu, Z.; Deng, Z.; Dong, J.; Lin, X.; Qing, K.; Zhang, W.; Chen, Q. Improving indoor air quality and thermal comfort in residential kitchens with a new ventilation system. *Build. Environ.* **2020**, *180*, 107016. [CrossRef]
12. Liu, S.; Dong, J.; Cao, Q.; Zhou, X.; Li, J.; Lin, X.; Qing, K.; Zhang, W.; Chen, Q. Indoor thermal environment and air quality in Chinese-style residential kitchens. *Indoor Air* **2020**, *30*, 198–212. [CrossRef]
13. Deng, N.; Fan, M.; Hao, R.; Zhang, A.; Li, Y. Field Measurements and Analysis on Temperature, Relative Humidity, Airflow Rate and Oil Fume Emission Concentration in a Typical Campus Canteen Kitchen in Tianjin, China. *Appl. Sci.* **2022**, *12*, 1755. [CrossRef]
14. Liu, Y.; Li, C.; Ma, H.; Dong, J. Investigation on the indoor environment during a whole cooking process under constant make-up air organization in a Chinese-style residential kitchen. *Indoor Built Environ.* **2023**, *32*, 1170–1186. [CrossRef]
15. World Health Organization. WHO Guidelines for Indoor Air Quality: Selected Pollutants, Geneva, Switzerland. Available online: https://www.who.int/publications/i/item/9789289002134 (accessed on 5 July 2023).
16. Reboul, C.; Thireau, J.; Meyer, G.; André, L.; Obert, P.; Cazorla, O.; Richard, S. Carbon monoxide exposure in the urban environment: An insidious foe for the heart? *Respir. Physiol. Neurobiol.* **2012**, *184*, 204–212. [CrossRef] [PubMed]
17. Jacobson, T.A.; Kler, J.S.; Hernke, M.T.; Braun, R.K.; Meyer, K.C.; Funk, W.E. Direct human health risks of increased atmospheric carbon dioxide. *Nat. Sustain.* **2019**, *2*, 691–701. [CrossRef]
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 Build.* **2008**, *40*, 175–184. [CrossRef]
19. Li, A.; Zhao, Y.; Jiang, D.; Hou, X. Measurement of temperature, relative humidity, concentration distribution and flow field in four typical Chinese commercial kitchens. *Build. Environ.* **2012**, *56*, 139–150. [CrossRef]
20. Grabow, K.; Still, D.; Bentson, S. Test Kitchen studies of indoor air pollution from biomass cookstoves. *Energy Sustain. Dev.* **2013**, *17*, 458–462. [CrossRef]
21. Zhou, B.; Chen, F.; Dong, Z.; Nielsen, P.V. Study on pollution control in residential kitchen based on the push-pull ventilation system. *Build. Environ.* **2016**, *107*, 99–112. [CrossRef]
22. Nejat, P.; Hussen, H.M.; Fadli, F.; Chaudhry, H.N.; Calautit, J.; Jomehzadeh, F. Indoor Environmental Quality (IEQ) Analysis of a Two-Sided Windcatcher Integrated with Anti-Short-Circuit Device for Low Wind Conditions. *Processes* **2020**, *8*, 840. [CrossRef]

23. Lu, S.; Zhou, B.; Zhang, J.; Hou, M.; Jiang, J.; Li, F.; Wang, Y. Performance evaluation of make-up air systems for pollutant removal from gas stove in residential kitchen by using a push-pull ventilation system. *Energy Build.* **2021**, *240*, 110907. [CrossRef]
24. Wang, L.; Xiang, Z.; Stevanovic, S.; Ristovski, Z.; Salimi, F.; Gao, J.; Wang, H.; Li, L. Role of Chinese cooking emissions on ambient air quality and human health. *Sci. Total Environ.* **2017**, *589*, 173–181. [CrossRef] [PubMed]
25. Chithra, V.S.; Shiva Nagendra, S.M. Impact of outdoor meteorology on indoor PM10, PM2.5 and PM1 concentrations in a naturally ventilated classroom. *Urban Clim.* **2014**, *10*, 77–91. [CrossRef]
26. Martins, V.; Moreno, T.; Mendes, L.; Eleftheriadis, K.; Diapouli, E.; Alves, C.A.; Duarte, M.; de Miguel, E.; Capdevila, M.; Querol, X.; et al. Factors controlling air quality in different European subway systems. *Environ. Res.* **2016**, *146*, 35–46. [CrossRef]
27. TSI. IAQ-Calc Indoor Air Quality Meter Model 7545 Operation and Service Manual. Available online: https://tsi.com/getmedia/812721b4-f84d-43aa-8b04-19a4ccab2bd7/7545-IAQ-Calc-1980576D?ext=.pdf (accessed on 9 July 2023).
28. Fengfeng, Y.; Zhang, W.; Dai, Z.; Xu, N. Study on ensuring indoor fresh air volume in winter. *Measurement* **2010**, *43*, 406–409. [CrossRef]
29. Wyon, D. Individual Microclimate Control: Required Range, Probable Benefits and Current Feasibility. Available online: https://www.researchgate.net/publication/310403150_Individual_microclimate_control_Required_range_probable_benefits_and_current_feasibility (accessed on 15 July 2023).
30. Giwa, S.O.; Nwaokocha, C.N.; Sharifpur, M. An appraisal of air quality, thermal comfort, acoustic, and health risk of household kitchens in a developing country. *Environ. Sci. Pollut. Res.* **2021**, *29*, 26202–26213. [CrossRef] [PubMed]
31. Giwa, S.O.; Nwaokocha, C.N.; Odufuwa, B.O. Air pollutants characterization of kitchen microenvironments in southwest Nigeria. *Build. Environ.* **2019**, *153*, 138–147. [CrossRef]
32. General Administration of Quality Supervision, Inspection and Quarantine Health of People's Republic of China; Ministry of Health of People's Republic of China; Ministry of Environmental Protection of People's Republic of China. Technical Specifications for Monitoring of Indoor Air Quality (HJ/T 167-2004). Available online: https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/jcffbz/200412/W020110127390160056847.pdf (accessed on 2 September 2023).
33. Raza, Z.; Akhter, S.; Shang, Y. Expected value of first Zagreb connection index in random cyclooctatetraene chain, random polyphenyls chain, and random chain network. *Front. Chem.* **2023**, *10*, 1067874. [CrossRef]
34. Tokmakoff, A. Chemical Dynamics in Condensed Phases-Fluctuations and Randomness—Some Definitions. Available online: https://chem.libretexts.org/@go/page/107300 (accessed on 25 July 2023).