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Capture efficiency and thermal comfort in Chinese residential kitchen with push-pull ventilation system in winter-a field study

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Abstract

The IAQ and thermal comfort in residential kitchen are two major concerns in built environment. The ventilation effectiveness is closely related to the IAQ of the residential kitchen. Therefore, it is necessary to design a cost-effective kitchen ventilation system. In this study, a field experimental study was conducted on a push-pull kitchen ventilation system. The experiment was divided into two parts. The first part was to test the capture efficiency of the push-pull ventilation system under various working conditions. The second part was to investigate the thermal comfort of the human body during cooking process with and without air curtain in winter. The results show that the push-pull ventilation system can effectively improve the capture efficiency of the range hood, and the low-momentum make-up air and the reasonable air distribution around the stove are important to obtain good performance. The optimal working condition of the push-pull ventilation system is a range hood mid gear plus an air curtain velocity of 0.5m/s when the kitchen window is closed. In winter, when people enter the non-air-conditioned kitchen from the air-conditioned room, the thermal sensation and thermal comfort of people were all decreased significantly. However, they can be improved during cooking processes. The prediction results show that models which used skin temperature as input parameter can predict the thermal sensation of most

parts of human body in kitchen. However, the prediction correction model is still needed for the body parts with movement or exposure to severe heat radiation.

Keywords: Residential kitchen, Capture efficiency, Thermal sensation, Thermal comfort, Skin temperature

1. Introduction

Indoor air quality (IAQ) and thermal comfort are two most of the important issues in a building environment. However, the indoor environment in a kitchen is usually the worst in a residential area because of its special working condition [1]. The terrible IAQ and thermal comfort levels can seriously affect people's health and productivity [2]. The space of the common Chinese residential kitchen is narrow. There is no air conditioning system inside the kitchen. A large amount of pollutants are generated through Chinese cooking [3]. However, existing studies have shown that traditional range hoods cannot effectively exhaust pollutants and waste heat from residential kitchens [4]. Moreover, the air-tightness level for residential buildings increases with the more stringent requirements of energy savings. In this case, the exhaust flowrate of the range hood becomes poorer when both door and window in the kitchen are closed [5]. Therefore, it is necessary to design a reasonable ventilation mode for the residential kitchen to improve its IAQ.

In recent years, many studies have focused on the IAQ in residential kitchens and its effects on human health [3, 6-12]. Studies generally found that a poor cooking environment in kitchen was significantly associated with incidences of lung cancer, chronic obstructive pulmonary disease (CODP) and even diabetes. There are many factors contributing to a poor IAQ in the kitchen, such as the type of cooking fuel, the type of cooking oil, the temperature of cooking oil and ventilation. The ventilation system in the kitchen is an important factor. The range hood is the main part of kitchen ventilation, and the capture efficiency (CE) of the range hood is a good index to evaluate the ventilation conditions of a kitchen [13-19].

To improve the ventilation performance in a residential kitchen, many studies have been conducted. Cao *et al*. [5] found that the makeup air system in a kitchen can effectively reduce the individual exposure level, and they also found that the required flow rate for upward makeup air system is less than the downward system. Liu *et al*. [20] used the air curtain and a guide plate in the range hood. They studied the influence of jet velocity, jet angle, jet width, area of guide plate and exhaust air rate on the perceived temperature and concentration of oil fumes, and the temperature and concentration of escaped oil fumes in the kitchen. Yi *et al*. [21] studied the effect in the variation of air volume on the performance of the concurrent supply and exhaust ventilation by experiment and numerical simulation, and they found that the capture efficiency will increase with the exhaust air rate of the range hood. Huang *et al*. [22] investigated the relative magnitude of spillage levels for wall-mounted and jet-isolated range hoods. They found that increasing the suction flow rate of the jet-isolated range hood can reduce the spillage levels moderately. Push-pull ventilation is widely used in industrial production[23, 24], but it is rarely used for pollution control in the kitchen. Zhou *et al*. [25] proposed a push-pull ventilation system for a residential kitchen, and they found that the push-pull ventilation system can improve IAQ with better air distribution.

Many studies related to the kitchen environment have focused on the IAQ, but there were few studies about thermal comfort in a kitchen. And there were studies [26,27] found that worse thermal environment can lead to adverse health effect, like heatstroke. Although much attention has been paid to the thermal comfort of a human body in an office and school [28], few studies focused on thermal comfort in a kitchen, particularly a residential kitchen [29-31]. Since there are heat sources and external windows in a residential kitchen, the thermal environment in a kitchen is usually transient and non-uniform. Studies about non-uniform environments have shown that different thermal conditions will affect different human body parts in a non-uniform environment [32-36]. Therefore, it is necessary to consider local thermal sensation and comfort in the study of kitchen thermal comfort.

PMV index is a commonly used in the prediction model of thermal sensation. However, because it is mainly based on uniform environmental parameters to predict the human body's thermal sensation, PMV is considered not suitable for predicting thermal sensation in a non-uniform environment [35,37-39]. In recent years, skin temperature, as a parameter that directly reflects the heat condition of a human body surface, has been used to predict human thermal sensation by increasing number of investigators[40-45]. It is necessary to investigate whether these models are validated to predict human thermal sensation in a kitchen.

2. Materials and methods

2.1. Kitchen laboratory

Based on the size characteristics of a traditional Chinese kitchen [4, 25,46], a kitchen laboratory with a push-pull ventilation system was built in Pukou Campus at Nanjing Tech University. The push-pull ventilation system is composed of four air-curtain slots located around the stove and a range hood above the stove. The air curtain can deliver outdoor air into the kitchen. The schematic diagram of the push-pull ventilation system in kitchen is shown in Fig.1(a). The dimensions of the kitchen are 3m(L)×1.9m(W)×2.4m(H). There is an external window on the left wall and a horizontal sliding door on the back wall. The dimensions of the floor cabinet are 3m(L)×0.6m(W)×0.8m(H), which is placed against the front wall. A two-hole gas stove is installed in the middle of the floor cabinet. Four air curtain slots are located around the stove.

Meanwhile, a side suction range hood is installed at 0.5m above the gas stove. The range hood has three gears: high, mid and low. The model of the kitchen laboratory is presented in Fig.1(b), and the dimensions of the four air curtain slots are shown in Fig.1(c).

Fig.1. Schematic diagram of kitchen laboratory and its ventilation system. (a) Diagram of the push-pull ventilation system in a residential kitchen. (b) Dimensions for the model of the kitchen laboratory. (c) Diagram of the air curtain slot inlets.

2.2. Capture efficiency test

The test method of the capture efficiency in a residential kitchen was put forward systematically by Walker *et al*. [13] and Kim *et al*. [17]. The formula for capture efficiency (CE) is given as follows:

$$CE = \frac{C_e - C_c}{C_e - C_i} \tag{1}$$

where C_C is the contaminant concentration inside the kitchen; C_i is the contaminant concentration at the inlet position; and C_e is the contaminant concentration at the exhaust position.

In our experiment, the height for occupant's breathing zone was 1.5m above the floor, and the distance between the human body and the cooking table during cooking processes was 0.35m. The relative positions of the measuring points in the kitchen are shown in Fig. 2. One of sampling point is placed with height 1.2m above the floor, which was recommended by Kim *et al*. [17]. In this way, the influence of the different sampling points on the capture efficiency can be investigated.

Fig.2. The relative position of the two measuring points in the kitchen. (a) Layout for horizontal measuring points and (b) Layout for vertical measuring points.

The other two measuring points were positioned at 1.5m above the floor outside the kitchen and at the exhaust outlet of the range hood. As the outdoor air was supplied through the air curtain slots directly, the pollutant concentrations at the inlet position and the outdoor were regarded as the same. CO_2 was selected as the measurement object of the pollutants. When people cooked in the residential kitchen, the kitchen door was always closed to prevent oil fumes from flowing into other adjacent rooms. When the outdoor climate was terrible, such as in winter or during an episode of haze, the external window in the kitchen was usually closed. Therefore, the kitchen was considered a closed room. In our experiment, the exhaust flowrate and the pressure difference between the kitchen and outdoors under various situations were measured. To improve the air-tightness of the door and window, gummed tape was used to seal the gaps at the door and window.

Our test mainly focused on the capture efficiency under different push-pull ventilation working conditions with the kitchen window open and closed. During each set of working conditions, the kitchen door is closed and the right-side gas stove is burning. Through measurement, the gas cooker power under each working condition was remained 836W. The CO_2 concentration values at each measuring point was averaged after the CO_2 concentration reached steady-state. Through Eq. (1), the CE values for different working conditions were obtained.

2.3. Thermal comfort experiment of kitchen in winter

The thermal comfort experiment of kitchen in winter was performed between November 2017 and January 2018. There were two experimental conditions. The Case 14 condition omits the air curtain, and the Case 17 condition contains optimal air curtain velocity. A total of forty experiments were conducted, which included 20 experiments without air curtain (Case 14) and 20 experiments with air curtain (Case 17).

2.3.1. Subjects

A total of twenty healthy college students (10 men and 10 women) participated in the experiment. Information about their age, height and weight are shown in Table 1. Each subject was involved in two sets of working conditions. The subjects were unaware of the working conditions of the experiment. The clothing insulation and metabolic rates of subjects during the different experiment phases were calculated through the ASHARE 55 standard [47]. The specific information is shown in Table 2.

Table 1 Information about the subjects.

Table 2 Clothing insulation and metabolic rates in experiment.

2.3.2. Experimental procedure

The real cooking process in an ordinary family was imitated in the experiment. In winter, people usually rest in the air-conditioned living room before entering the non-air-conditioned kitchen for cooking. Entering the kitchen from the living room involves a step-change of temperature decrease. In our experiment, subjects were asked to arrive in a dressing room 30 min ahead of the experiment, and then the subjects used 30 min to change clothes and tape wireless iButtons in the dressing room. Afterwards, they sit in the living room for 10 minutes and completed the first questionnaire during this phase. The air temperatures of the dressing room and the living room were maintained at 22.4°C, which was calculated as the neutral air temperature with people with a clothing insulation of 1.0clo and a metabolic rate of 1.1met [48]. The subjects reached the same neutral thermal condition before entering the kitchen. After entering the kitchen, the subjects stood for 10 minutes and completed the second questionnaire to evaluate the thermal sensation and thermal comfort condition during this step-change of temperature. Chinese people like to stir-fry dishes. There is usually more than one cooking process during the preparation of lunch or dinner. Therefore, two consecutive cooking processes were set up, between which there was a 5 min break. Each cooking process lasted for 5 min, which consuming 30mL of soybean oil and 100g of cowpeas. After each cooking process, the subjects were asked to complete a recall questionnaire to evaluate the thermal condition of the body during the cooking process. The specific experimental procedure is shown in Fig. 3.

Fig.3. Detailed explanation of experimental procedure.

2.3.3. Measurement of environmental parameters

During the experiment, the air temperature, relative humidity, black-ball temperature, air velocity, and wall temperature in the residential kitchen were measured. The instruments used for experiment and their setting parameters are shown in Table 3. According to the ASHARE 55 standard [47], two horizontal measuring points were placed on the left and right sides, which were 0.4m away from the human body. Meanwhile, four vertical measuring points were placed at 0.1 m, 1.1 m, 1.5 m and 1.7 m above the floor. They represent the heights of the ankle, waist, breathing zones and head of the standing human body, respectively. The layout of the specific measuring points and measured parameters are displayed in Fig. 4. The temperatures of the wall surface were obtained by placing the measurement points at the center of the anterior-posterior, right-left, and up-down surfaces of the walls.

Fig.4. Sampling locations and measurement parameters in experiment. (a) Layout for horizontal measuring points and (b) Layout for vertical measuring points and measured parameters.

Table 3 Detailed information of the environmental measurement instruments.

2.3.4. Measurement of skin temperature

During the experiment, the skin temperatures from16 body parts of the body of the subjects were recorded. The locations of the measuring points were set by the method of Hagino *et al.* [49]. The skin temperature was measured by wireless iButtons (model: DS1923, range: -20-85 °C, accuracy: ±0.1 °C, interval: 20s), which had been used in previous studies [34,35] to measure the skin temperature. Since the subjects have to move and cook in this experiment, this kind of wireless instrument was selected.

The mean skin temperature was calculated by the 10-point method [45]. The specific formula was as follows:

$$T_{\mathrm{skin}}=0.06\times T_{\mathrm{forehead}}+0.08\times T_{\mathrm{right,upper\text{-}arm}}+0.06\times T_{\mathrm{left,lower\ arm}}+0.05\times T_{\mathrm{right,hand}}+0.12\times T_{\mathrm{back}}+0.12\times T_{\mathrm{chest}}$$
$$+0.12\times T_{\mathrm{abdomen}}+0.19\times T_{\mathrm{right,thigh}}+0.13\times T_{\mathrm{right,calf}}+0.07\times T_{\mathrm{right,foot}} \quad (2)$$

where T_{skin} is the mean skin temperature; T_{forehead} is the forehead skin temperature; $T_{\mathrm{right,upper\text{-}arm}}$ is the right upper arm skin temperature; $T_{\mathrm{left,lower\text{-}arm}}$ is the left lower arm skin temperature; $T_{\mathrm{right,hand}}$ is the right hand skin temperature; T_{back} is the back skin temperature; T_{chest} is the chest skin temperature; T_{abdomen} is the abdomen skin temperature; $T_{\mathrm{right,thigh}}$ is the right thigh skin temperature; $T_{\mathrm{right,calf}}$ is the right calf skin temperature; $T_{\mathrm{right,foot}}$ is the right foot skin temperature.

2.3.5. Questionnaire

Questionnaires were conducted in the experiment, two of which were the recall questionnaires after the cooking phase. The thermal sensation and thermal comfort of the whole body and the 16 individual parts were collected by the questionnaire. The thermal sensation was evaluated by the continuous 7-point scale of the ASHRAE 55 standard [47]. The thermal comfort was evaluated by the discontinuous 6-point scale, which was used by Deng *et al*. [34]. Thermal sensation and thermal comfort scales are shown as Appendix A in supplementary material.

2.3.6. Statistical analysis

The kitchen environmental parameters, human skin temperature and actual vote tails from the questionnaires under the two working conditions were presented. Meanwhile, two- sample *t*-test were carried out to evaluate the differences in thermal sensation and thermal comfort between the two working conditions and the adjacent experimental phases. In general, there is a significant difference between the two samples when the *P* value is less than 0.05.

2.3.7. Thermal sensation modeling

Using the data of skin temperature and the change rate of skin temperature obtained from the experiment, three thermal sensation prediction models in transient non-uniform environments were used to predict the whole and local thermal sensation in our study.

The model of Zhang [40] was shown in Eq. (3).

$$S_{\mathrm{Local}} = 4 \times \left\{ \frac{2}{1 + e^{-C_1 (T_{\mathrm{S,L}} - T_{\mathrm{S,L,set}}) - k_1 [(T_{\mathrm{S,L}} - \bar{T}_{\mathrm{S}}) - (T_{\mathrm{S,L,set}} - \bar{T}_{\mathrm{S,set}})]}} - 1 \right\} + C_{2i} \frac{dT_{\mathrm{S,L}}}{dt} + C_{3i} \frac{dT_{\mathrm{C}}}{dt} \quad (3)$$

where the input parameters were as follows: the local skin temperature, $T_{\mathrm{S,L}}$; the set point of the local skin temperature, $T_{\mathrm{S,L,set}}$, which was the local neutral skin temperature; the mean skin temperature, $\overline{T}_{\mathrm{S}}$; the set point of the mean skin temperature, $\overline{T}_{\mathrm{S,set}}$, which was the neutral mean skin temperature; the change rate of the local skin temperature, $dT_{\mathrm{S,L}}/dt$; the change rate of the core temperature, dT_{C}/dt; and coefficients C_1, k_1, $C_{2\mathrm{i}}$, and $C_{3\mathrm{i}}$, which varied for different body parts. Some coefficients were modified by the model developer [48], which were used in this study.

The model of Zhou [41] was presented as follows:

$$S_{\mathrm{Local}} = 3 \times \left\{1 - \frac{2}{1+e^{\mathrm{K}_1(T-T_{\mathrm{S}})+\mathrm{K}_2\left(T_{\mathrm{skm}}-T_{\mathrm{skm,s}}\right)+\mathrm{K}_3(T_{\mathrm{A}}-T_0)/(t-t_0)}}\right\} \tag{4}$$

where the input parameters were as follows: the local skin temperature, T; the set point of the local skin temperature, T_{S}, which was the local neutral skin temperature; the mean skin temperature, T_{skm}; the set point of the mean skin temperature, $T_{\mathrm{skm,s}}$, which was the neutral mean skin temperature; the change rate of ambient air temperature, $(T_{\mathrm{A}}\text{-}T_0)/(t\text{-}t_0)$; K_1, K_2, and K_3, which varied for different body parts. Compared to the model of Zhang, the environmental input parameters were included in this model.

The model of Takada [42] was presented as follows:

$$\mathrm{TSV} = a_1 + a_2\left\{\frac{1}{2} + \frac{atan\left(\frac{T_{sk}-T_{sk,0}-a_3}{a_4}\right)}{\pi}\right\} + a_5\left\{\frac{1}{2} + \frac{atan\left(\frac{\frac{dT_{sk}}{dt}-a_6}{a_7}\right)}{\pi}\right\} \tag{5}$$

where the input parameters were as follows: the mean skin temperature, T_{sk}; the set point of the mean skin temperature, $T_{\mathrm{sk,0}}$, which was the neutral mean skin temperature; the change rate of the mean skin temperature, dT_{sk}/dt; and regression coefficient a_1–a_7.

Both models of Zhang and Zhou are local thermal sensation prediction models, and the model of Takada is a whole thermal sensation prediction model. In the Zhang model, the core temperatures are needed as input parameters to predict the thermal sensations in the chest, back, and abdomen. However, the core temperature cannot be obtained in our experiments. Therefore, the thermal sensation of local body parts with C3i=0 was predicted. In the Zhou model, the change rate of air temperature is needed as an input parameter. According to the local environment conditions which different body parts were exposed to, the change rates of air temperature at 1.7 m, 1.1 m and 0.1m were used for forehead, upper limb and lower limb, respectively.

3. Results and discussion

3.1. Results of capture efficiency test

The measurement results of the exhaust flowrate of the range hood and the pressure difference between the kitchen and outdoors under different conditions are shown in Table 4. The complete closure of the door and window reduces the exhaust flowrate of the kitchen range hood and produces a large pressure difference between kitchen and outdoors. The exhaust flowrate for the high, mid and low gears reduced by 5.8%, 5.6%, and 5.0%, respectively. However, after the air curtain was introduced, with the continuous increase in the make-up flowrate, the negative impact of the door and window closure will be improved. The larger the pressure difference between kitchen and outdoor is, the more difficult it is for the range hood to receive air, which results in more energy consumption. When the air curtain was used, the greater the make-up flowrate of the air curtain was, the lower the pressure difference was between the kitchen and the outdoors. This means that the air flowrate passing through the door and window was less, and the resultant energy consumption of the range hood was less as well.

The capture efficiency values obtained from two different indoor measuring points are shown in Table 5. It is found the differences between CE [1.5m] and CE [1.2m] values for Case 1, Case 2 and Case 3 are quite large. The reason is that when the hood is working alone and the kitchen window is open, the CO_2 concentration distribution in the kitchen is un-uniform. It is caused by un-uniform indoor air distribution when the window is open. However, when the air curtain is working or the window is closed, the differences between CE [1.5m] and CE[1.2m] are not large, the maximum difference of which is less than 5%. Therefore, it can be considered that there are no differences between the capture efficiency values obtained from these two indoor measuring points. By closing the window or applying the air curtain, a more uniform indoor air distribution can be created.

In Table 5, it is illustrated that when the air curtain is working, the capture efficiency of the hood will be improved. Moreover, the improvement of the capture efficiency in the case of window opening (indoor and outdoor mass balance) is larger than that in the case of window closing (indoor and outdoor mass imbalance). For example, when Case 4 and Case 16 are compared, although the range hood gear and air curtain velocity between them are the same, the capture efficiency under Case 4 is obviously higher than that under Case 16. The reason for this situation may be that when the kitchen window and door all closed, it is difficult for the hood to obtain the make-up air from the vicinity area of the kitchen. The pressure difference between kitchen and outdoor can indicate the difficulty of obtaining the supplemental air. The greater the pressure difference is, the more difficult the range hood obtains the make-up air, and thus the lower exhaust the flowrate of the range hood will be (Table 4). Therefore, the pressure difference between kitchen and outdoor, which is caused by the working range hood, should not be large. However, some special phenomenon appeared in our experiment. In Fig.5, there are frontal views of flow field visualization under five working conditions. From Fig.5(a) and Fig.5(b), it can be observed that the capture efficiency under the working condition with window open is lower than that under the condition with window closed. This should be caused by the poor air distribution around the stove which came from the opening window shown in Fig.5(a), where an obvious disturbance occurs for the airflow on the right. Similarly, in Fig.5(e), although the exhaust flowrate of range hood is not small and the pressure difference is not large, the capture efficiency is low, which is caused by the disordered air distribution around the stove provoked by the air curtain velocity with 1.5m/s. The influences of the momentum of the make-up air and the air distribution around the stove on the capture efficiency of the range hood are significant. This conclusion had been elaborated in VDI 2052 [50]. In VDI 2052, it is found that the induction effect of the supply-air jet with good indoor air distribution improves the capture efficiency of the kitchen extraction hood considerably. In Fig.5(c) and Fig.5(d), the momentum of the make-up air is small and the air distribution around the stove is reasonable. Under these conditions, their capture efficiencies are good. Meanwhile, when Fig.5(c) and Fig.5(d) are compared, the working condition with the window open will have a better capture efficiency.

At the same time, it can be found in Table 5 that when the door and window are fully closed, a larger air curtain velocity will not definitely bring the higher capture efficiency of range hood. In the low range of air curtain velocity, the larger the velocity through the air curtain was, the better the capture efficiency was. However, for a larger range of air curtain velocity, a larger air curtain velocity makes the capture efficiency lower. Sometimes, it is even lower than that without air curtain. For example, the capture efficiencies for Case 13, Case 16, Case 19 and Case 22 (the same high gear of the range hood is used) are 82.50%, 86.52%, 86.73% and 77.46%, respectively. With the increase in the air curtain velocity, the capture efficiency increases during the first stage and decreases later. And the same phenomenon can be seen under the conditions with low or mid gears of the range hood. It is known that the combination of higher range hood gear and larger air curtain velocity will result in greater building energy consumption. Moreover, it is found in Table 5 that the higher range hood gear and the larger air curtain velocity will not certainly bring the high capture efficiency. Therefore, it is not appropriate to adopt the scheme with high range hood gear and large air curtain velocity. In the case of door and window all closed, the highest capture efficiency value appears in Case 19, which is 86.73%. However, the capture efficiency of Case 17 is 85.25%, which is almost the same as Case 19. Since both range hood gear and air curtain velocity for Case 17 are lower than that for Case 19, Case 17 is considered as the optimal working condition of the push-pull ventilation system with the kitchen door and window closed.

Fig.5. Frontal view of air distribution visualization under five working conditions. (a) window: open + range hood: mid gear + air curtain: 0m/s. (b) window: closed + range hood: mid gear + air curtain: 0m/s. (c) window: open + range hood: mid gear + air curtain: 1m/s. (d) window: closed + range hood: mid gear + air curtain: 1m/s. (e) window: closed + range hood: mid gear + air curtain: 1.5m/s.

Table 4 Exhaust flowrate of range hood and pressure difference between kitchen and outdoors under different working conditions.

Table 5 The results of the capture efficiency (CE) test.

3.2. Thermal environment characteristics of residential kitchen in winter

The environmental parameters at different heights at the left and right side of the subject were measured during the experiment. By contrast, no significant difference in the measured parameters was found between the parameters measured at the left and right measuring points. Therefore, the parameters at the left and right points were averaged.

3.2.1. Air temperature and vertical air temperature difference

The air temperature at different heights and vertical air temperature difference between 1.7 m and 0.1m during the experiment are shown in Fig. 6. It can be seen that in the P1 phase, the air temperatures at the heights of 0.1 m, 1.1 m, 1.5 m and 1.7 m were slightly higher than the outdoor air temperature. The vertical air temperature difference was not significant. In the P2 phase, the subject entered the kitchen. During this process, the temperature in the kitchen rose slightly due to the body's heat dissipation. In the P3 phase, the subject began to cook. The temperature at other heights increased significantly, except at the height of 0.1 m, causing the vertical air temperature difference between 1.7 m and 0.1 m to increase. At this stage, the maximum vertical air temperature difference reached 2.5 °C and 2.3 °C under Case 14 and Case 17, respectively. In the P5 phase, it was found that during the second cooking process, the difference in the air temperature at different heights was found to be greater than that in the P3 phase. The temperatures at 1.7 m and 1.5 m under Case 17 were lower than that under Case 14. The maximum vertical air temperature difference reached 4.0 °C and 3.5 °C under Case 14 and Case 17, respectively. The vertical air temperature difference is an important index to evaluate the thermal comfort of the human body in a non-uniform thermal environment. It is generally believed that the allowable vertical air temperature difference cannot exceed 3°C [47]. Therefore, the air curtain can be used to control the vertical air temperature difference.

Fig.6. The air temperature and vertical air temperature difference in the kitchen during the experiment.

3.2.2. Black-ball temperature

Black-ball temperature is an important index that affects human thermal comfort. A large amount of radiant heat was released from the fire source during the cooking process, which resulted in the sharp increase in the black-ball temperature near the human body. It can be inferred from Fig.6 that the black-ball temperature rose significantly faster than the air temperature. The peak value of black ball temperature reached 15.6 °C and 15.5 °C under Case 14 and Case 17, respectively, in the P3 phase. While in the P5 phase, the peak values of the black-ball temperature reached 17.7 °C and 17.5 °C under Case 14 and Case 17, respectively. The air curtain seems to have no control effect on the radiation temperature.

3.2.3. Wall temperature

The temperatures of the anterior–posterior, right–left, and up–down surfaces of the walls during the experiment are shown in Fig.7. It can be seen from the figure that the cooking processes exert the greatest influence on the temperature of the front wall in the kitchen. Considering that the body's chest, abdomen and forehead face the front wall, the temperature change of the front wall represents the heat gain of these body parts to some extent. By contrast, the temperature of the back wall was always low, causing the back of the human body to always be in a cold thermal environment. It can be concluded that the heat radiation before and after the human body during the cooking process was extremely asymmetric.

The thermal flow which was not captured by the range hood during the cooking process will rise and transfer to the ceiling, causing a large increase in the ceiling temperature. However, the ceiling temperature under the air curtain condition (Case 17) was significantly lower than that with no air curtain (Case 14), indicating that the push-pull ventilation system can improve the exhaust efficiency of waste heat.

Fig.7. The wall temperature in the kitchen during the experiment.

3.2.4. Air velocity

The air velocity at the left and right of the human body was close to zero during the cooking process. A possible explanation is that the door and window were always closed during the experiment. The exhaust of the range hood did not cause significant air movement around the human body. The flow field induced by the range hood may be mainly concentrated near the exhaust outlet of the hood.

3.2.5. Relative humidity

The average relative humidity in the kitchen was maintained between 40% and 50% throughout the experiment (Fig .8). The air curtain had no great effect on the relative humidity in the kitchen.

Fig.8. The relative humidity in the kitchen during the experiment.

3.3. Skin temperature, thermal sensation and thermal comfort

Two- sample t-test results on the thermal sensation and thermal comfort of adjacent phases together with change values before and after are shown in the Table 6 and Table 7, respectively. From the P1 to P2 phase, the thermal sensation and thermal comfort of most human body parts significantly declined except the feet. After entering the first cooking phase (P3), the body's thermal sensation and thermal comfort began to increase. The thermal sensation and thermal comfort of forehead, chest, abdomen, left upper arm, left lower arm and right upper limb all increased significantly. Compared with the P2 phase, the overall thermal sensation in the P3 phase under two different working conditions showed significant improvement. However, the thermal comfort was significantly improved only under Case 14, while no significant improvement appeared under Case 17. The thermal comfort of the chest, abdomen, and right lower arm under Case 14 appeared to significantly increase. In the second cooking phase (P5), compared with the P3 phase, only the overall thermal sensation under Case 14 increased significantly. Detailed information on variation of skin temperature, the change rate of the skin temperature, thermal sensation, and thermal comfort of different body parts throughout the experiment can be found in Appendix B.

Table 6 Thermal sensation change values and P values of adjacent phases.

Table 7 Thermal comfort change values and P values of adjacent phases.

Fig.9 illustrates that the mean skin temperature dropped sharply during the temperature step-change process, while the cooking process only caused a slight increase in the mean skin temperature. The overall thermal sensation can be greatly improved during the first cooking phase. In the second cooking phase, the overall thermal sensation under Case 14 rose above neutral status. However, it remained below neutral status under Case 17. This may be related to the fact that the local thermal sensation of some body parts (forehead, right upper arm, right lower arm, right hand, left upper arm, left hand, and left thigh) under Case 14 was higher than that under Case 17. The cooking process improved overall thermal comfort in winter. In the second cooking phase, the overall thermal comfort rose to just comfortable condition. Although the air temperature in the kitchen was still low during the cooking process, with the thermal environment improving a little, the subjects felt more comfortable. This result is similar to the conclusion obtained by the study of Ji *et al*. [51].

Fig.9. Mean skin temperature, overall thermal sensation and thermal comfort during the experiment.

3.4. Prediction of whole and local thermal sensation

3.4.1. Prediction results of forehead

Fig.10 shows that the results predicted by the two models are generally lower than the actual vote tallies. The possible reason is that the forehead is not very sensitive to cold stimuli. Therefore, the C_1 and K_1 coefficients of the forehead in both models may need to be reduced appropriately. During the temperature step-change process, the predicted result of Zhang was even lower than the lower limit of -3. This may be caused by the excessive C_{2i} value of the forehead (C_{2i}^{-}=543) in the Zhang model, which causes the change rate of the skin temperature to influence the prediction result of the thermal sensation too much.

Fig.10. Local thermal sensation prediction results of forehead during the experiment.

3.4.2. Prediction results of upper limb

Fig.11 shows that the prediction results of the two local models for the upper arm are different. The Zhang prediction value was closer to the actual vote tally, while that of the Zhou model during the cooking phases was lower than the actual vote tally. For the lower arm, it seems that the predicted results of both models were slightly higher than the actual perception during the temperature step-change. However, during the cooking phase, the prediction results of the two models are good for the left lower arm, but low for the right lower arm. For the hand, the predicted results of the two models in the temperature step-change phase matched well with the actual vote tally. However, in the cooking phase, the predicted results for the left and right hand by the two models were lower than the actual thermal sensation. At the same time, the actual thermal sensation of the right hand in Case 14 was higher than that in Case 17 during the cooking phase. The trend of this difference was well predicted in both models.

In summary, the body part with more exercise will feel hotter than the prediction value. The possible reason is that both models of Zhang and Zhou were developed based on subjects with less movement. Therefore, the prediction results for the upper arm and left lower arm were good, but they were lower than the actual thermal sensation for the hand and right lower arm with more movement.

Fig.11. Local thermal sensation prediction results of upper limb during the experiment.

(a) Left upper arm. (b) Right upper arm. (c) Left lower arm. (d) Right lower arm. (e) Left hand. (f) Right hand.

3.4.3. Prediction results of lower limb

The thermal sensation prediction results of the left lower limb are shown in Fig.12. For the thigh, the prediction results of the Zhang model were closer to the actual vote tallies, while that of the Zhou model was lower during the cooking phases. For the calf, the predicted results of the two models were lower than the actual vote results during the cooking phases. Meanwhile for the foot, the prediction of the Zhang model was higher than the actual vote tallies, but that of the Zhou model was lower than that of the Zhang model.

In summary, although the skin temperature of lower limb kept decreasing, a gentle rise in the thermal sensation appeared. It seems that the two models cannot predict the thermal sensation well at the calf and foot when people stand and cook in kitchen.

Fig.12. Local thermal sensation prediction results of lower limb during the experiment.

(a) Left thigh. (b) Left calf. (c) Left foot.

3.4.4. Prediction results of whole sensation

Taking the mean skin temperature and the mean change rate of skin temperature as input parameters, the whole thermal sensation prediction model of Takada was used to predict the whole thermal sensation in our experiment. The prediction results are shown in Fig.13, which show that the prediction of the Takada model is quite good. The only shortcoming is that during the second cooking phase, the prediction of Case14 is lower than the actual voting results.

Fig.13. Whole thermal sensation prediction results during the experiment.

3.5. Discussion

In winter, the outdoor air temperature is low, so a heating or air conditioning system is usually used to maintain a higher air temperature in the living room to eliminate the cold discomfort. However, for rooms that people do not often stay in, such as the kitchen, there is no heating or air conditioning system. The interior door between the kitchen and the air-conditioned area is usually closed to save energy. This keeps the air temperature in the kitchen at a low level. Through our study, it is found that when people entered the kitchen from the air-conditioned room, a significant decrease in people's skin temperature, thermal sensation, and thermal comfort was the result.

In winter, because the outdoor air temperature is low, the exterior window of the kitchen is usually closed. Meanwhile, the interior door is also closed. As a result, the kitchen becomes a closed space, and as the air-tightness of doors and windows continues to improve in residential buildings, the problem of air-tightness will become more serious. Under this condition, through our measurements, it is shown that the exhaust flowrate of the range hood is reduced. The exhaust flowrate for the high, mid and low range hood gears can be decreased by 5.8%, 5.6% and 5.0%, respectively.

Through measurements, it is found that the push-pull ventilation system of the kitchen eliminated the adverse effects by the air-tightness of the kitchen. At the same time, through the capture efficiency test of the range hood, it is also found that too large air supply velocity resulted in poor range hood capture efficiency, similar to the results of Du *et al*. [52]. However, the small air curtain velocity combined with a suitable range hood gear could improve the capture efficiency of the range hood. From our test, the recommended working condition of the push-pull ventilation system was an air curtain velocity of 0.5m/s plus a range hood mid gear when the kitchen window is closed.

In winter, people cook in non-air-conditioned kitchens. Although the air temperature in the kitchen is still very low, the overall thermal sensation and thermal comfort of the human body is greatly improved during cooking processes. After two cooking processes, the thermal sensation and thermal comfort of the human body reaches neutral and just comfortable states, respectively. The thermal sensation and thermal comfort of different body parts would be different during the cooking processes. For instance, the back, left upper limb and lower limbs remind in a cold state. The forehead, chest, abdomen and right upper limb reached a warm state after the cooking phases. The right hand could even feel hot and uncomfortable at the second cooking phase. However, the influence of the hand on the whole body is small [53]. The hot condition of the right hand did not have a great impact on the whole body, but attention should be paid to the cold back. The clothing insulation of a cook's back should be increased appropriately in winter. The air curtain only had a significant effect on the thermal sensation of the forehead and right hand. Although the air curtain directly delivered the cold outdoor air into the kitchen, due to the low velocity of the air curtain, the influence on the thermal sensation and thermal comfort of the whole body is not very large.

The thermal sensation prediction model, which used the skin temperature as the input parameter, has the potential to predict the thermal sensation of the cook. However, because these models were developed based on the sitting posture and static condition of human body, the local thermal sensation model was better for the thermal sensation prediction for the stationary condition. However, it is not very good at the prediction of body parts where severe temperature exposure or significant movement occurs, such as the forehead, hand, and right lower arm. Some coefficients of the model may need to be corrected. At the same time, it is necessary to improve the prediction effect of the feet and calf for a standing human body.

For the air supply modes with different combinations of air curtain slots, there can be one slot, two slots, three slots and four slots. The capturing processes under these conditions are still unclear. Systematically study is needed during further investigation process.

The experiment only simulates two cooking processes. The cooking time during the actual family cooking process may be longer. Therefore, it is necessary to investigate the influence of longer cooking period on thermal comfort in kitchen environment.

4. Conclusions

In this study, the capture efficiency test was conducted under different working conditions of the push-pull ventilation system with the kitchen window open and closed. The optimal working condition of the system in winter was obtained. Then a thermal comfort study inside a kitchen was performed in winter under two different working conditions. Finally, three transient thermal sensation prediction models in a non-uniform environment, which takes the skin temperature and its change rate as input parameters, were used to predict the whole and local thermal sensation in our experiment. Prediction results were compared with actual vote tallies. This study provides data support for improving ventilation efficiency and thermal comfort in a residential kitchen with a push-pull ventilation system.

Some conclusions can be obtained as follows:

(1) When the push-pull ventilation system is used in the kitchen, the capture efficiency of the hood will be improved. However, the low-momentum make-up air and the reasonable air distribution are important to obtain good performance. The larger air curtain velocity will not definitely bring the higher capture efficiency of range hood. When the air curtain velocity is too large, it will make the capture efficiency even lower than that without air curtain. With comprehensive consideration of energy saving and capture efficiency, the best working conditions of the push-pull ventilation system is the combined scheme of the range hood with mid-gear plus the air curtain with a velocity of 0.5m/s when the kitchen window is closed.

(2) In winter, people entered the non-air-conditioned kitchen from the air-conditioned room, the whole thermal sensation and comfort significantly decreased during this temperature step-change. During the cooking processes, the whole thermal sensation and comfort improved. The back, left upper limb and lower limb of the human body are in a cold condition. However, the forehead, chest, abdomen and right upper limb can reach a warm condition during cooking processes. The overall thermal sensation and comfort of the human body can reach neutral and just comfortable conditions during cooking processes, although the right hand may feel slightly hot and uncomfortable.

(3) The whole and local thermal sensation prediction models using skin temperature as input parameters have the potential to predict human body thermal sensation in kitchen environment. These models can predict the thermal sensation of most parts of the human body in a kitchen. However, the correction for prediction the thermal sensation for the body parts with movement or exposure to severe heat radiation is still needed.

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Table 1 Information about the subjects.

Gender	Age (years)	Height (cm)	Weight (kg)
Male (n=10)	18.8±0.9	174.3±8.4	66±9.3
Female (n=10)	21.5±2.5	165.8±5	56.5±6
Total (n=20)	20.2±2.3	170±8.1	61.3±9.1

Table 2 Clothing insulation and metabolic rates in experiment.

Room	Activity	Clothing Insulation (clo)	Metabolic Rates (met)
Sitting room	Playing mobile phone, Seated	1.02+0.1[a]=1.12	1.1
Kitchen	Standing, relaxed	1.02	1.2
	Cooking	1.02	1.6-2.0

[a] 1.02 is insulation of clothing, 0.1 is insulation of seat

Table 3 Detailed information of the environmental measurement instruments.

Parameters	Instrument	Range	Accuracy	Interval
Air and wall temperature	PT100 thermal resistor	-50-450 ºC	±0.5 ºC	20s
CO_2 concentration	HINTEST HT-2000	0-9999 ppm	±5%	20s
Relative humidity	HINTEST HT-2000	3-99.9%	±3%	20s
Black-ball temperature	AZ8778[a]	0-80 ºC	±1 ºC	20s
Air velocity	KIMO VT100	0-30 m/s	±0.05 m/s	20s

[a] the diameter of the black ball is 75mm

Table 4 Exhaust flowrate of range hood and pressure difference between kitchen and outdoors under different working conditions.

Case	Window	Hood gear	AC velocity (m/s)	Make-up flowrate (m^3/h)	Exhaust flowrate (m^3/h)	Pressure difference [c] (Pa)
1	Open	High	0	—	518.8±5.2(508-531) [b]	0
2	Open	Mid	0	—	496.6±4.5(486-506)	0
3	Open	Low	0	—	444.1±3(436-451)	0
4	Open	High	0.5	157(31.4%) [a]	—	0
5	Open	Mid	0.5	157(33.0%)	—	0
6	Open	Low	0.5	157(36.7%)	—	0
7	Open	High	1.0	314(61.5%)	—	0
8	Open	Mid	1.0	314(65.2%)	—	0
9	Open	Low	1.0	314(72.1%)	—	0
10	Open	High	1.5	471(91.2%)	—	0
11	Open	Mid	1.5	471(96.8%)	—	0
12	Open	Low	1.5	471(107%)	—	0
13	Closed	High	0	—	488.8±4(483-498)	-44
14	Closed	Mid	0	—	468.7±3.2(461-480)	-40
15	Closed	Low	0	—	421.7±3.6(412-430)	-32.5
16	Closed	High	0.5	157(31.4%)	500.3±3.2(495-508)	-27.5
17	Closed	Mid	0.5	157(33.0%)	476.2±2.8(472-483)	-23
18	Closed	Low	0.5	157(36.7%)	427.9±3.3(420-436)	-18.5
19	Closed	High	1.0	314(61.5%)	510.4±3.7(498-519)	-16
20	Closed	Mid	1.0	314(65.2%)	481.7±3(476-488)	-12.5
21	Closed	Low	1.0	314(72.1%)	435.6±2.6(431-441)	-9
22	Closed	High	1.5	471(91.2%)	516.7±3.5(508-524)	-8
23	Closed	Mid	1.5	471(96.8%)	486.5±4.4(474-496)	-6.5
24	Closed	Low	1.5	471(107%)	440.1±2.9(434-446)	—

[a] (make-up flowrate/exhaust flowrate*100%)

[b] Mean±SD (minimum-maximum)

[c] Indoor pressure-Outdoor pressure

Table 5 The results of the capture efficiency (CE) test.

Case	Window	Hood gear	AC velocity (m/s)	Indoor[1.5m] concentration(ppm)	Indoor[1.2m] concentration(ppm)	Outdoor concentration(ppm)	Exhaust concentration(ppm)	CE[1.5m] (%)	CE[1.2m] (%)	∣ΔCE(1.5m-1.2m)∣ (%)
1	Open	High	0	999.3±39.8 [a]	859.5±25.7	614.2±27.2	2123.8±21	74.49±2.98	83.75±2.29	9.26
2	Open	Mid	0	1018.5±29.4	899.3±26.3	643.6±33.6	2130±23.3	74.78±2.63	82.80±2.59	8.02
3	Open	Low	0	983.9±38.4	788.4±46	672.4±55.6	1942.2±56	75.47±4.61	90.86±5.40	15.40
4	Open	High	0.5	759.8±44.3	728.9±50.7	634.4±31.4	2139.2±34.8	91.67±3.52	93.72±3.90	2.05
5	Open	Mid	0.5	832.6±29.2	830.6±20.8	616.6±15.3	2266.6±15.4	86.91±1.95	87.03±1.50	0.12
6	Open	Low	0.5	696.5±27.9	683.5±31.4	648.6±31	1834.6±58.4	95.96±3.44	97.06±3.67	1.10
7	Open	High	1.0	683.9±33.7	703.4±38.1	551.5±14.7	2183±28.7	91.88±2.23	90.69±2.48	1.20
8	Open	Mid	1.0	677.3±17.3	693.4±26.4	606.3±22.9	2222.6±23.2	95.61±1.73	94.61±2.11	1.00
9	Open	Low	1.0	720.8±52.5	790.8±15.9	673.1±41.9	2438.3±64	97.30±3.77	93.33±2.40	3.97
10	Open	High	1.5	667.4±10.6	667.3±13.8	571.5±48.2	2014.7±21.2	93.36±3.20	93.36±3.26	0.01
11	Open	Mid	1.5	751.3±4.2	782.7±6.6	596.9±10.8	1856.4±25.7	87.74±0.86	85.25±0.95	2.49
12	Open	Low	1.5	825.5±11	841.5±17.2	637.3±10	2206.8±26.7	88.01±0.92	86.99±1.25	1.02
13	Closed	High	0	881.8±18.4	906.5±17.2	541.9±3.3	2484.6±25.8	82.50±0.99	81.23±0.93	1.27
14	Closed	Mid	0	856.8±7.7	873.5±5.4	551.1±8.2	1956.8±60.6	78.25±1.18	77.06±1.15	1.19
15	Closed	Low	0	883.3±9.1	896.4±7.7	557.9±7.2	2095.3±94.1	78.83±1.47	77.98±1.48	0.85
16	Closed	High	0.5	797.8±5.1	791.8±3.5	545±9.8	2419.8±2.3	86.52±0.53	86.84±0.49	0.32
17	**Closed**	**Mid**	**0.5**	**838.7±1.7**	**848.6±11.1**	**555.3±5.6**	**2476.9±12.5**	**85.25±0.28**	**84.74±0.64**	**0.52**
18	Closed	Low	0.5	861.2±8.2	858.7±8.5	570.8±11.6	2194.9±66.1	82.12±1.06	82.27±1.07	0.15
19	Closed	High	1.0	850.6±10.7	874.8±8.3	617.5±11.5	2374.6±49	86.73±0.91	85.36±0.84	1.38
20	Closed	Mid	1.0	868.4±18.1	893.5±7.3	609.7±9.1	2264.1±10.9	84.36±1.19	82.85±0.64	1.52
21	Closed	Low	1.0	889.5±2.7	870±3.2	533.3±2.8	2297.6±16.3	79.81±0.27	80.92±0.28	1.11
22	Closed	High	1.5	913.3±11.5	938±13.3	579.5±9.8	2060.4±37.9	77.46±1.09	75.79±1.20	1.67
23	Closed	Mid	1.5	964±3.1	978.3±4.1	568.8±6.8	2094±50.5	74.09±0.94	73.15±0.98	0.94
24	Closed	Low	1.5	1060.2±35.8	984.9±12	570±21.8	2333.3±17.4	72.20±2.23	76.47±1.19	4.27

[a] Mean±SD

Table 6 Thermal sensation change values and P values of adjacent phases.

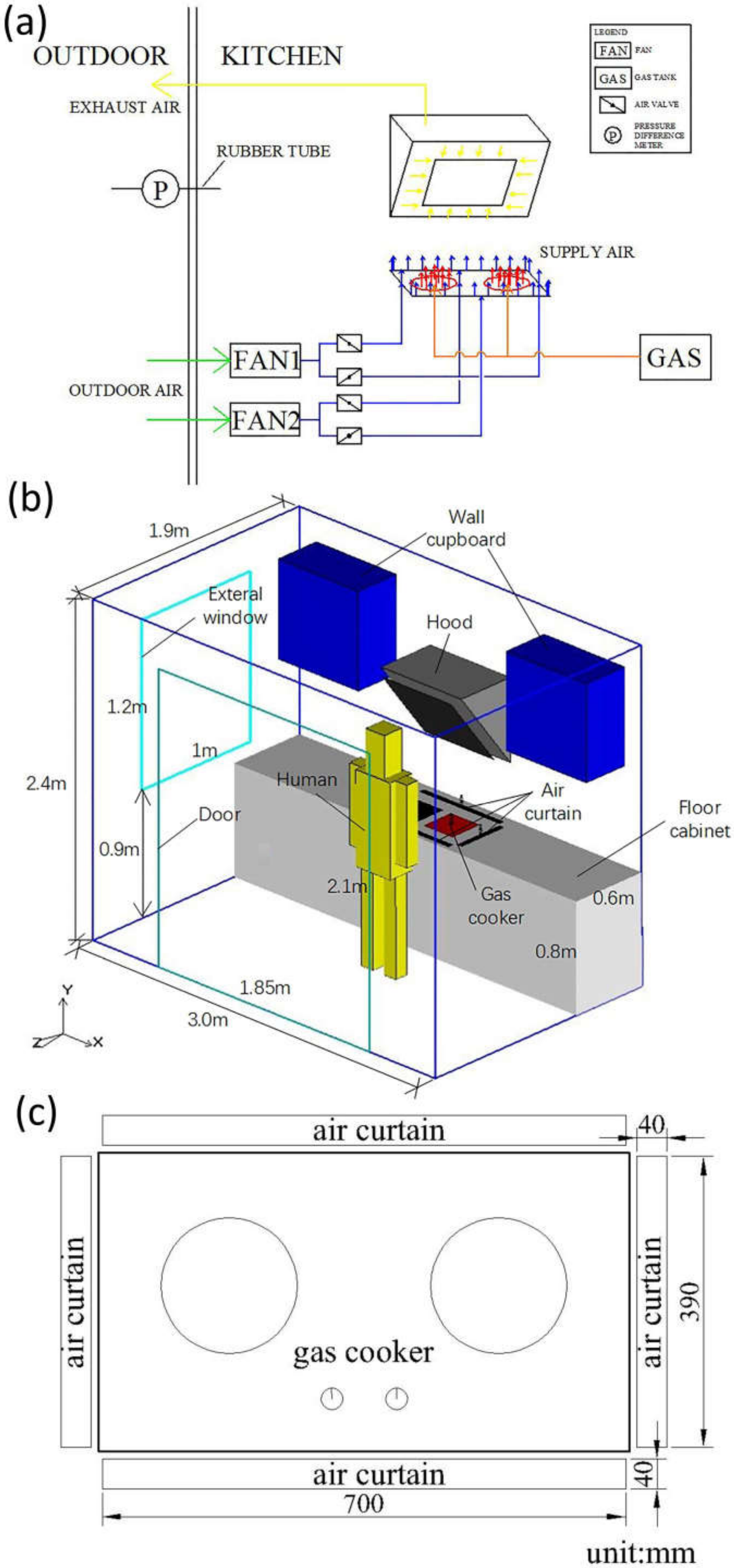
Body parts	P1 vs P2		P2 vs P3		P3 vs P5	
	Case 14	Case 17	Case 14	Case 17	Case 14	Case 17
forehead	**-0.7****	**-0.7****	**0.7****	**0.7****	0.3	-0.1
back	**-1.0*****	**-1.1****	0.3	0.4	0.1	0.2
chest	**-0.7****	**-0.6****	**0.6****	**0.4***	0.2	0.3
abdomen	**-0.6****	**-0.6****	**0.8****	**0.8****	0.1	0.1
left upper arm	**-1.2*****	**-1.2*****	**0.6***	0.5	0.2	0.3
left lower arm	**-1.2*****	**-1.1*****	**0.7****	**0.5***	0.2	0.2
left hand	**-1.1*****	**-1.2*****	0.7	0.7	0.3	0.3
right upper arm	**-1.1*****	**-1.0*****	**1.1*****	**0.8****	0.3	0.1
right lower arm	**-1.2*****	**-1.0*****	**1.5*****	**1.2*****	0.3	0.0
right hand	**-1.2*****	**-1.2*****	**2.3*****	**2.1*****	0.4	0.2
left thigh	**-0.7*****	**-0.6****	0.2	0.3	0.4	0.0
left calf	**-0.8****	**-0.5***	0.3	0.0	0.2	0.1
left foot	-0.4	-0.3	0.1	0.0	0.1	0.2
right thigh	**-0.7)*****	**-0.6****	0.3	0.3	0.4	0.1
right calf	**-0.8****	**-0.5***	0.3	0.0	0.2	0.1
right foot	-0.5	-0.3	0.1	0.0	0.1	0.1
whole	**-1.5*****	**-1.4*****	**1.3*****	**1.0*****	**0.5***	0.2

Note: P value is shown in the brackets. *P<0.05, **P<0.01, ***P<0.001.

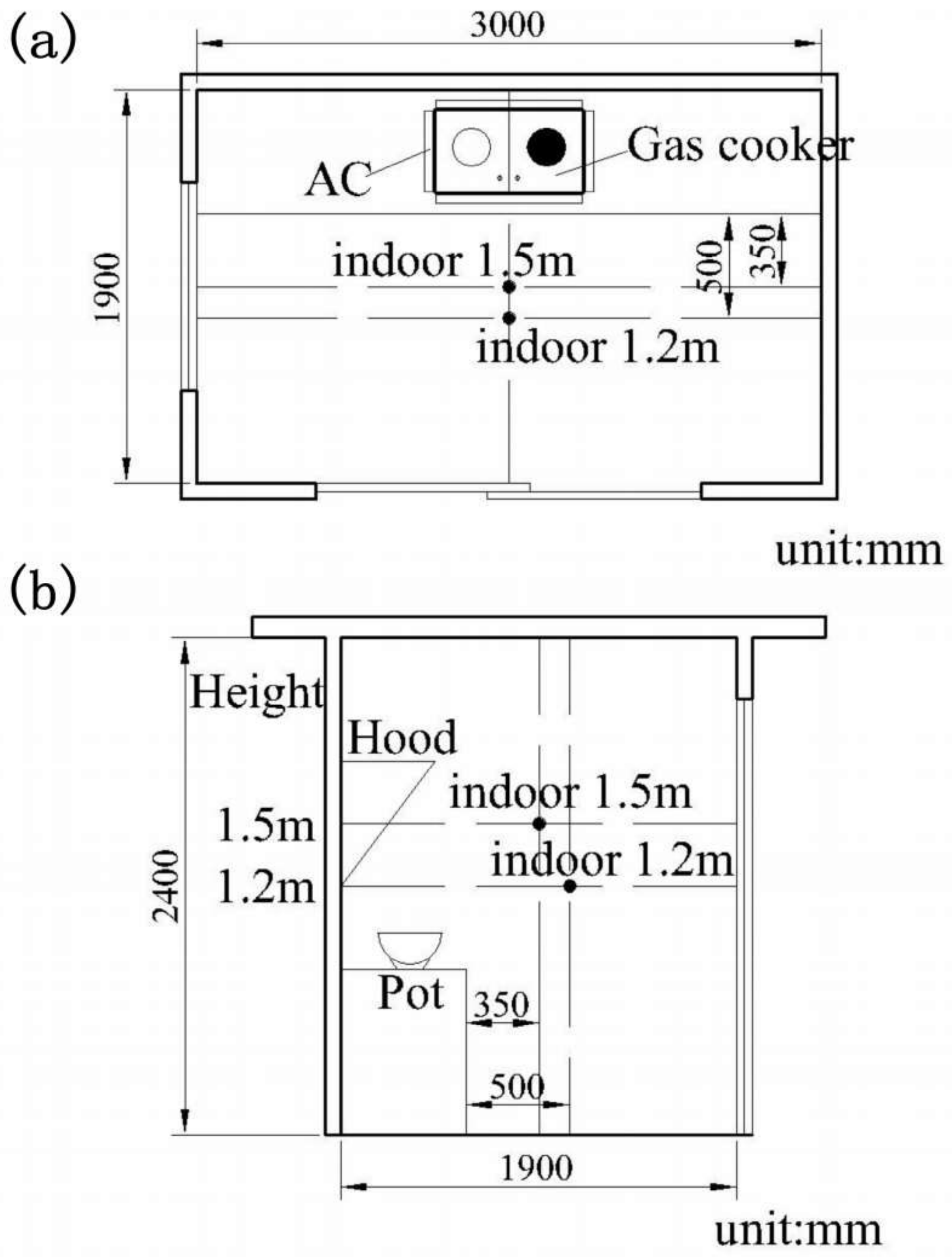
Table 7 Thermal comfort change values and P values of adjacent phases.

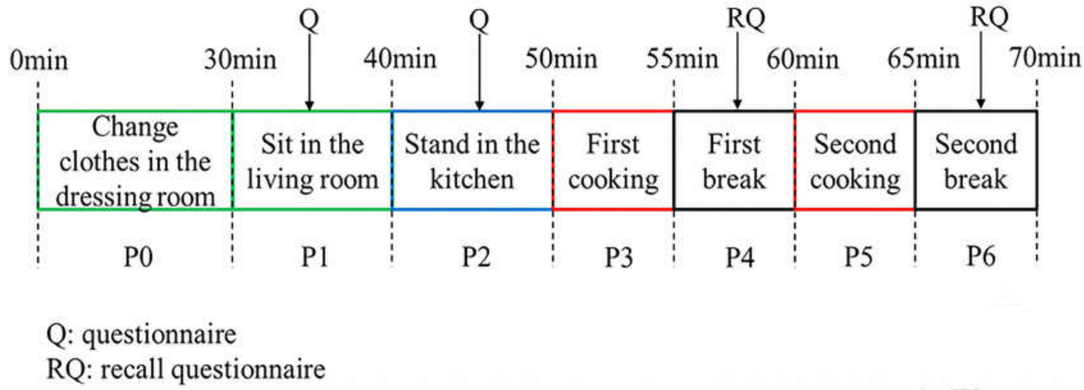
Body parts	P1 vs P2		P2 vs P3		P3 vs P5	
	Case 14	Case 17	Case 14	Case 17	Case 14	Case 17
forehead	**-0.5***	**-0.7****	0.1	0.2	0.1	0.1
back	**-1.0*****	**-0.7***	0.2	0.2	0.2	0.1
chest	**-0.7****	**-0.5***	**0.4***	0.2	0.2	0.0
abdomen	**-0.7****	-0.4	**0.5***	0.1	0.0	0.0
left upper arm	**-0.9*****	**-0.8*****	0.2	0.0	0.2	0.2
left lower arm	**-1.0*****	**-0.8*****	0.3	0.1	0.2	0.2
left hand	**-0.7****	**-0.9****	-0.2	0.0	0.2	0.1
right upper arm	**-0.9*****	**-0.7*****	0.4	0.1	0.1	0.0
right lower arm	**-1.0*****	**-0.7*****	**0.6****	0.2	-0.1	0.0
right hand	**-0.7****	**-0.9****	0.2	0.3	-0.4	-0.3
left thigh	**-0.5***	**-0.5***	0.1	0.1	0.1	0.2
left calf	**-0.5***	**-0.6****	0.1	0.0	0.2	0.3
left foot	-0.4	**-0.6****	0.2	0.1	0.1	0.1
right thigh	**-0.5***	**-0.5***	0.1	0.1	0.1	0.2
right calf	**-0.6***	**-0.6****	0.1	0.0	0.2	0.3
right foot	**-0.5***	**-0.6****	0.2	0.2	0.1	0.0
whole	**-1.3*****	**-1.1*****	**0.4***	0.3	0.1	0.3

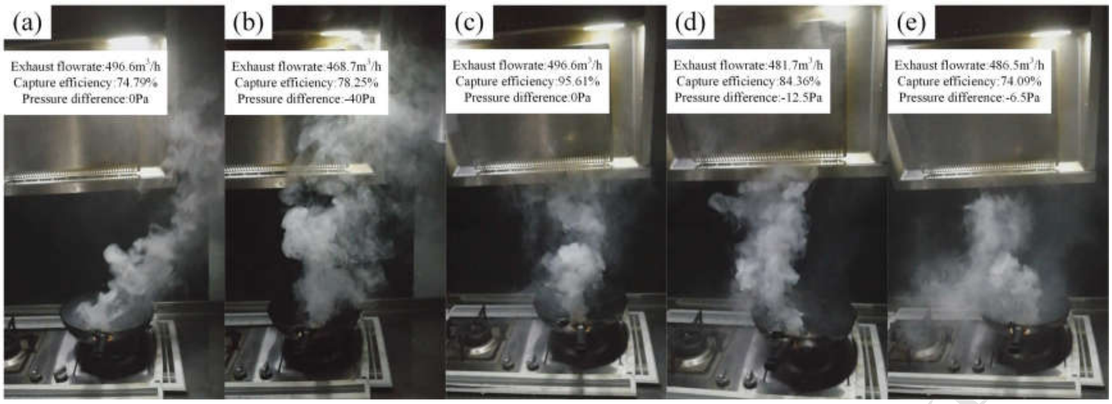
Note: P value is presented in the brackets. *P<0.05, **P<0.01, ***P<0.001.

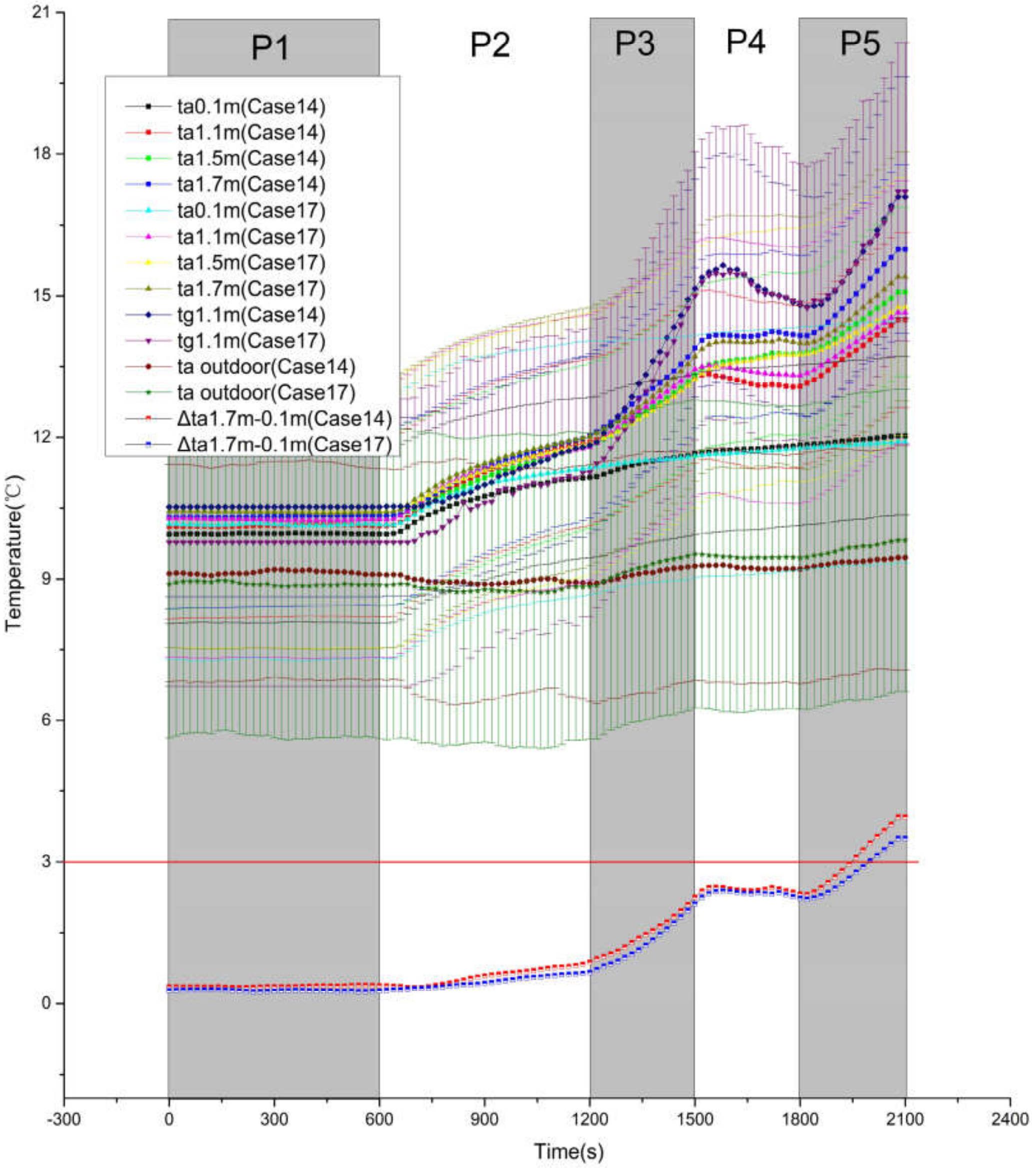


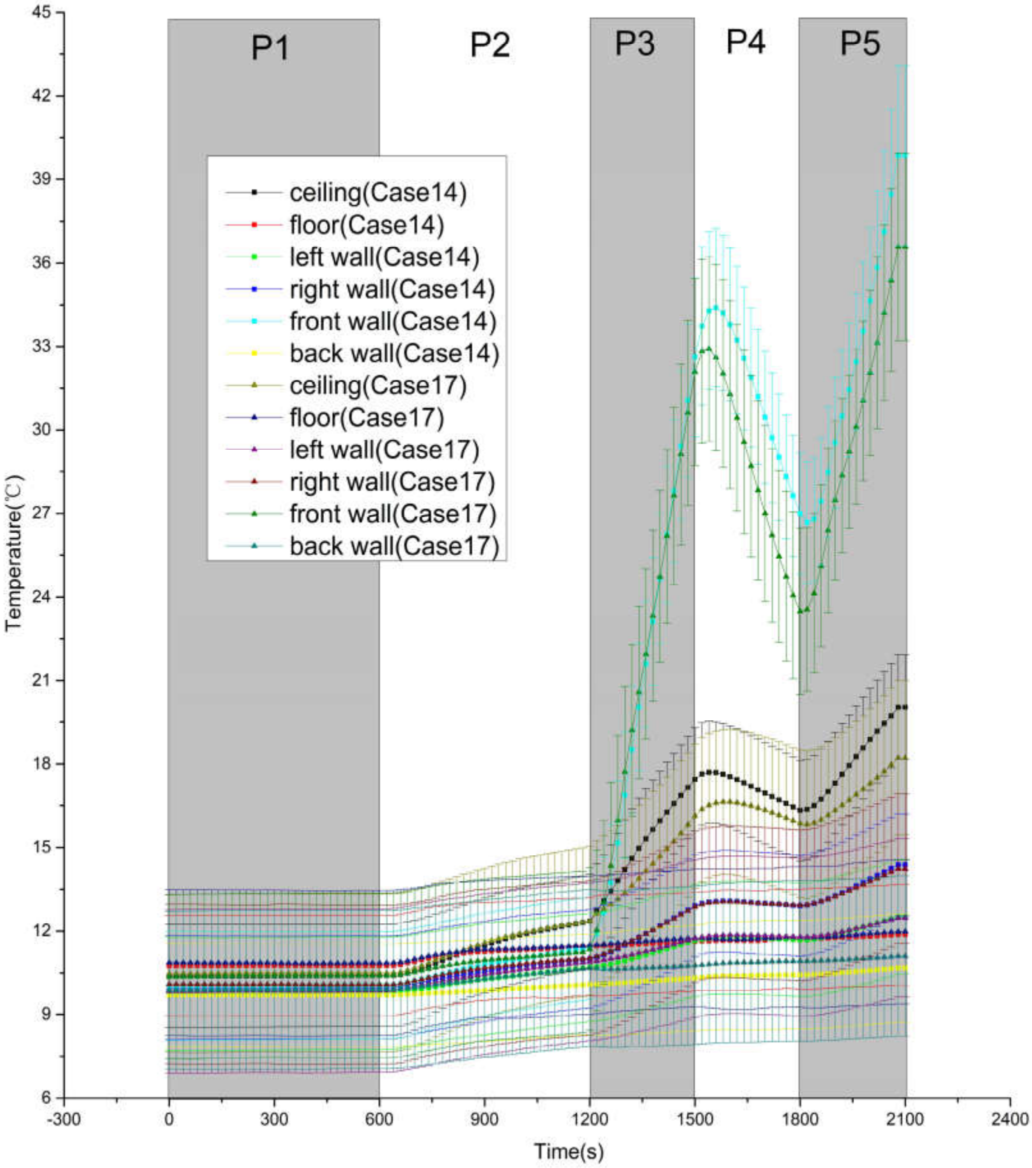
(a)
OUTDOOR
KITCHEN
EXHAUST AIR
RUBBER TUBE
P
LEGEND
FAN FAN
GAS GAS TANK
AIR VALVE
PRESSURE DIFFERENCE METER
SUPPLY AIR
FAN1
FAN2
OUTDOOR AIR
GAS
(b)
1.9m
Wall cupboard
Exteral window
Hood
1.2m
1m
2.4m
Human
Air curtain
Floor cabinet
Door
0.9m
2.1m
Gas cooker
0.6m
0.8m
1.85m
3.0m
Y
Z
X
(c)
air curtain
40
air curtain
air curtain
390
gas cooker
air curtain
40
700
unit:mm

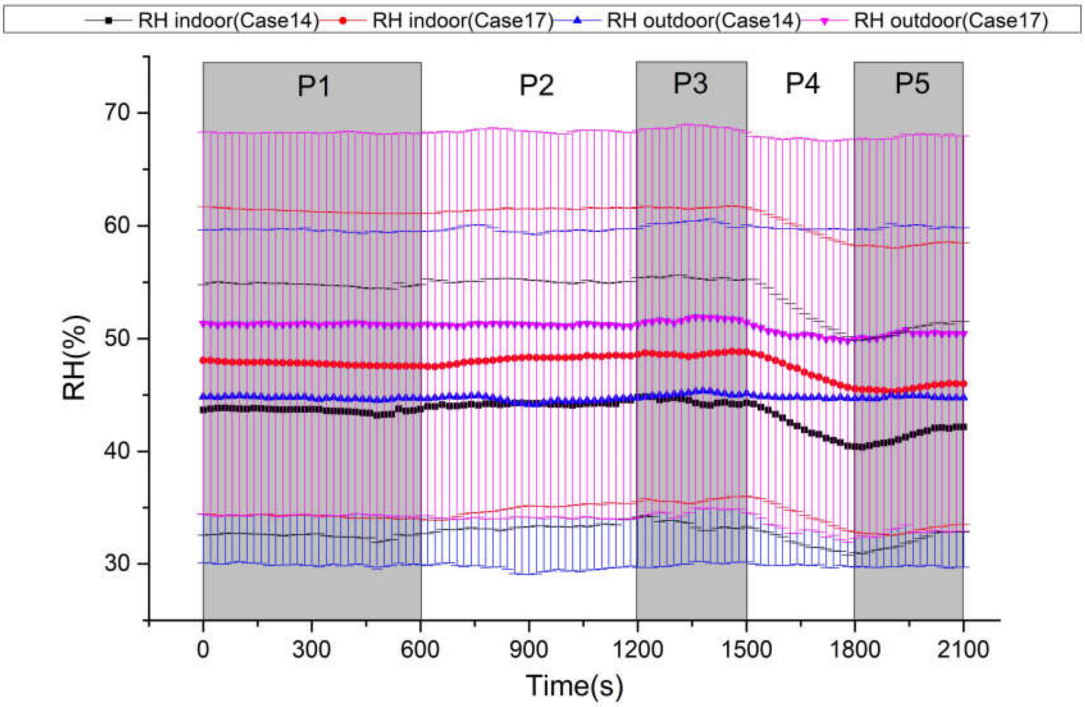

(a)
3000
1900
AC
Gas cooker
indoor 1.5m
indoor 1.2m
500
350
unit:mm
(b)
Height
Hood
indoor 1.5m
indoor 1.2m
1.5m
1.2m
2400
Pot
350
500
1900
unit:mm


Q
Q
RQ
RQ
0min
30min
40min
50min
55min
60min
65min
70min
Change clothes in the dressing room
Sit in the living room
Stand in the kitchen
First cooking
First break
Second cooking
Second break
P0
P1
P2
P3
P4
P5
P6
Q: questionnaire
RQ: recall questionnaire

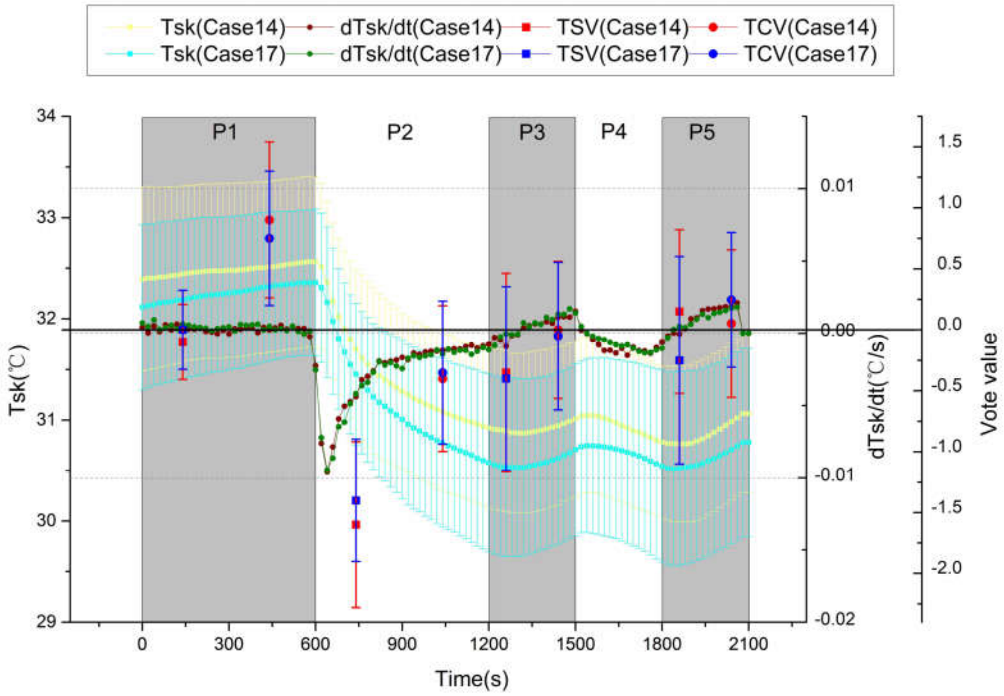

(a)
Exhaust flowrate:496.6m³/h
Capture efficiency:74.79%
Pressure difference:0Pa
(b)
Exhaust flowrate:468.7m³/h
Capture efficiency:78.25%
Pressure difference:-40Pa
(c)
Exhaust flowrate:496.6m³/h
Capture efficiency:95.61%
Pressure difference:0Pa
(d)
Exhaust flowrate:481.7m³/h
Capture efficiency:84.36%
Pressure difference:-12.5Pa
(e)
Exhaust flowrate:486.5m³/h
Capture efficiency:74.09%
Pressure difference:-6.5Pa

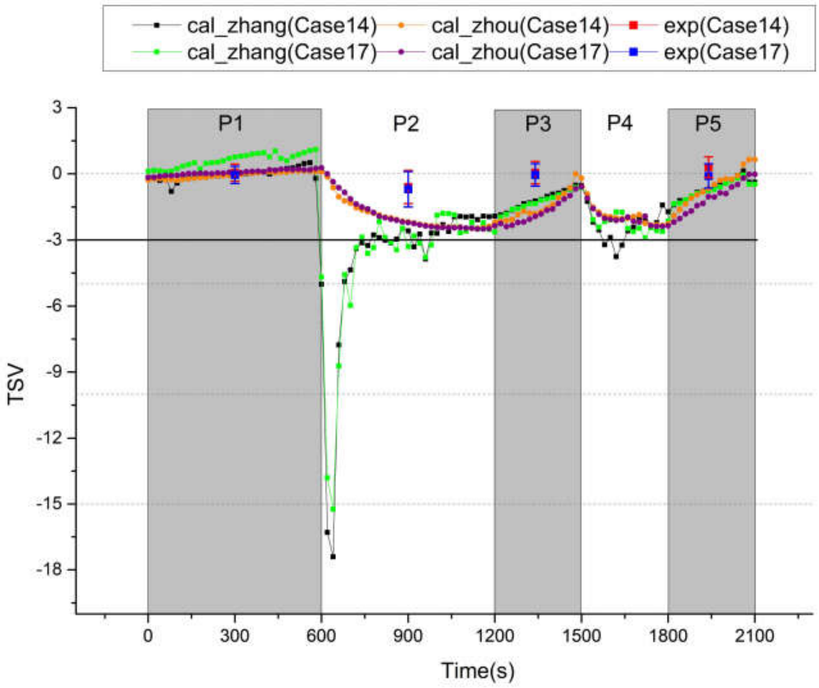

P1
P2
P3
P4
P5
ta0.1m(Case14)
ta1.1m(Case14)
ta1.5m(Case14)
ta1.7m(Case14)
ta0.1m(Case17)
ta1.1m(Case17)
ta1.5m(Case17)
ta1.7m(Case17)
tg1.1m(Case14)
tg1.1m(Case17)
ta outdoor(Case14)
ta outdoor(Case17)
Δta1.7m-0.1m(Case14)
Δta1.7m-0.1m(Case17)
Temperature(℃)
Time(s)
21
18
15
12
9
6
3
0
-300
0
300
600
900
1200
1500
1800
2100
2400


P1
P2
P3
P4
P5
ceiling(Case14)
floor(Case14)
left wall(Case14)
right wall(Case14)
front wall(Case14)
back wall(Case14)
ceiling(Case17)
floor(Case17)
left wall(Case17)
right wall(Case17)
front wall(Case17)
back wall(Case17)
Temperature(℃)
Time(s)
45
42
39
36
33
30
27
24
21
18
15
12
9
6
-300
0
300
600
900
1200
1500
1800
2100
2400

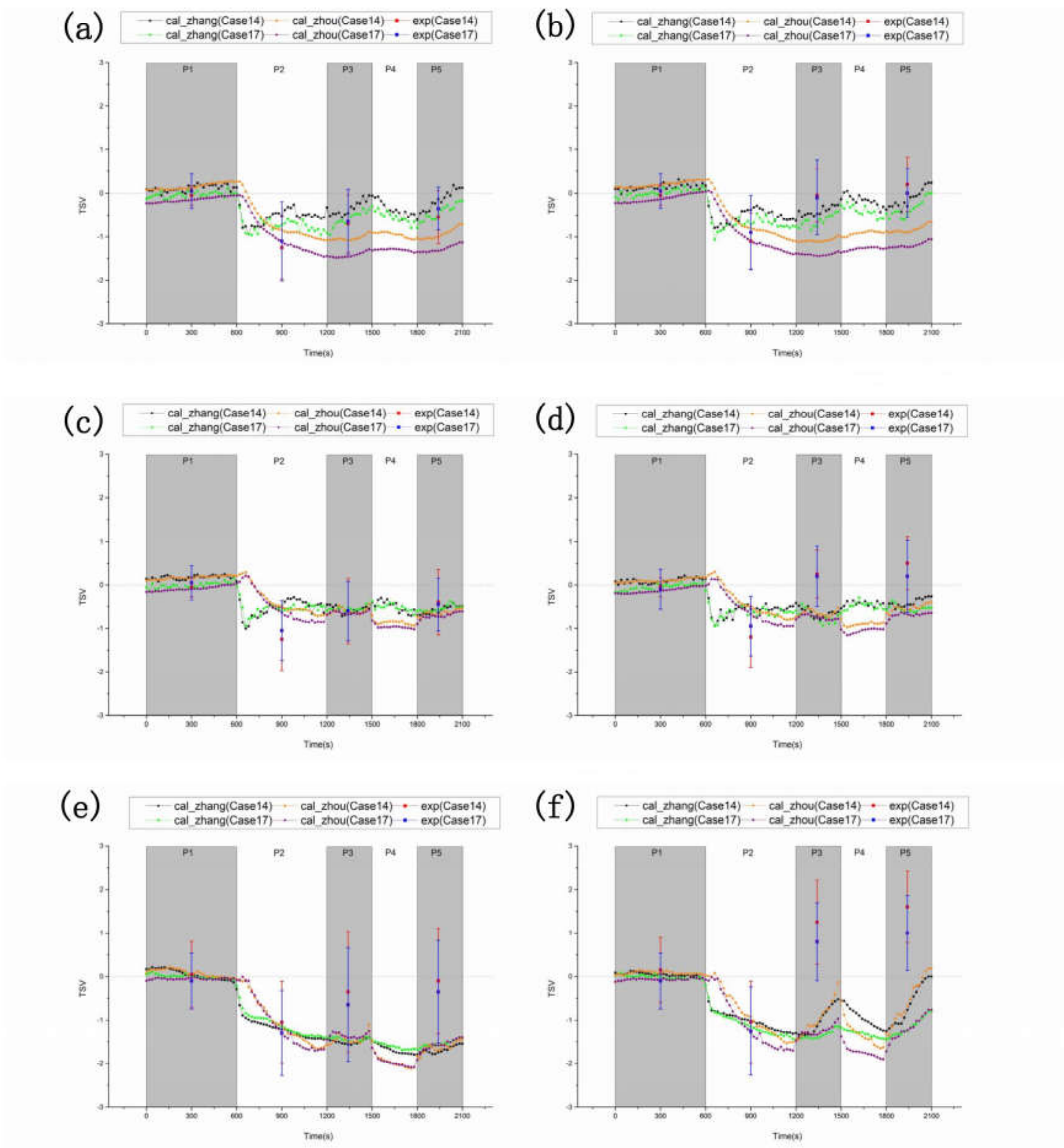


RH indoor(Case14)
RH indoor(Case17)
RH outdoor(Case14)
RH outdoor(Case17)
P1
P2
P3
P4
P5
RH(%)
70
60
50
40
30
0
300
600
900
1200
1500
1800
2100
Time(s)


Tsk(Case14)
dTsk/dt(Case14)
TSV(Case14)
TCV(Case14)
Tsk(Case17)
dTsk/dt(Case17)
TSV(Case17)
TCV(Case17)
P1
P2
P3
P4
P5
Tsk(℃)
dTsk/dt(℃/s)
Vote value
Time(s)
0
300
600
900
1200
1500
1800
2100
29
30
31
32
33
34
0.01
0.00
-0.01
-0.02
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0



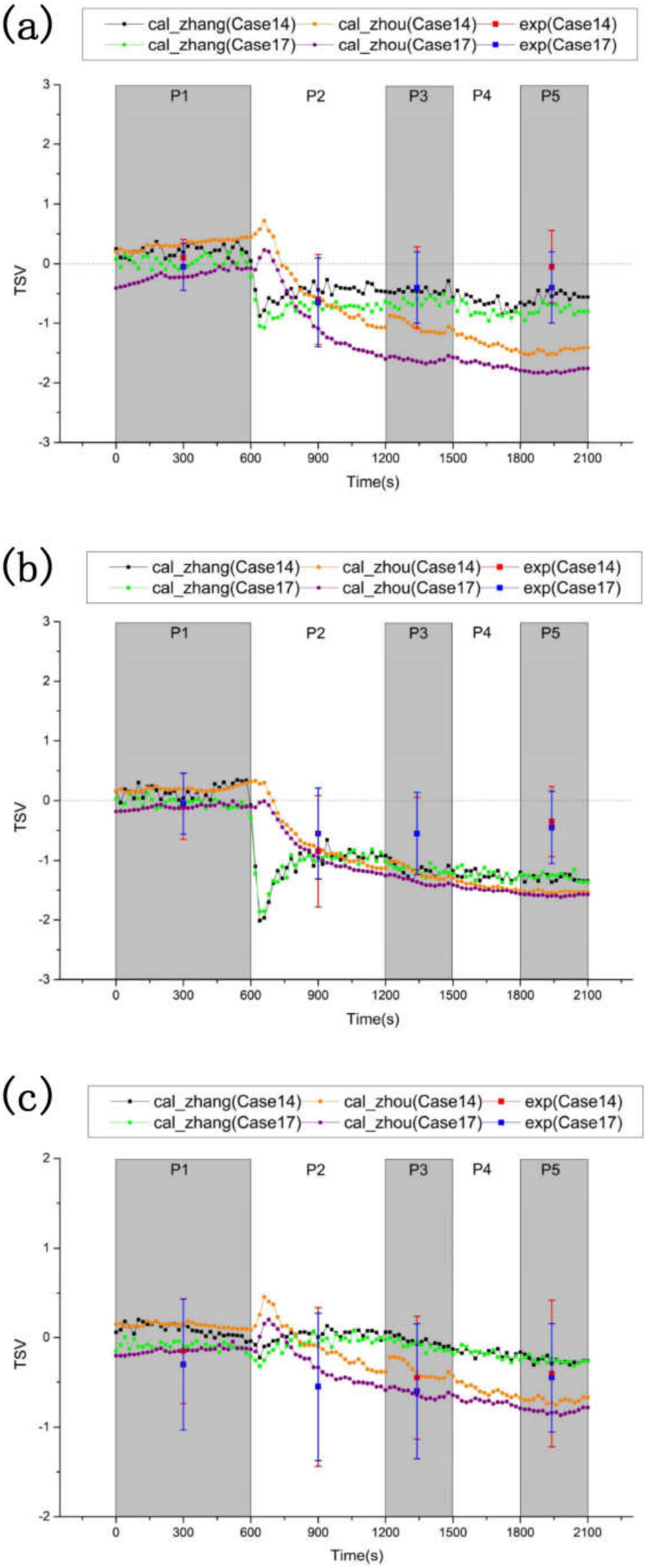
cal_zhang(Case14)
cal_zhou(Case14)
exp(Case14)
cal_zhang(Case17)
cal_zhou(Case17)
exp(Case17)
P1
P2
P3
P4
P5
TSV
Time(s)
3
0
-3
-6
-9
-12
-15
-18
0
300
600
900
1200
1500
1800
2100

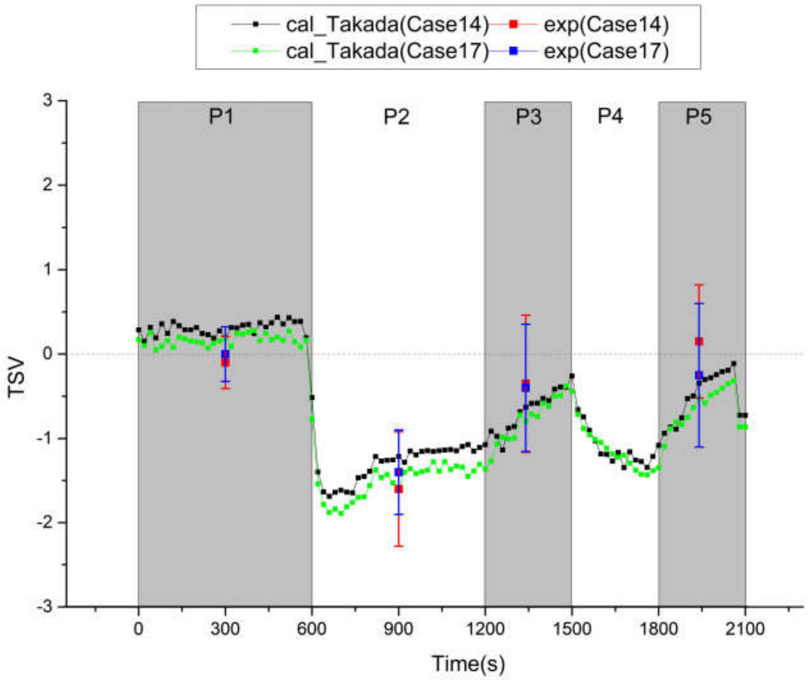

(a)
(b)
(c)
(d)
(e)
(f)
cal_zhang(Case14)
cal_zhou(Case14)
exp(Case14)
cal_zhang(Case17)
cal_zhou(Case17)
exp(Case17)
P1
P2
P3
P4
P5
TSV
Time(s)

(a)

(b)

(c)


cal_zhang(Case14)
cal_zhou(Case14)
exp(Case14)
cal_zhang(Case17)
cal_zhou(Case17)
exp(Case17)
P1
P2
P3
P4
P5
TSV
Time(s)


cal_Takada(Case14)
exp(Case14)
cal_Takada(Case17)
exp(Case17)
P1
P2
P3
P4
P5
TSV
Time(s)
3
2
1
0
-1
-2
-3
0
300
600
900
1200
1500
1800
2100

Highlights

- Air curtain with optimal velocity can improve capture efficiency of range hood.
- In winter, cooking process can improve thermal comfort of human body.
- Air curtain has no significant effect on thermal comfort of human body in winter.
- Different thermal sensation models were compared for kitchen environment.