Influence of Fresh Air System of Range Hood on Kitchen Thermal Comfort

Jun Zhang[1(✉)], Bingsong Yu[1], and Jian Ye[2]

[1] Fotile Group Ningbo Fotile Kitchenware CO., LTD., Ningbo 315336, China
zhangjund@fotile.com

[2] Jiaxing Research Institute, Southern University of Science and Technology, Jiaxing 315032, China

Abstract. To evaluate and optimize the thermal comfort of a kitchen environment, the effect of the fresh air system of range hood is analyzed quantitatively by means of experimental and numerical approaches. The thermal comfort of kitchen is assessed by both indexes PMV (expected mean thermal sensory index) and PPD (expected dissatisfaction rate), and the thermal comfort of the fresh air system is evaluated for different working states. The results show that the hood fresh air system has a significant impact on the kitchen environment. It not only improves the thermal comfort of the kitchen environment by 83% in PMV and 89% in PPD, but also has a good inhibitory effect on the diffusion of oil fume.

Keywords: Fresh Air System · Analyzed Quantitatively · Thermal Comfort · Predicted Mean Vote · Predicted Percentage Dissatisfied

1 Introduction

With the improvement of people's living standards and the development of social economy, people have higher requirements for indoor thermal comfort and quality of life. Therefore, a lot of practice and research has been done on the comfort of the kitchen environment.

For a long time, domestic and foreign scholars have continued to study thermal comfort. In 1936, Professor Bedford [1] proposed the classical 7-level scale evaluation index, which laid the foundation of thermal comfort research from then on, while Carlos et al. [2] used the exergy analysis method to evaluate the thermal comfort index of the human body. Wang et al. [8] analyzed the indoor thermal comfort of four classrooms in a university in Xi'an in autumn by means of questionnaires. Wang et al. [9, 10] used the method of on-site questionnaire survey to study and analyze the thermal environment and thermal adaptability of houses and dormitories, respectively. According to the characteristics of indoor and outdoor climate, environment and human body as well as the relationship between human comfort temperature and indoor and outdoor thermal environment is obtained. However, there are human factors in the study of thermal comfort through questionnaires [8–11, 13].

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With the advancement of computer simulation technology, computational fluid dynamics (CFD) technology has been gradually applied to the study of indoor environments such as kitchens and air-conditioned rooms, and has become one of the important means of airflow organization research. Yang et al. [4] used CFD numerical simulation technology to analyze the wind velocity field, temperature field and wind age field in a wall-mounted air conditioning room in summer. It is proved that CFD software has many advantages in simulating indoor environment compared with traditional measurement methods. Hu et al. [3] simulated the velocity and temperature fields of a large space building with different ventilation methods, such as louvered side-feed and side-return, nozzle side-feed and side-return, diffuser top-feed and bottom-return, stratified air conditioning, and displacement ventilation. Yang et al. [12] simulated and analyzed the indoor airflow distribution and thermal environment in the atrium of a certain engineering building in spring and summer, and evaluated the indoor thermal comfort through the effective blowing temperature to provide a reference for engineering design. Shang et al. [6] carried out numerical simulation calculation and analysis on the air distribution, temperature field, pollutant concentration field, etc. of the public kitchen, which provided the basis for the actual engineering design. However, it does not consider the influence of other factors such as ambient air humidity, clothing thermal resistance and human metabolism on thermal comfort.

At present, thermal comfort is mainly evaluated by on-site investigation or CFD simulation of temperature field and velocity field analysis. However, there are relatively few domestic literatures using CFD technology to analyze the impact of kitchen environment on human thermal comfort. How to reasonably and effectively quantify and optimize the thermal comfort of the kitchen environment is one of the current research hotspots.

In this paper, the method of combining experimental test and simulation is used to study the residential kitchen. Taking PMV and PPD as evaluation indicators, using C language combined with Fluent user-defined functions, the influencing factors of human thermal comfort are comprehensively considered and completed by presenting of the contour plot of PMV and PPD data at the kitchen environment. By quantitatively analyzing the influence of the fresh air system of the range hood on the thermal comfort of the kitchen environment, it can provide a reference for the optimization of the thermal comfort of the kitchen environment.

2 Kitchen Pilot Testing and Data Analysis Construction and Geometrical Dimensions of Specimens

2.1 Kitchen Environment

A test kitchen with 4.2m in length, 2.4m in width and 2.6m in height was built as shown in Fig. 1. It has built-in storage areas (cabinet, shelves, table tops, etc.), cooking areas (stoves, range hoods, smoke shields, etc.), and washing areas (dishwashers, etc.). There is a fresh air system of the range hood (two fresh air outlets, upper and lower) as shown in Fig. 2. The purpose of the fresh air system is to improve the thermal comfort in the kitchen and block the diffusion of oil fume.

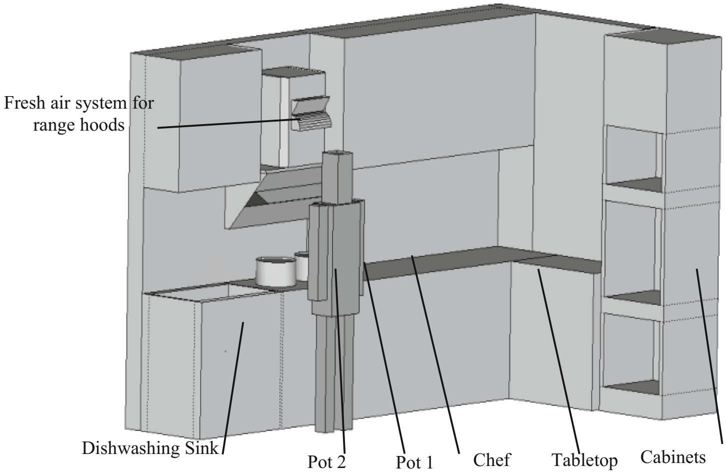


Fig. 1. Test kitchen environment layout

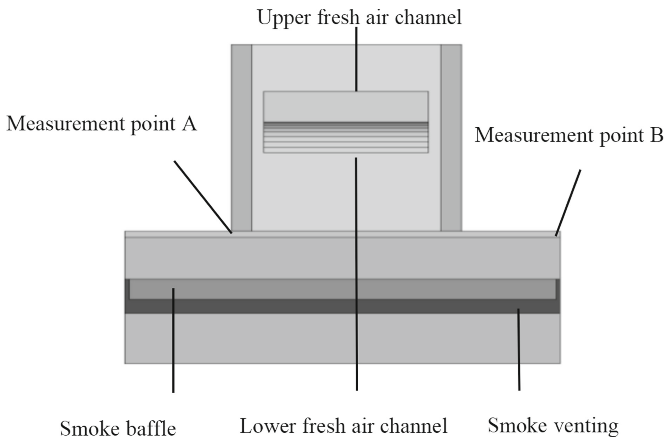


Fig. 2. Range hood fresh air system layout

2.2 Test Condition Setting

According to the kitchen cooking habits in daily life, the test conditions are set as follows:

(1) In order to explore the influence of the fresh air system on the thermal comfort of the kitchen, the fresh air system was turned on for the first 900 s and turned off for the next 900 s. The temperature of the upper and lower fresh air outlets is 20°, and the wind speed is 2.42 m/s.
(2) The exhaust port of the cooker hood was open during the whole test.
(3) The stove is the main heat source. As shown in Fig. 3, when only the pot 2 is used for cooking, the specific cooking time are between 46s ~ 95 s time and 946s ~

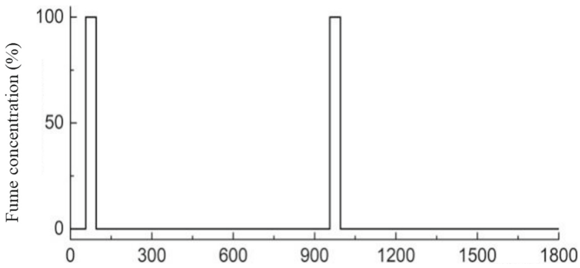
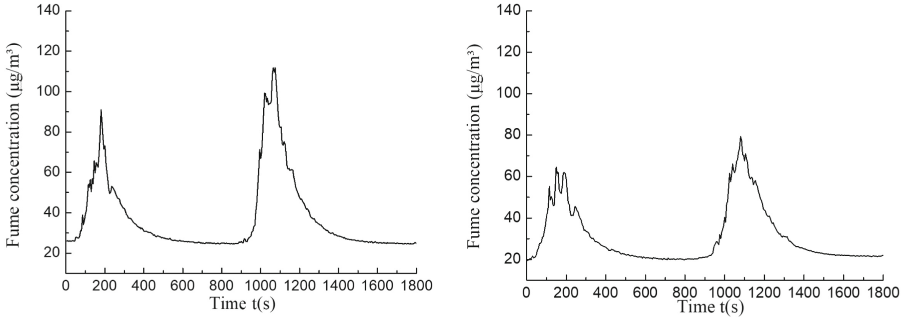


Fig. 3. Generation of oil smoke from pot 2



(a) Measurement point A (b) Measurement point B

Fig. 4. Curve of experimental data with time for 6σ treatment

995 s time for the fresh air system on and off, respectively. The measured oil smoke temperature is 70 °C and the speed is 2.0 m/s.

(4) In order to reduce the interference of human factors on the test, except for the necessary experimental operations, only the chef is responsible for the overall operation of the test.

(5) As shown in Fig. 2, the particle samplers were arranged at two positions, A and B, respectively. The measuring point A is 188 cm away from the ground, 107 cm away from the back wall of the cabinet, and 40 cm away from the left side of the range hood. The measurement point B is 166 cm away from the ground, 77 cm away from the back wall of the cabinet, and 28 cm away from the left side of the range hood.

2.3 Analysis of Experimental Data

The test process was carried out in strict accordance with the established test process. The particulate matter sampling instrument was used to test and record the fume concentration of the two measuring points A and B. The data was collected and recorded every 5 s, and the process was repeated 20 times. By using 6σtest data processing method, the abnormal test data below 5% and exceeds 95% were removed. Figure 4 shows the average of the rest test data.

3 Kitchen CFD Simulation and Analysis of its Calibration with Real Measurements

3.1 Mathematical Models

The flow and heat transfer process of air and grease within the kitchen environment can be described by the continuity equation, momentum equation, energy equation [13] and the k-ε turbulence model equation, in the following order.

(1) Continuity equation

$$\frac{\partial \rho}{\partial t} + div(\rho U) = 0 \tag{1}$$

where: ρ is the density and t is time, div(ρU) denotes the net flow ratio per unit volume of fluid in space.

(2) Momentum equation

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial \left(\rho u_i u_j\right)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \mu \nabla^2 u_i + \frac{\partial}{\partial x_j}\left(-\overline{\rho u_i u_j'}\right) \tag{2}$$

where: P is the flow pressure, μ is the fluid viscosity, u is the momentum.

(3) Energy equation

$$\frac{\partial (ph)}{\partial t} + \frac{\partial (\rho v h)}{\partial x} + \frac{\partial (\rho v h)}{\partial y} + \frac{\partial (\rho v h)}{\partial z} = - pdivU + div(\lambda\, grad\,)T + \phi + S_h \tag{3}$$

where: λ is the thermal conductivity of the fluid, h is the specific enthalpy of the fluid, Sh the internal heat source of the microfluid, φ is the dissipation function, Eq.

$$\phi = \eta \left\{ \begin{array}{l} \left(\frac{\partial \mu}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial \mu}{\partial z} + \frac{\partial w}{\partial x}\right)^2 \\ 2\left[\left(\frac{\partial \mu}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right] \\ 2\left[\left(\frac{\partial \mu}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right] \end{array} \right\} + \lambda divU \tag{4}$$

(4) k-ε turbulence model equation

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{5}$$

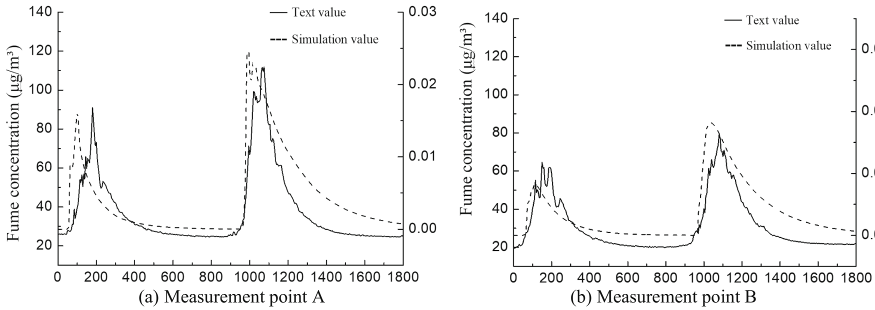


Fig. 5. Calibration of soot concentration test data compared with CFD simulation data

where: μ_t is the turbulent viscosity coefficient. k is the turbulent kinetic energy. ε is the turbulent kinetic energy dissipation rate.

3.2 Kitchen Flow Field Simulation and Calibration Analysis of Experimental Data

Firstly, we completed the analysis of the thermal comfort of the kitchen through the CFD flow field analysis, the simulation analysis of the fume concentration and the calibration analysis of the test data. It can be seen from the figure that the simulation and test curves of the two measurement points have approximately the same trend, with peaks in the time periods of 100s to 200s and 1100s to 1200s, and the peak of the latter is higher than the peak of the former. The simulation results basically reflect the changing law of the actual kitchen indoor environment (Fig. 5).

4 Thermal Comfort Evaluation Analysis

4.1 Thermal Comfort PMV Evaluation Index

PMV is the predicted average thermal sensation index. The full name is Predicted Mean Vote, which is an evaluation index proposed by Professor Fanger to characterize the thermal response (hot and cold sensation) of the human body, representing the average of the hot and cold sensations of most people in the same environment. [5–7] The PMV value is related to factors such as air temperature, average radiant temperature, relative air velocity and air humidity, as well as the thermal resistance of human clothing. Its value ranges from −3 to + 3. When PMV is 0, it means that the indoor thermal environment is the best thermal comfort state. The larger the PMV value, the greater the heat load, the hotter the human body feels and vice versa. List below is its calculation formula.

$$PMV = \left(0.0303e^{0.036M} + 0.028\right)\times \left\{\begin{array}{l} (M-W) - 0.42[(M-W) - 58.15]- \\ 3.05\times 10^{-3}\times[5733 - 6.99(M-W) - P_a]- \\ 1.7\times 10^{-5}M(5867 - P_a) - 0.0014M(34 - t_a) \\ -3.96\times 10^{-8}f_{cl}\times\left[(t_{cl}\times 273)^4 - (t_r + 273)^4\right] \end{array}\right\} \tag{6}$$

where: M is the human metabolic rate in W/m2.

W is the mechanical work done by the body, in W/m2.

t_r is the average radiation temperature, which can be approximated as ta, in °C.

t_a is the air temperature in °C.

P_a is the partial pressure of water vapor in Pa, and is related to the relative humidity of air RH, the calculation formula is

$$P_a = RH \times 10e^{16.6536 - \frac{4030.183}{t_a + 235}} \tag{7}$$

f_{cl} is the ratio of the surface area of the human body when dressed to the surface area of the human body when naked. Calculated by the formula

$$f_{cl} = \begin{cases} 1.00 + 1.29I_{cl} & I_{cl} \leq 0.078 \\ 1.05 + 0.645I_{cl} & I_{cl} > 0.078 \end{cases} \tag{8}$$

I_{cl} is the thermal resistance of the garment, in m2-°C/W.

h_c is the heat transfer coefficient, the calculation formula is

$$h_c = \begin{cases} 2.38(t_{cl} - t_a)^{0.25} \\ 12.1\sqrt{v_{\text{air}}} \end{cases} \tag{9}$$

t_{cl} is the garment surface temperature in °C, the formula is

$$\begin{aligned} t_{cl} &= 35.7 - 0.028(M - W) - I_{cl} \times \\ &\left\{ \begin{array}{l} 3.96 \times 10^{-8} f_{cl} \times \left[(t_{cl} + 273)^4 - (t_r + 273)^4 \right] \\ + f_{cl} h_c (t_{cl} - t_a) \end{array} \right\} \end{aligned} \tag{10}$$

4.2 Thermal Comfort PPD Evaluation Index

The full name of PPD is Predicted Percentage Dissatisfied, which means the expected dissatisfaction rate. Due therefore, the dissatisfaction percentage PPD evaluation index is used to express the dissatisfaction rate of the human body to the thermal environment, and the quantitative relationship between PMV and PPD is listed in Eq. 11 [5, 13]. The PPD value ranges from 5% to 100%. The smaller the PPD value is, the more suitable the current thermal comfort will be.

List below is its calculation formula.

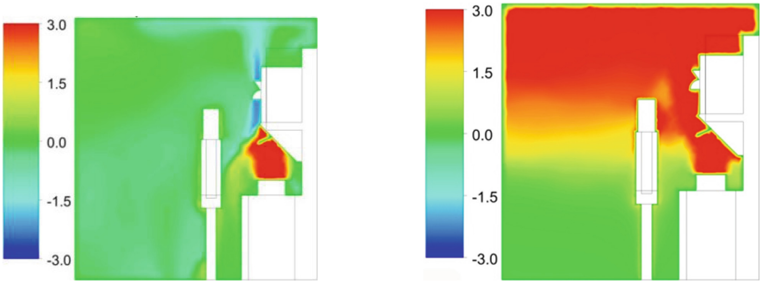
$$PPD = 100 - 95 \times e^{-0.03353 \times PMV^4 - 0.2179 \times PMV^2} \tag{11}$$

where: PMV is the expected average thermal sensory index.

Table 1 shows the correspondence of PMV and PPD with thermal sensation.

Table 1. Correspondence of PMV and PPD with thermal sensation

Hot Feeling	Cold	Cool	Slightly cooler	Comfort	Slightly warmer	Warmth	Heat
PMV	-3	-2	-1	0	+ 1	+ 2	+ 3
PPD/%	100	75	25	5	25	75	100



(a) Fresh air system open state (b) Fresh air system off state

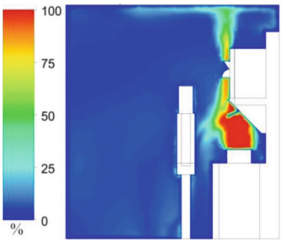
Fig. 6. Distribution of PMV in the kitchen environment

4.3 Simulation Analysis of the Effect of Fresh Air System on Thermal Comfort

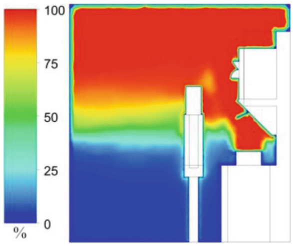
After completing the CFD flow field simulation of the open and closed conditions of the fresh air system of the cooker hood and the calibration analysis of the concentration of the cooking fume in the test kitchen, this paper uses C language to compile UDF (User Defined Functions) programs for PMV and PPD calculation in Fluent user-defined functions. The results show contour plots of PMV and PPD value at each location in the kitchen environment, which realizes the quantitative analysis of the thermal comfort of the kitchen environment.

Figure 6 is a distribution diagram of PMV in the kitchen environment when the fresh air system of the range hood is turned on and off. It can be seen from Fig. 6 that when the fresh air system is turned on, the PMV value distribution of the kitchen environment is relatively uniform. The PMV value of 80% of the area is between -1.0 ~ 0.5. The PMV value around the human body is between -0.5 ~ 0.5, the human body feels comfortable thermally. When the fresh air is turned off, the PMV value distribution of the kitchen environment is messy, and the PMV value in 60% of the area is above 1.5. The PMV value around the human body is between -0.5 and 3, the facial PMV value is large, and the human body feels warm.

Figure 7 is a distribution diagram of PPD in the kitchen environment when the fresh air system of the range hood is turned on and off. As can be seen from Fig. 7, when the fresh air system is turned on, the PPD value of 90% of the kitchen environment is between 0% and 25%. The PPD value of the surrounding environment around the human body is 0% to 15%, the dissatisfaction rate of human thermal sensation is low. When the fresh air is turned off, the PPD value of 60% of the kitchen environment is above 50%, the dissatisfaction rate of thermal sensation in the human face area is as high as 95%, and the dissatisfaction rate of human thermal sensation is high.



(a) Fresh air system open state



(b) Fresh air system off state

Fig. 7. Distribution of PPD in the kitchen environment

Table 2. PMV and PPD values for each body part

Fresh Air System	Content	forehead	Nose	Mouth	Right shoulder	Right Hand	Left shoulder	Left hand
Open Start	PMV	0.50	0.52	0.34	0.96	-0.14	-0.11	-0.66
	PPD/%	10.56	10.56	7.43	24.44	5.25	2.23	14.24
Off Close	PMV	3.00	3.00	3.00	2.65	0.50	2.58	0.60
	PPD/%	99.25	99.25	99.25	96.41	10.29	95.43	12.67

Table 2 shows the PMV and PPD values of various parts of the human body. It can be seen from Table 2 that the forehead part with the highest thermal comfort sensitivity has a PMV value of 0.50 when the fresh air system is turned on, the PPD value was 10.56%; the PMV values of other parts were between -1 and 1, and the average PPD value was 10.67%. In summary, the human body is in a relatively comfortable state when the fresh air system is turned on. In addition, compared with the closed state of the fresh air system, the thermal comfort of various parts of the human body has a more obvious change. The PMV value of each part of the human body increased by nearly 2 times after the fresh air system was turned off, especially in the face area. The average PPD value increased from 10% to 73% when the fresh air system was closed, and the PPD value of the face was as high as 99% or more. It can be seen that the fresh air system effectively improves the perceived comfort of the human body surface.

5 Conclusions

In this paper, numerical and experimental approaches are utilized to simulate and analyze the influence of the fresh air system of range hood on the thermal comfort at kitchen. By using the expected average thermal sensory index PMV and the expected dissatisfaction rate PPD as evaluation indexes, the thermal comfort of the kitchen environment is assessed quantitatively. List below are the conclusions.

(1) The presented paper quantitatively analyzes the influence of fresh air system of range hood on the thermal comfort of kitchen environment. The PMV value at the

human forehead in kitchen is 0.50 when the fresh air system is on. It is 83% lower when the fresh air system is off. The PPD value is 10.56% for the same case which is 89% lower when the fresh air system is off.

(2) The fresh air system not only has an efficient improvement on the thermal comfort of the kitchen environment, but also has a significant inhibiting effect on the spread of grease and smoke.

(3) The thermal comfort of the kitchen environment is evaluated by using simulation analysis, which can provide a reference for in-depth study of the thermal comfort of the kitchen and quantitative evaluation of the fresh air system.

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