

Numerical investigation on kitchen environment in cooking under three types of natural make-up airflow with a Chinese-style residential kitchen

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Abstract. Kitchen indoor environment is not always satisfied due to unfavourable thermal condition and poor air quality in domestic cooking especially for Chinese-style residential kitchen (CRK). Traditional CRKs are only equipped with a range hood with natural make-up air from window openings or cracks. Thus, this paper made numerical simulation to study kitchen indoor environment under three natural air make-ups. Three kinds of natural make-up conditions were selected in this simulation. Computational fluid dynamics (CFD) method was conducted. Results show that there was a uniform temperature distribution in working zone of occupant under window open condition but was up to 34.4°C. In breathing zone, air temperature exceeded the accepted thermal comfort. Velocity magnitude was up to 0.9 m/s among three conditions, and was the highest in the vicinity of the stove under window open condition. Under insufficient air make-up, maximum velocity was observed in the central line of the kitchen. Through sufficient controlled well-organized air make-up in kitchen, particle mean and maximum concentration could be reduced by 77% and 68%, respectively.

Key words. Chinese-style residential kitchen (CRK), Computational fluid dynamics (CFD), Natural make-up airflow, Particle distribution.

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1 Introduction

Cooking occupant spend much of time on meal preparation [1]. Chinese-style cooking method makes food in high temperature that generates large amounts of heat. Zhao et al. [2] measured air temperature during cooking in a CRK, and found that the temperature could increase by up to 11.5°C, which largely exceeded the accepted thermal comfort in temperature difference within 3.0°C. Furthermore, cooking-generated fume contributes greatly to indoor pollution level. These air pollutants are also proved to have association with many deleterious health effects, such as respiratory and cardiovascular system diseases from toxicological and epidemiological studies. Therefore, it is important to study indoor environment in CRKs.

There are some studies on characteristics of particles and concentration during Chinese-style cooking process. Chen et al. [3] and Zhao et al. [4] determined the emission rate of PM_{2.5} in an experimental kitchen. Lu et al. [5] compared different cooking styles on PM_{2.5} concentrations. For kitchen ventilation, Cao et al. [2] conducted an exposure measurement, and found that personal exposure reduction of 2-3 orders of magnitude could be achieved by well-organized local downward or upward make-up airflow. Du et al. [5] measured COF exposure level with different percentage of slot air make-up during a typical Chinese-style cooking. These studies are conducted in the experimental chambers with well controlled make-up airflow. However, most CRKs are merely equipped with a simple range hood. Existing kitchen hood does not fully support the absorption of smoke and heat [6]. Air supply in a CRK is generally in form of natural make-up air which comes from openings of exterior window and interior door.

Make-up air through windows, doors or gaps is still widely used in CRK, and the kitchen interior environment under natural make-up air should be studied thoughtfully. In this study, numerical simulations were performed to investigate the kitchen interior environment under three common natural make-up air patterns, including uncontrolled air intake with windows fully open, inadequate air intake through window gaps, and controlled air intake through window openings. A zoned home model with a typical CRK and adjacent room is developed in the computational domain. The steady-state computational fluid dynamics (CFD) method was used to simulate and evaluate the indoor air temperature, velocity and particle distribution in the kitchen.

2 Methodology

2.1 Computational model

To study indoor environment under different natural make-up air conditions, a partitioned household with kitchen and adjacent room was established. Geometry size of the model is X = 4.5 m, Z = 2.4 m and Y = 2.4 m. Exterior window size of the kitchen is 0.5 m × 1.0

m (z × y) and at height of 1.0 m. Kitchen length is 2.5 m. The kitchen table is 0.8 m × 0.5 m (z × y). Pot was presented with cube shape with size of 0.2 m × 0.1 m × 0.2 m (x × y × z). Emission surface of the particle source is applied in top surface of the right-side pot. Fig. 1 shows the room model.

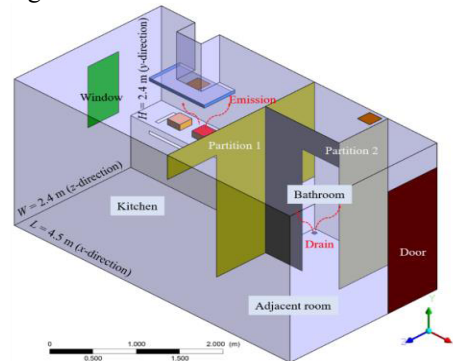


Fig.1. Layout of the computational model.

2.2 Governing equations

For simulating indoor airflow and particle, turbulent flow model and particle track model were used. Followings are governing equations:

$$\frac{\partial(\rho \cdot k)}{\partial t} + \frac{\partial(\rho \cdot \bar{u}_j \cdot k)}{\partial x_j} = P_k - \rho \cdot \varepsilon + \frac{\partial}{\partial x_j} \cdot \left(\Gamma_k \cdot \frac{\partial k}{\partial x_j} \right) \quad (1)$$

$$\frac{\partial(\rho \cdot \varepsilon)}{\partial t} + \frac{\partial(\rho \cdot \bar{u}_j \cdot \varepsilon)}{\partial x_j} = C_{\varepsilon 1} \cdot \frac{\varepsilon}{k} \cdot P_k - C_{\varepsilon 2} \cdot \rho \cdot \frac{\varepsilon^2}{k} + \frac{\partial}{\partial x_j} \cdot \left(\Gamma_{\varepsilon} \cdot \frac{\partial \varepsilon}{\partial x_j} \right) \quad (2)$$

and

$$\Gamma_k = \mu + \frac{\mu_t}{\sigma_k} \text{ and } \Gamma_{\varepsilon} = \mu + \frac{\mu_t}{\sigma_{\varepsilon}} \quad (3)$$

$$P_k = \mu_t \cdot \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \cdot \frac{\partial \bar{u}_i}{\partial x_j} + \frac{2}{3} \cdot \rho \cdot k \cdot \delta_{ij} \cdot \frac{\mu_t}{\sigma_k} \cdot \frac{\partial \bar{u}_i}{\partial x_j} \quad (4)$$

In these equations, $C_{\varepsilon 1}$, $C_{\varepsilon 2}$, σ_k , and σ_{ε} are constant with the value of 1.44, 1.92, 1.0 and 1.3, respectively. Turbulent viscosity (μ_t) is calculated by:

$$\mu_t = C_{\mu} \cdot \rho \cdot \frac{k^2}{\varepsilon} \quad (5)$$

where C_{μ} is constant value of 0.09.

$$\frac{d\vec{u}_p}{dt} = F_D \cdot (\vec{u}_a - \vec{u}_p) + \frac{\vec{g} \cdot (\rho_p - \rho_a)}{\rho_p} + \vec{F}_a \quad (6)$$

where \vec{u}_p and \vec{u}_a are velocity vector of particle and of air, respectively, F_D is inverse of relaxation time, \vec{g} is vector of gravitational acceleration, ρ_p and ρ_a are the particle and air density, respectively, and \vec{F}_a is the Brownian motion force. \vec{u}_a is air viscosity.

Turbulent dispersion effect on particle trajectories were solved based on the discrete random walk model [7] and was calculated in Eq. (7).

$$C_j = \frac{M \cdot \sum_{i=1}^m dt_{(i,j)}}{V_j} \quad (7)$$

where C_j is mean particle concentration in the j th cell, V volume of a computational cell, $dt_{(i,j)}$ particle residence time in the i th trajectory and the j th cell [8].

2.3 Boundary conditions

Table 1 depicts boundary positions. In actual cooking practise, it often lasts about half a minute in heating oil.

100°C was applied in pot surface to. Radiation heat exchanges are not included in the simulation [10].

Table 1. Boundary conditions for grid sensitivity.

Position	Type	Parameter	Temperature (°C)
Pot (Exterior)	Wall	—	100
Pot (Top)	Mass-flow inlet	0.1 mg/s	100
Window	Pressure-inlet	0 Pa	18
Range hood	Outlet-vent	-80 Pa	—

This simulation reasonably defined the emission rate of 0.1 mg/s, which resulted in a mass flow rate of 10^{-7} kg/s from pot surface. Particles released from pot surface are assumed to be the density of 850 kg/m^3 with diameter of $2.5 \mu\text{m}$ [11].

2.4 Grid sensitivity analysis

Grid resolution determines the CFD accuracy. Four discretized grid resolutions of the case were computed with 299,972, 899,916, 1,640,248 and 2,540,164 grid numbers from coarse to fine. To balance the computation accuracy and expense, 1,640,248 uniform grids were chosen in the grid sensitivity analysis.

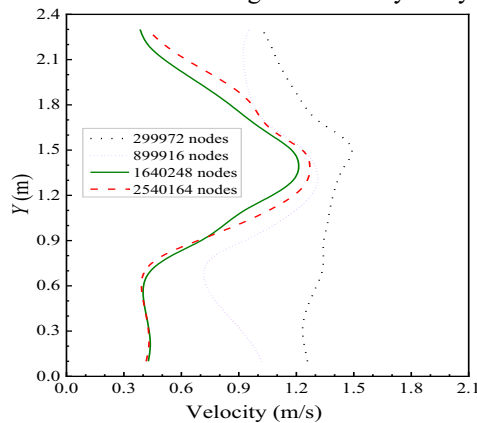


Fig. 2. Grid sensitivity tests.

2.5 Specifications of natural make-up air

The air temperature and volume are very different for different conditions of natural ventilation from the external window. The study is divided into three scenarios with the following wind replenishment. Scenario 1 simulated with uncontrolled inflow with window fully open for summer season and air temperature is 27°C. In scenario 2, insufficient inflow from window crack was implemented for winter season. Air infiltration with $9.0 \text{ m}^3/\text{h}$ and its temperature of -5°C was selected in this scenario. For controlled inflow from window opening in scenario 3, ventilation rate was determined according to the study of Gao et al. [1] and Cao et al. [2] with around $560 \text{ m}^3/\text{h}$. Based on this air volume, velocity-inlet of 0.3 m/s and air temperature of 18°C were set in the exterior window opening.

2.6 Simulation analysis

For further simulation analysis, geometric model is divided into working zone ($x=0.95 \text{ m}$), breathing zone ($y=1.5 \text{ m}$) as depicted in Fig. 3. Cross-section lines of Line A1-A3 and B1-B6 and were selected to make analysis of the kitchen indoor environment. Detailed position of each line is also illustrated.

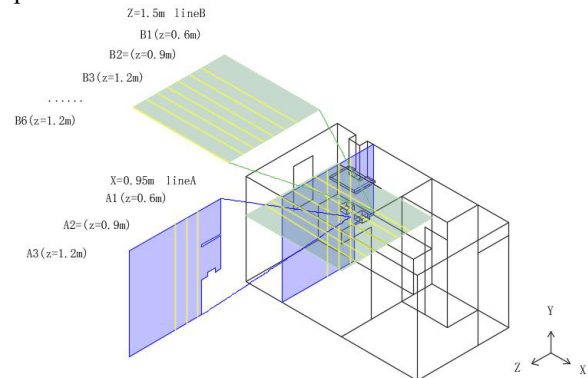


Fig.3. Schematic diagram of zone division and position in the model.

3 Results

3.1 Effect of different natural make-up air on environment different positions of kitchen

3.1.1 Velocity and air temperature distribution

In working zone of lines A1-A3 depicted in Fig. 4, larger velocity variation was observed under uncontrolled inlet air in scenario 1. For the well-organized make-up air in scenario 3, there was little difference between positions. In the breathing zone for three positions, maximum velocity differences of 81.4%, 66.7% and 18.4% were found, respectively. Overall velocity magnitude was in the same level for three conditions. As shown in Fig. 5, air temperature along the lines remained higher level in scenario 1 with peak value of 34.4°C . However, there was a uniform temperature distribution in this scenario. Temperature difference of 1.7°C was within height of 2.0 m. While for scenario 2 and 3, the temperature differences were 4.0°C and 3.1°C . The large air velocity and temperature difference could lead to thermal discomfort for the occupant. In the breathing zone for three positions, maximum temperature differences of 0.6%, 8.8% and 15.7% were found, respectively.

In breathing zone along the Lines B1-B6 as depicted in Fig. 6, there were wider ranges. Highest velocity magnitude was observed of 0.9 m/s along B1, 0.7 m/s along B4 and 0.9 m/s along B3 in each scenario, respectively. Under widow open conditions in scenario 1 and 3, there were higher velocity magnitude in the vicinity of the stove. However, for the insufficient make-up air condition in scenario 2, maximum velocity was observed in the central line of the kitchen.

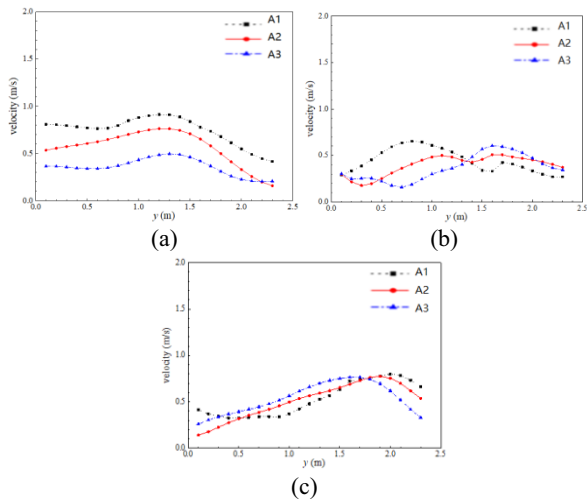


Fig. 4. Velocity distribution along the Lines A1-A3: (a) scenario 1; (b) scenario 2; (c) scenario 3.

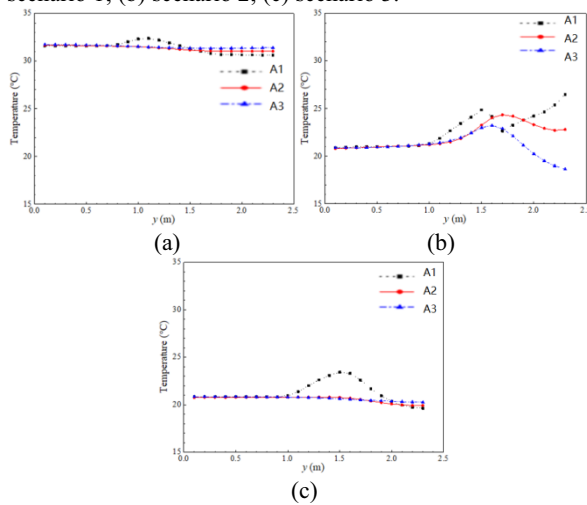


Fig. 5. Temperature distribution along the Lines A1-A3: (a) scenario 1; (b) scenario 2; (c) scenario 3.

For temperature distribution, there was more uniform distribution in scenario 1 due to the same temperature level between make-up air and indoor environment in Fig. 7. But the condition was quite different in scenario 2. Cold make-up air led to the large temperature difference between cooker and the window, especially in the vicinity of the stove. Temperature in breathing zone of the occupant could reach 35 °C, which was merely 20 °C around. The large temperature difference in > 15 °C led to thermal discomfort. Around the occupant, the temperature difference in breathing zone were within 6 °C and 4.7 °C in scenario 1 and 3, respectively. It is demonstrated that there was small temperature difference under well-organized make-up air, and leading to better thermal comfort.

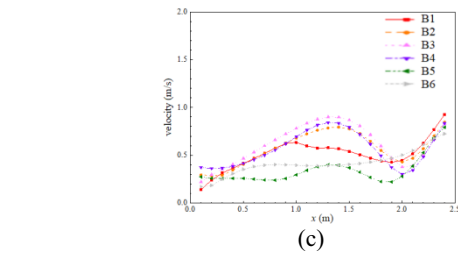
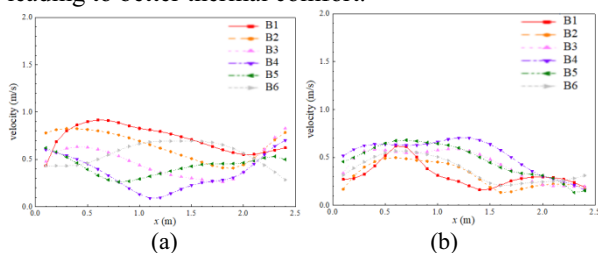


Fig. 6. Velocity distribution along the Lines B1-B6: (a) scenario 1; (b) scenario 2; (c) scenario 3.

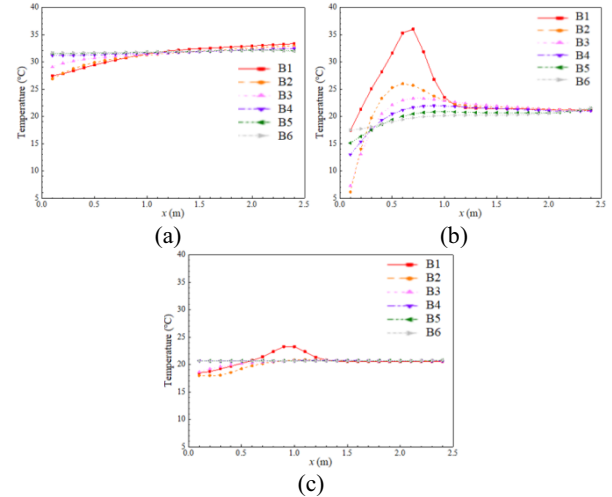
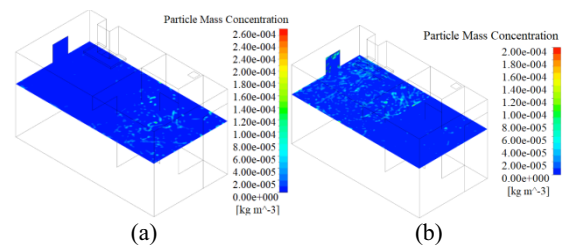
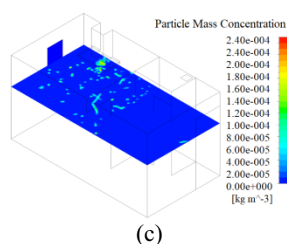


Fig. 7. Temperature distribution along the Lines B1-B6: (a) scenario 1; (b) scenario 2; (c) scenario 3.

3.1.2 Particle mass concentration

Fig. 8 shows the effect of different natural make-up air on particle mass concentration of kitchen. Under window fully open make-up natural air, the mass concentration of particulate matter in the kitchen was smaller than that in scenario 2 and scenario 3, but the mass concentration of particulate matter in the kitchen adjacent room was higher. Airflow from closed window did not bring too much outside air as depicted in. In kitchen environment, large amount of heat and particle pollutant generated from cooking stove were brought to the occupant. It is demonstrated that particle pervaded in the kitchen space with highest concentration of 200 $\mu\text{g}/\text{m}^3$ in breathing zone, whereas it was much lower in adjacent room. Under controlled make-up air, airflow from opening window was well-organized. Under condition of constant inlet airflow in window, particle pollutant was mostly exhausted by the range hood. Concentration was merely 24 $\mu\text{g}/\text{m}^3$ in breathing zone, which was much lower than that in other scenarios.





(c)

Fig. 8. Distributions of particle mass concentration in $y=1.5$ m: (a) scenario 1; (b) scenario 2; (c) scenario 3.

3.1.3 Particle concentration profile

Fig. 9 depicts the particle mass concentrations in the kitchen breathing zone for each scenario. As can be seen from the box line plot, the concentrations have a large variation between scenarios and locations. The highest average concentrations are found in kitchen scenario 2. The high concentration level in kitchen was caused by the insufficient make-up air, which lowered removal efficiency of particles. By contrast, concentration level in scenario 1 and 3 under adequate make-up air in kitchen were largely reduced. In addition, the mean and maximum concentration were reduced by 77% and 68% under well-organized make-up air compared with uncontrolled inlet airflow in kitchen. Mean concentration under air infiltration in kitchen was more than 4 folds than that under window fully open condition. It can be concluded that ventilation mode in kitchen have largely impact on particle concentration in kitchen environment.

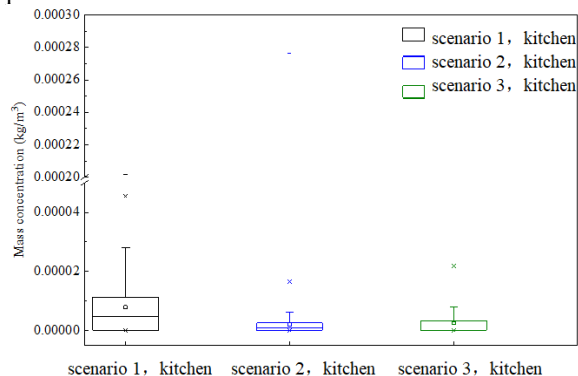


Fig.9. Particle mass concentration in each scenario in kitchen and adjacent room in $y=1.5$ m

4 Conclusions

This study numerically simulated the indoor environment of a typical household CRK under three common natural ventilation conditions. Uncontrolled inflow with window fully open, insufficient inflow from window crack and controlled well-organized inflow from window opening were included. Following conclusions can be made.

(1) Ventilation rate under three natural air make-up ventilation scenarios in this numerical simulation were obtained, which resulted air exchange rate with 50 h^{-1} , 8 h^{-1} and 27 h^{-1} , respectively. Ventilation rate of the range hood was highest with $1272.6 \text{ m}^3/\text{h}$ under uncontrolled inflow with window fully open condition,

and was lowest with $215.7 \text{ m}^3/\text{h}$ under insufficient inflow from window crack.

(2) Large velocity variation was observed under uncontrolled air make-up in working zone, while there was little difference between positions for well-organized air make-up. Under three positions of 0 m, 0.3 m and 0.6 m in front of the stove in breathing zone, maximum velocity differences of 81.4%, 66.7% and 18.4% were found, respectively.

(3) Under window fully open make-up natural air, the mass concentration of particulate matter in the kitchen was lower, but the mass concentration of particulate matter in the kitchen adjacent room was higher. Under well-organized make-up air, the mass concentrations of particulate matter in the kitchen and the adjacent rooms of the kitchen are smaller, with a 68% reduction in the maximum concentration of particulate matter.

5 Acknowledgement

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