Simulation on air temperature and particle distribution under natural make-up air in indoor environment with a Chinese-style residential kitchen

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Abstract. Kitchen is an important place in Chinese residential building. However, unfavourable thermal environment and unsatisfied air quality occur during cooking. Studies on kitchen environment are experimentally investigated with enough make-up airflow. But mostly normal kitchens are merely installed with a exhaust hood and have not installed air supply system. This work carried out numerical simulation to investigate kitchen indoor environment under natural make-ups. Air inflow under window fully open, insufficient air inflow from window crack and well-controlled constant inflow volume from window opening are included. Results show that there was a uniform temperature distribution in occupant’s working zone under window open condition. Vertical temperature differences were 4.0 °C under insufficient air make-up. In breathing zone, temperature difference was 6.0 °C and 4.7 °C under uncontrolled and well-controlled airflow, respectively. Mean particle concentration could be largely reduced under controlled and well-organized enough make-up air in kitchen.

1 Introduction

Kitchen in Chinese family is an important place, where in average more than 3 h per day is spend on meal preparation [1]. Thus, it is necessary to focus on kitchen indoor environment. However, residents complained about suffering the cooking oil fume (COF) [2]. There were also dissatisfactions with thermal environment in Chinese-style residential kitchens (CRKs).

Most CRKs were found to suffer from pollutants in form of particle matter (PM) and gaseous substances that largely exceeded the limits of the Chinese national standard even by more than 10 folds [3-4]. 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 [5-6]. CRKs are mostly small and enclosed with partition walls. Intensive frying produces more pollutants. Applications of gas stoves as the energy source in CRKs also lead to higher PM concentration level than those with electric stoves in western kitchens [7-8]. Therefore, it is important to study indoor environment in CRKs.

In view of make-up air through openings or cracks of windows and doors is still the currently widely used in CRKs, kitchen indoor environment under natural make-up airflow should be thoughtfully investigated. This work carried out CFD simulation to investigate kitchen indoor environment under three common natural make-up air modes, including uncontrolled inflow under window fully open condition, insufficient inflow from window crack and controlled inflow from window opening. A partitioned household model with a typical CRK and adjacent room was established for the computational domain. Kitchen indoor air temperature and particle distribution were simulated and evaluated.

2 Methodology

2.1 Computational model

A partitioned household type was set up as computational model. Model size of whole space is 4.5 m in length (x), 2.4 m in width (z) and 2.4 m in height (y). Three indoor spaces, including kitchen, adjacent room and bathroom are involved in the model. The room and its adjacent space are associated with a door in a partition wall. Size of the window is 0.5 m in width, 1.0 m in height and 1.0 m above the floor. Length size of the kitchen is 2.5 m. The table is 0.5 m in width and 0.8 m in height. Two cubes represent to the pot with size of 0.2 m × 0.2 m (x × z) and 0.1 m in height. Top side in the right of the pot is applied for source emission of particles. In this model, dry floor drain of the bathroom was included to present the possible airflow inlet. Door of the living room kept closed. Layout of the household and arrangement is depicted in Fig. 1.

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conducted with a constant heat flux [9]. Whereas the boundary condition with temperature of cook stove was proved with the rationality. This work reasonably simplified with the constant temperature in the pot surface. Oil temperature reached the peak value at the end of oil heating in practical domestic cooking. When food ingredients were added into the pan, oil temperature dropped dramatically. In 0.5-min heating different types of oil resulted average oil temperature from 79.6 °C to 119.3 °C. However, in some studies, average temperature could reach up to 216 °C in 2-min heating different types of oil [12-14]. The higher oil temperature was due to the constant heating with a long time. In domestic cooking practise, oil heating process often lasts about half a minute. Thus, it is reasonable to set the temperature in pot surface to 100 °C.

### 2.2 Governing equations

#### 2.2.1 Turbulent airflow model

Turbulent airflow field was simulated with Reynolds averaged Naiver-Stokes equations with standard k-ε model. Standard k-ε model has been validated its reliability to simulate indoor airflow fields [9-11]. The representative governing equations are as follows.

\[
\frac{\partial (\rho u_k)}{\partial t} + \frac{\partial (\rho u_i u_k)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial u_k}{\partial x_j} \right] - \frac{\partial}{\partial x_j} \left( \rho e \right) + \frac{\partial}{\partial x_j} \left( \rho \frac{\partial \theta}{\partial x_j} \right) \tag{1}
\]

\[
C_{e1} \cdot \varepsilon \cdot \frac{\partial \theta}{\partial t} - C_{e2} \cdot \frac{\partial \varepsilon}{\partial x_j} + \frac{\partial}{\partial x_j} \left( \frac{\partial \varepsilon}{\partial x_j} \right) \tag{2}
\]

#### 2.2.2 Particle track model

Lagrangian model is applied to study transport of particles. Lagrangian method tracks a huge number of particle trajectories with particle momentum equation. Inertial force per unit mass can be expressed in equation (3).

\[
\frac{d \delta_p}{dt} = F_p \cdot \left( \vec{u}_a - \vec{u}_p \right) + \frac{\partial (\rho_p \delta_p)}{\partial x_j} \tag{3}
\]

\[
F_p \cdot \left( \vec{u}_a - \vec{u}_p \right) = \frac{18 \mu_u}{\rho_p d_p^2} \cdot \left( \vec{u}_a - \vec{u}_p \right) \tag{4}
\]

A discrete random walk model is applied to explain the turbulent dispersion effect on particle trajectories. Particle boundary conditions were set as trap boundary at walls, floors in the envelop, escape boundary at window, range hood, floor drain and reflect boundary at pot of the model. To express the trajectory information to concentration distributions, particle source in cell method was calculated in equation (5).

\[
C_j = \frac{M \sum_{i=1}^{n} \delta x_{i,j}}{\delta x_{i,j}} \tag{5}
\]

### 2.3 Modelling procedure

#### 2.3.1 Boundary conditions

Boundary position, type and parameter are listed in Table 1. Thermal boundary condition for pot can be

| Position          | Type          | Parameter | Temperature (°C) |
|-------------------|---------------|-----------|-----------------|
| Pot (Exterior)    | Wall          | —         | 100             |
| Pot (Top)         | Mass-flow     | 10^{-7} kg/s | 100             |
| Window            | Pressure-inlet| 0 Pa      | 27              |
| Range hood        | Outlet-vent   | -80 Pa    | —               |
| Floor drain       | Pressure-inlet| 0 Pa      | 25              |
| Envelop           | Wall          | —         | 25              |

Particles were injected from top surface of the right-side pot. For the estimated emission rate of cooking-generated PM$_{2.5}$, wide range from 0.06 to 87.6 mg/min were deprived from previous studies. This diversity was mainly caused by types of ingredients and cooking styles [8]. In this study, flow rate of 10$^{-7}$ kg/s was applied for the particle injection surface, which resulted in emission rate of 6 mg/min. Particles released from pot surface are assumed to be the density of 850 kg/m$^3$ with diameter of 2.5 μm.

#### 2.3.2 Grid sensitivity analysis

Grid resolution determines the CFD accuracy. In simulation work, discretization should be fine enough to capture precisely information of turbulent flow. Thus, grid sensitivity analysis was conducted prior to performing simulation of the study. Appropriate grid resolution is able to satisfy both sufficient accuracy and acceptable computation expense. 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. Averaged velocity profiles in two locations for different grid densities are depicted in Fig. 2. It is demonstrated that the solutions were convergent with grid numbers more than 1,640,248. To balance the computation accuracy and expense, 1,640,248 uniform grids were chosen in the grid sensitivity analysis.
2.3.3 Specifications of numerical scenario simulations

For different scenarios of natural make-up air from exterior window, the air temperature and volume are quite different, which are listed in Table 2. Scenario 1 simulated with uncontrolled inflow with window fully open for summer season. In scenario 2, insufficient inflow from window crack was implemented for winter season. Air infiltration volume was determined from Chinese design standard for energy efficiency of residential buildings in different climate zones (JGJ 26-2018, JGJ 134-2010, JGJ 75-2012 and JGJ 475-2019). Air volume per length of crack < 2.5 m³/h was able to meet the standard. Based on this regulation, air infiltration with 9.0 m³/h was selected in this scenario. For controlled inflow from window opening in scenario 3, ventilation rate was determined to around 560 m³/h [2]. Based on this air volume, velocity-inlet of 0.3 m/s was set in the exterior window opening.

Table 2. Three scenarios in the simulation.

| Scenario | 1     | 2     | 3     |
|----------|-------|-------|-------|
| Window status | Fully open | Closed | Open |
| Air inlet | Disorganized | Infiltration | Well-organized |
| Air volume (m³/h) | — | 9 | 540 |
| Temperature (°C) | 27 | -5 | 18 |

3 Results

3.1 Validation from experimental measurement

To verify the reliability of the model, an experiment was conducted in an actual residential kitchen. Indoor air quality experimental instrument was used to measure air temperature of the occupant. The measurement was in height of 1.5 m above the floor, and 0.9 m away from the window in representative for the breathing position of cooking occupant, as shown in Fig. 3. The range of measurement is from 0 to 45 °C with an accuracy of 0.1 °C, and the interval time is set to 5 s. Calibration was completed by the manufacturer. The experiment was repeated three times by same individuals and were arranged in different days. Cooking practice was performed with the following sequence: heating edible oil of 120 s, making ingredients and food of 600 s and turn off fire of 120 s. During the period of adding ingredients and food within 600 s, oil temperature was complex and difficult to characterize its simulation. Therefore, to better compare experiment and simulation work, oil heating within 120 s before adding ingredients and fire off within 120 s after cooking were chosen in this experimental validation.

CFD and experiment result of air temperature in the position during and after 2-min oil heating process were compared and validated as shown in Fig. 4 and Fig. 5. Air temperature rise in both simulation and measurement in oil heating. In 2-min of heating, average temperature increased by 1.4 °C and 1.2 °C for measurement and simulation. After cooking process within 2 min, experimental data decreased. However, due to the high temperature of stove and pot surface, measurement data dropped by 0.4 °C from 30 s to 120 s. In simulation, temperature of air supply with 28.0 °C varied by 0.4 °C after cooking within 2 min. Besides, temperature of air supply could be under unsteady-state for the difference between experiment and simulation results. In the whole cooking process, air temperature deviation in the position of within ± 0.5 °C confirmed the reliability of the CFD model.
3.2 Effect of different natural make-up air on particle concentration

Particle mass concentration in each scenario in kitchen and adjacent room in breathing zone was depicted in Fig. 6. Concentration had large diversity among scenarios and positions. Highest mean concentration was found in scenario 2 in kitchen, while the lowest was observed in adjacent room. 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.

Uncontrolled inlet air from window made particle diffuse to the adjacent room. Mean and maximum concentration could be reduced by 78% and 68% under sufficient make-up air in kitchen, respectively. In addition, the mean and maximum concentration were reduced by 77% and 60% 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. While in the adjacent room, mean concentration under window fully open condition was more than 6 folds than that under air infiltration condition. Ventilation mode in kitchen have largely impact on particle concentration in kitchen and indoor living environment.

4 Conclusions

This study numerically simulated indoor environment with a CRK in a typical partitioned household under three common natural air make-up conditions.

(1) For air temperature distribution above the stove, larger temperature gradient was observed under insufficient air make-up condition. Temperature degradation of 35 °C within 0.1 m was deprived. For well-organized make-up air, there was more uniform temperature distribution in the vicinity of stove. In working zone, temperature difference of 1.7 °C was within height of 2.0 m. In breathing zone, temperature differences around the occupant were 6 °C and 4.7 °C under uncontrolled and well-controlled inflow.

(2) Highest mean particle concentration was found under insufficient inflow in kitchen, while the lowest was observed in adjacent room. In kitchen, mean and maximum concentration could be reduced by 78% and 68% under sufficient air make-up, respectively.

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