Analysis of the effect of emission rate of PM2.5 with different setting forms on indoor air quality in CFD

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Abstract
Experimental were conducted on residential kitchens, and the flow field of indoor particulate matter in the kitchen was simulated using CFD software and UDF compilation. The numerical simulation results were compared and analyzed with the experimental data under two different setup conditions of uniform and time-dependent particulate matter emission rates. The differences of PM2.5 concentrations between the two setting forms of the emitted rate in the breathing zone and the experimental data were 173 μg/m³ and 78 μg/m³. The difference values in the central indoor area are 45μg/m³ and 76μg/m³. Different settings of particle emission rate have little influence on particle concentration in the respiratory area and the central area of the room. However, UDF can be more close to the experimental data.

Highlights
- Improve the accuracy of numerical simulation using UDF.
- Control PM2.5 emission concentrations and improve indoor air quality in kitchens.
- Numerical study of kitchen emission control.

Introduction
With the rapid development of China's economy and the continuous improvement of people's living standards, people are more and more concerned about the safety and health of the building indoor environment. People spend more than 70% of their time indoors, and indoor air quality directly affects people's health. Several studies have shown that when there is no indoor smoking pollution source, particulate matter from cooking accounts for most of the indoor particulate matter. Cooking is an integral part of people's lives. Frying, deep-frying, stir-frying and other high-temperature Chinese cooking methods are more likely to produce particulate matter and organic compounds, including volatile organic compounds (VOCs), fats and oils, hydrocarbons and aldehydes and ketones, which are especially important sources of carcinogenic polycyclic aromatic hydrocarbons (PAHs). Multiple toxic chemicals, immunotoxicity, genotoxicity, and potential carcinogenicity to the body have emerged as potential health hazards for home cooks (Zhou C and Zhan Y 2020). Traditional kitchens in Chinese urban houses are characterized by small spaces and hidden locations. The long cooking time, high oil temperature and large amount of oil in China lead to high concentration and long residence time of kitchen fumes. Especially in winter, when doors and windows are closed, the impact of kitchen fumes on the building's indoor environment is more obvious. In traditional Chinese homes, cooking personnel are close to the source of pollution and are more likely to be exposed to pollutants (Liu J J and Dai X L 2018). The kitchen is an essential and important functional space in people's lives, and a major area of long-term persistent indoor pollution in China. Over the years, more research has been conducted on the dispersion and control of pollutants in the indoor environment of buildings, but less research has been conducted on the dispersion patterns of pollutants in domestic kitchens and the concentrations of pollutants when controlling the breathing of personnel, and the results of these studies are an important guide to grasp the exposure of cooking personnel.

In this study, a CFD model was developed to simulate the kitchen cooking environment and was calibrated in conjunction with experiments. To verify the reliability of the current CFD method, it was validated by experiments and simulations (Yin H G and Liu C X 2019). Using this CFD model, the temperature and pollutant concentration in the kitchen under different ventilation methods were investigated and the accuracy of the model was improved based on experimental data and UDF. The following conclusions are drawn from this study. The average error of two measurement points in the new model was reduced by 10% compared to the original CFD model. Based on the calibrated CFD model, the effect of air quality and thermal comfort on the chef during cooking can be evaluated. It was found that lower room temperature with open windows affects the chef's thermal comfort, while room temperature and pollutant concentration are somewhat controlled when ceiling ventilation is used.

Methods
The experimental data are highly reliable but vulnerable to external influences and unpredictability. The theoretical study relies heavily on simulation software, which has the advantage of excluding external disturbances and easy computation. Therefore, a combination of experimental and simulation methods will be investigated in this section.

Firstly, an experimental platform was established to monitor the PM2.5 concentration distribution in the kitchen in real time. The distribution of contaminants and temperature changes in the kitchen were recorded using...
instruments such as TSI 8530 aerosol detector and HOBO temperature loggers. The experimental kitchen is a residential kitchen (3.45m × 2.18m × 2.40m). There is an external window and an internal door in the kitchen, and the door and window are opposite to each other. The actual condition of this experimental kitchen is consistent with the ventilation conditions of a residential kitchen. The experimental system consisted of an extractor hood, a heating pot and a gas stove with natural gas as the heating method. The experimental materials were shredded potatoes with scallion, cooking oil, soy sauce and salt.

The experimental test points were chosen to avoid ventilation ducts and vents as much as possible to minimize external influences and to be located in a more active indoor location for people. The instrument was placed on two test points (Zhen Z and Xin J 2020). Measurement point P1 was the breathing zone test point for cooking personnel, 150 cm above the floor, and measurement point P2 was the center of the room in the residential kitchen. The test time was 300 seconds, and monitoring data were collected every 5 seconds. In order to ensure the accuracy of the results, approximately 10 measurements were taken at each sampling point during the actual sampling process and all test results were averaged.

The experimental procedure is shown in the following table.

<table>
<thead>
<tr>
<th>Time/s</th>
<th>Act</th>
</tr>
</thead>
<tbody>
<tr>
<td>0s</td>
<td>Open fire and kitchen hood</td>
</tr>
<tr>
<td>60s</td>
<td>Add oil to the pan</td>
</tr>
<tr>
<td>70s</td>
<td>Add minced green onion</td>
</tr>
<tr>
<td>90s</td>
<td>Add shredded potatoes</td>
</tr>
<tr>
<td>230s</td>
<td>Add soy sauce</td>
</tr>
<tr>
<td>290s</td>
<td>Add salt</td>
</tr>
<tr>
<td>300s</td>
<td>Close fire and kitchen hood</td>
</tr>
</tbody>
</table>

Before cooking, measure the initial concentration of PM2.5 in the kitchen. Start the kitchen hood at the beginning of the experiment, continuously monitor the concentration change of particulate matter during cooking, and close the kitchen hood after cooking (Zhao Y and Zhao B 2020). The total process of the experiment is 300s, including heating pot and adding raw materials. Only the right pot and range hood were used in the experiment. In order to approach the actual cooking situation, 50 ml of edible oil and 20 ml of soy sauce were added. Considering the diversity and complexity of cooking, in order to obtain a relatively simple and stable source of particulate matter, about 500g of shredded potato was selected as the cooking material.
Next, numerical simulations were performed in CDF. SpaceClaim software created a 3D model of a residential kitchen of 3.45m (x) × 2.18m (y) × 2.40m (z). The door dimensions were 1.895m × 0.81m (y × z) and the window dimensions were 1.45m × 1.16m (y × z). Considering the diversity and complexity of kitchenware, the kitchen model is simplified reasonably. The exhaust surfaces of the stove fire and exhaust hood are simplified to circular surfaces with diameters of 0.225m and 0.15m respectively. The cooker is simplified to a rectangular multiblock model with a height of 1.63m (with 20% of the head, 40% of the body and 40% of the lower part) and the cooker is 0.15m from the stove. Considering the space and accuracy required for the calculation, it was divided into a 60w hexahedral mesh using icem software (Zhao Y J and Chen C 2018).

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_i} (\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left( \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial x_j} \right) + C_{1e} \varepsilon \left( G_k + G_b \right) - C_{2e} \rho \frac{\varepsilon^2}{k} \tag{2}
\]

where \( G_k \) is the turbulent kinetic energy generation term due to velocity gradient, \( G_b \) is the generation term due to buoyancy, \( \sigma_k \) and \( \sigma_\varepsilon \) are the Prandtl numbers corresponding to \( \varepsilon \) and \( k \), respectively, and \( C_{1e} \) and \( C_{2e} \) are empirical constants.

Particle simulations in the kitchen were performed using a discrete-phase model, with the source of contamination being particles emitted from the surface of a pot on the stove top. Particle size is set to 2.5 µm and material properties are set to the default low hydrophilic anthracite fines. Particle density was set to 950 kg/m³ and particle emission was set to 0.38 x 10⁻⁶ kg/s. No consideration was given to the infiltration effects of outdoor particulate matter through doors, windows, or maintenance structures.

The DPM boundary conditions for the pressure and velocity inlet and outlet are set to fugitive, and the rest are set to reflective.

UDF is a user-defined function, which is a user-programmed program whose main purpose is to connect to the Fluent solver in a passive way to further improve the performance of the solver. User-defined functions are...
written in C and defined using the DEFINE macro. They can use standard C library functions or predefined macros to get the data that the Fluent solver wants. The UDF method is used to achieve the time-dependent variation of the emitted source concentration.

Through simulation data, it can be found that when the doors and windows are closed and the range hood is turned on, the PM2.5 concentration in the breathing area of personnel is lower. On the contrary, due to the diffusion and accumulation of particulate matter, the concentration of PM2.5 in the center of the room gradually increases. When doors and windows are closed in winter, the pollutant mass fraction in the breathing area of cooking personnel is the highest. Under the condition of window ventilation, the concentration of PM2.5 in the center of the room has been controlled to a certain extent. The concentration of pollutants in the center of the room can be reduced by 73.3%, and the respiratory area of personnel can be reduced by 39.7%. However, at the same time, low outdoor temperatures may lead to poor thermal comfort for personnel.

Although the current model accuracy has been improved to some extent by controlling the divergence source, there is still room for exploration and improvement in other parts of the model, such as the selection of boundary conditions and formulas. Further research should be conducted on the setting of numerical simulation parameters for pollutants, and the model should be optimized based on the non-stationary stage of personnel breathing, in order to better approach the actual situation and improve the accuracy and reliability of simulation results. In future simulations, the author will consider further improving the model. In addition, other ventilation openings can be added in the kitchen to control the concentration of indoor pollutants, such as using ceiling ventilation or adding air purifiers.

**Conclusion**

Numerical simulation parameters were set for the pollutants and the model was optimized by UDF to make it closer to the actual situation, improving the accuracy and reliability of the simulation results, simulating the concentration of pollutants when the cooks breathe, and providing a firmer basis for studying the pollutant exposure levels. Particulate matter moves in such a way during the cooking process that it escapes outward during source emissions and then diffuses, suspends or settles in the kitchen while accumulating.

Physical models and simulations of PM2.5 diffusion under different working conditions show that PM2.5 diffusion rate plays a decisive role in indoor PM2.5 concentration. In winter, the mass fraction of pollutants in the breathing zone of cooking personnel is greatest when windows and doors are closed. The maximum reduction in pollutant concentration in the center of the room can be 73.3% by opening the windows and 39.7% by opening the ventilation.

**Discussion**

The authors thank the reviewers for their suggestions. The authors have added to and revised the discussion. For a quick review, this subsection is shown below:

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**Conclusion**

Numerical simulation parameters were set for the pollutants and the model was optimized by UDF to make it closer to the actual situation, improving the accuracy and reliability of the simulation results, simulating the concentration of pollutants when the cooking personnel breathe, and providing a more solid basis for studying the level of exposure to pollutants. Particulate matter moves during cooking in such a way that it escapes to the outside during the emission from the source and then diffuses, suspends or settles in the kitchen while accumulating. Physical models and simulations of PM2.5 diffusion under different working conditions show that PM2.5 diffusion rate plays a decisive role in indoor PM2.5 concentration. In winter, the mass fraction of pollutants in the breathing zone of cooking personnel is greatest when windows and doors are closed. The maximum reduction in pollutant concentration in the center of the room can be 73.3% by opening the windows and 39.7% by opening the ventilation.
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References


