Abstract
This article studies the improvement of indoor temperature field, \( \text{CO}_2 \), and PM2.5 concentration field under the ceiling air supplement scheme in residential kitchens. The on-site test was carried out under the ceiling air supplement scheme to monitor the pollutant concentration diffusion law and temperature change, and a typical residential kitchen physical model was established using CFD fluid mechanics software to compare with the natural infiltration condition and the window opening condition. The results showed that the reasonable installation of air supply outlets on the ceiling effectively improved the air quality of the kitchen. After 5 minutes of cooking, the concentration of pollutants was higher than that of the window opening condition, but significantly lower than that of the natural infiltration condition. The indoor temperature field was the most suitable compared to the natural infiltration condition and window opening condition, ensuring comfort while improving the air quality of the kitchen. The effectiveness of the ceiling scheme was verified. The research results provide theoretical basis and strategic guidance for improving the reasonable airflow distribution and creating a thermal comfortable environment in residential kitchens in severe cold areas.

Highlights
- Pollutant concentration distribution under ceiling make-up air solution
- Combination of experiments and simulations
- Improving the status of kitchen pollutants

Introduction
Creating a healthy and comfortable living environment is the key to improving people's happiness index and an effective way to improve people's quality of life. In recent decades, household air pollution has been identified as a global threat\(^1\). As a core part of residential buildings and one of the main sources of pollution in the residential environment, the air quality of the kitchen is extremely important\(^2\). Kitchen cooking pollutants mainly include exhaust gas and oil fumes generated by combustion, which cause indoor air pollution, damage human immune function, and seriously damage human health\(^3\). Therefore, improving ventilation efficiency and indoor air quality is an urgent issue related to personnel health in kitchen design\(^4\). In the past, people mostly used natural ventilation methods such as opening windows and doors to improve the air quality in kitchens. However, with the gradual changes in people's lifestyles, the continuous development of air conditioning technology, and the continuous improvement of door and window sealing performance, especially for residential buildings that require sealed doors and windows during winter heating in severe cold areas, Relying solely on natural ventilation methods can no longer balance indoor thermal comfort while ensuring good air quality. In the northern region of China, the use of natural ventilation during cooking is limited by various natural conditions such as high outdoor noise and cold climate. In this situation, how to ensure reasonable ventilation and exchange of air in the kitchen in winter has become a prominent and urgent problem to be solved. Research has found that setting up air outlets in the kitchen can not only alleviate environmental pollution problems in residential kitchens, but also supplement fresh air for the kitchen, reduce harmful gas generation, improve air quality, and ultimately achieve the goal of controlling indoor pollutant concentrations. From this, the scheme of supplementing air with suspended ceiling is introduced. The ceiling air supplement scheme adopts the form of opening on the external wall and ceiling, and introduces outdoor fresh air into the room through the indoor and outdoor pressure difference, which has a certain preheating effect of fresh air. It can not only solve the problem of ventilation and exchange in winter kitchens in severe cold areas, but also ensure the thermal comfort of kitchen cooking personnel, providing suitable ventilation strategies for residents.

In order to facilitate the study of the improvement effect of ceiling ventilation on the concentration of pollutants in the kitchen, carbon dioxide is used as a general indicator to measure the degree of air pollution in the kitchen. Because carbon dioxide is non-toxic, easy to measure, and cost-effective\(^5\). In the kitchen, \( \text{CO}_2 \) concentration can be used as an indicator of ventilation rate and degree of pollution removal. Von Pettenkofer pointed out in 1858 that carbon dioxide itself is not important, but it can indicate the amount of other harmful substances produced by humans. As the concentration of other indoor pollutants increases, carbon dioxide also increases proportionally, so carbon dioxide is used to measure indoor air pollution. Early studies have shown that carbon dioxide concentration can serve as an alternative target for indoor air quality.
and ventilation efficiency[6]. During the cooking process, indoor PM2.5 concentrations exhibit short-term and high-dose characteristics[7]. The chemical components of PM2.5 include polycyclic aromatic hydrocarbons, chemical elements (especially heavy metals), etc[8]. Long term inhalation of PM2.5 will cause serious damage to the respiratory system, cardiovascular system, reproductive system and blood system[9]. Therefore, it is necessary to study the concentration distribution of PM2.5 in the kitchen. In response to the above situation, this article conducts on-site measurement and software modeling.

**Methods**

**Field testing**

This experiment selected representative Chinese residential kitchens for testing, with a common L-shaped internal layout and a kitchen size of 3.45m × 2.18m × 3.3m (length × wide × Height), door size is 0.81m × 1.9m, window size 1.16m × 1.45m, with a ceiling air vent size of 0.3m × 0.3m, the height of the stove surface is 0.81m. Generally, the people who cook in the kitchen are women. The average height of Chinese females does not exceed 170 cm. In this study, the height of the cooking staff was set at 165cm. The range hood is a direct suction (top suction) type, designed in European style with an exhaust air volume of 20m³/min, and the product model is CXW-258-EMC5. The stove is equipped with an embedded stove and dual stove eyes. Only the left stove is used in experiments and simulations. The range hood and stove are shown in Figure 1.

![Figure 1: Smoke lampblack machine and kitchen range.](image)

**Figure 1: Smoke lampblack machine and kitchen range.**

The layout principle of PM2.5 measurement points is based on the monitoring technical requirements of national standards for indoor ambient air quality. The standard requires that during the process of experimental sampling, air ducts and vents should be avoided as much as possible to reduce irrelevant effects. The testing points should be selected in indoor locations where work and living personnel are frequently active, and the layout of the sampling positions should meet various requirements. The horizontal direction should be more than 0.5m away from the wall, and the vertical height should be within the range of 1.0-1.5m from the ground. This area is generally the breathing area for cooking personnel. In this experiment, two PM2.5 testers were placed at a height of 1.4m at the location of the cooking personnel and 1.4m at the center of the room. There are a total of 10 HOBO thermometers, which are placed at 0.15m, 1.2m, 1.4m, and 1.8m of the cooking personnel's location, 0.15m, 1.2m, 1.4m, and 1.8m of the center of the room, as well as in front of the cooking personnel's chest and outdoors. Place the CO₂ detector in the center of the room. The specific testing conditions are shown in Table 1, the experimental instruments and models are shown in Table 2, the experimental instruments are shown in Figure 2, and the on-site testing images are shown in Figure 3.

<table>
<thead>
<tr>
<th>Case</th>
<th>Air inlet</th>
<th>Door</th>
<th>window</th>
<th>Numbers</th>
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<tr>
<td>1</td>
<td>Close</td>
<td>Close</td>
<td>Close</td>
<td>10</td>
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<tr>
<td>2</td>
<td>Close</td>
<td>Close</td>
<td>Open 30°</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Open</td>
<td>Close</td>
<td>Close</td>
<td>1</td>
</tr>
</tbody>
</table>

**Table 1: Test conditions.**

**Table 2: Experimental instruments and models.**

<table>
<thead>
<tr>
<th>Instruments</th>
<th>Model</th>
<th>Numbers</th>
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</thead>
<tbody>
<tr>
<td>HOBO hygrometer</td>
<td>U12-012</td>
<td>10</td>
</tr>
<tr>
<td>CO₂ detector</td>
<td>HT-2000</td>
<td>1</td>
</tr>
<tr>
<td>Aerosol detector</td>
<td>TSI 8530</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>TSI 8534</td>
<td></td>
</tr>
<tr>
<td>Anemometer</td>
<td>Testo 405i</td>
<td>1</td>
</tr>
</tbody>
</table>

**Figure 2: Experimental instruments.**

This experiment adopts a typical Chinese cooking method, with the dish being fried shredded potatoes. When the oil content is low, the ingredients are prone to local overheating and burning, resulting in higher concentrations of particulate matter; When there is a large amount of oil, the edible oil itself will produce a large amount of particulate matter due to heat evaporation and cracking. In order to avoid the impact of the variety and quality of ingredients, the experimental design strictly controls the quantity of ingredients for each dish to ensure a consistent amount of main ingredients. Strictly control the cooking process during the cooking process, set a fixed input time of oil,
scallions, shredded potatoes, soy sauce, and salt, with a total duration of 5 minutes. Ensure that the room state and pot bottom temperature are consistent before each cooking to control variables. Conduct the experiment in sequence according to the three set operating conditions, and record the data every 10 seconds until the end of the experiment. To ensure the accuracy of the experimental results, three experiments were conducted for each operating condition, and the average of the results was taken.

Figures 4 and 5 show the curves of PM2.5 and CO₂ concentration with cooking time under three different working conditions. It can be seen from the graph that under different ventilation conditions, the concentration of PM2.5 in the breathing area of the cooking personnel shows an overall upward trend. Within 5 minutes of cooking under infiltration working condition (case 1), the CO₂ concentration in the kitchen is much higher than that in case 2, always showing an upward trend, with a maximum value of 1485 ppm. The increase in oil temperature and the addition of dishes and seasonings in the early stages of cooking result in a sharp increase in concentration. The range hood is continuously turned on to exhaust air to the outside, but the room can only rely on the gaps between doors and windows for air replenishment, which will cause the static pressure in the kitchen to continue to decrease during the cooking process. Under this negative pressure state, it will significantly affect the cooking effect, reduce the efficiency of the range hood in the kitchen, and cause the high-temperature smoke generated during cooking to be unable to be effectively discharged. In case 2, opening windows during the cooking process is more conducive to the emission of indoor pollutants, and the CO₂ concentration is always at a low level, with an average concentration of 816.3 ppm, making it suitable for cooking personnel to engage in activities. In case 3, the ceiling air supply outlet is opened, and appropriate air supply can help improve the kitchen environment. The CO₂ concentration in the breathing area of the cooking personnel shows an upward trend, but overall it is much lower than the infiltration condition.

Figure 4: PM2.5 concentration change under different ventilation conditions.

Figure 5: CO₂ concentration change under different ventilation conditions.

Figure 6: Temperature change under different ventilation conditions.

Figure 6 shows the temperature change curve at a distance of 1.4 m from the ground where the cooking personnel are located under three working conditions. It can be seen from the figure that under natural infiltration conditions, due to the lack of fresh air in the kitchen, the flame temperature is high during the cooking process, resulting in high temperatures in the kitchen and causing strong discomfort for the cooking personnel. As cooking progresses, the efficiency of the range hood is affected by indoor negative pressure, resulting in a decrease in work efficiency. The high-temperature smoke generated during cooking cannot be effectively discharged, and a large amount of high-temperature smoke overflows from above the range hood, causing the room temperature to continue to rise. At this time, the room's thermal environment is poor. In case 2, due to the continuous decrease in temperature caused by opening windows, the outdoor environment is poor in winter for residents in severely cold areas. The continuous decrease in indoor temperature and the direct introduction of cold air from outside lead to poor thermal comfort for the human body. Overall, the suspended ceiling condition can maintain indoor temperature while also ensuring effective supplementation of indoor fresh air, and the effectiveness of the suspended ceiling scheme has been verified.
Numerical simulation

Numerical simulations can be effective in simulating the real time working dynamics of the exhaust hood and pollutant collection[10]. Numerical simulations can be used to ascertain the distribution of pollutants in order to take appropriate measures and optimization methods[11], and it can also be applied to test the effectiveness of optimized exhaust hoods[12]. In this paper, the simulated and experimental conditions are set under the same conditions, and the results of the simulated and experimental conditions are analyzed to verify the accuracy of the model.

A geometric model is established according to the actual kitchen size, and Fluent software is used to simulate the distribution of CO₂ and PM2.5 concentrations in the kitchen under different working conditions. Figure 7 shows the models under three different working conditions. The FLUENTMESHING module is used for mesh division, and the physical model is converted into the mathematical model required for calculation. The grid should be locally encrypted and refined for places with large temperature gradient and velocity gradient such as exhaust outlets, make-up air outlets and gaps. The gaps, windows and make-up air openings are set as pressure inlets, and the hood vent is set as velocity outlet. Solid wall boundary conditions (walls and doors) and other boundary surfaces are set as non-slip boundary conditions.

\[
\frac{\partial p}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = S_i \tag{1}
\]

Energy conservation equation:

\[
\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + F_i \tag{2}
\]

The RNG equation model was selected for calculation, and the calculation equation for air turbulence is:

\[
\frac{\partial}{\partial t} (\rho v) + \nabla \cdot (\rho v v) = -\nabla p + \nabla \cdot (T) + \rho \bar{g} \tag{3}
\]

The specifications component transportation model is as follows:

\[
\frac{\partial}{\partial t} (\rho Y_i) + \frac{\partial}{\partial x} (\rho u Y_i) = -\nabla J_i + R_i + S_i \tag{4}
\]

The boundary conditions are set in Table 3.

<table>
<thead>
<tr>
<th>Part of the model</th>
<th>Boundary type</th>
<th>Details</th>
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<tbody>
<tr>
<td>Door and Window gap</td>
<td>Pressure-inlet</td>
<td>-</td>
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<tr>
<td>Air inlet</td>
<td>Velocity-inlet</td>
<td>-</td>
</tr>
<tr>
<td>Exhaust outlet</td>
<td>Velocity-inlet</td>
<td>-6m/s</td>
</tr>
<tr>
<td>Pollutant</td>
<td>Velocity-inlet</td>
<td>Speed: 0.5m/s</td>
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<tr>
<td></td>
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<td>PM2.5 mass flow rate: 3 x 10e⁶kg/s</td>
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<td></td>
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<td>CO₂ generation: 1000ppm</td>
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<td>Indoor initial CO₂: 500ppm</td>
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Comparison of experimental data and numerical simulation analysis

Table 4 shows the test results of the air change frequency and actual air supply volume of typical residential kitchens in Shenyang during winter under the conditions of door and window penetration and three different window opening angles (15°, 30°, and 45°). Comparing and analyzing the two working conditions, it can be found that relying solely on infiltration for air replenishment cannot meet the actual fresh air demand, resulting in poor indoor air quality. In contrast, the indoor air change frequency under the window opening condition has significantly increased compared to the closed condition, which can effectively meet the indoor fresh air demand and improve indoor air quality. According to the experimental results, under three operating conditions of window opening angles of 15°, 30°, and 45°, the number of air changes is 30.50 times/h, 32.70 times/h, and 33.65 times/h, respectively. The number of air changes increases with the increase of
window opening angle. However, compared to the three operating conditions, the supplementary air volume did not significantly increase.

Table 4: Test results of air changes of ventilation by infiltration and variable-scale windowing ventilation.

<table>
<thead>
<tr>
<th>State</th>
<th>Ventilation rate (times/h)</th>
<th>Supplementary air volume (m³/h)</th>
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<tbody>
<tr>
<td>Penetration of door and window gaps</td>
<td>7.21</td>
<td>102.21</td>
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<td>Window opening 15° range hood low speed</td>
<td>30.48</td>
<td>416.04</td>
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<td>Window opening 30° range hood low speed</td>
<td>32.69</td>
<td>446.29</td>
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<tr>
<td>Window opening 45° range hood low speed</td>
<td>33.67</td>
<td>457.93</td>
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As shown in Figure 8, CFD numerical simulations were conducted for the above door and window penetration conditions and three different window opening angles (15°, 30°, and 45°), and the simulation results were compared with the air change times in the experimental data. In the experiment and simulation, the initial CO₂ concentration in the kitchen was 500ppm. However, due to the first group of tests conducted under closed conditions during the experiment, the CO₂ released into the kitchen may exhibit uneven distribution, resulting in a smaller number of air changes compared to the simulation results. During the three window opening conditions, the unavoidable entry and exit of the tester into the kitchen may cause the loss of indoor CO₂, resulting in a higher number of air changes compared to the simulation results.

Figure 8: Comparison between experimental data and simulated data

Results

In order to observe the distribution status of pollutants from different dimensions, cloud maps with y=1.4m and x=0.7m were selected to analyze the concentration of CO₂ during the cooking process. Due to the similarity between PM2.5 and CO₂ under three operating conditions, and the fact that CO₂ can be used to measure indoor air pollution, only the CO₂ simulation results will be analyzed here. The specific analysis results are as follows:

Analysis of simulation results under infiltration conditions

Figure 9: Distributions of CO₂ concentration on the cross-sectional plane y = 1.4m and x=0.7m of case 1.

Figure 9 shows the cloud diagram of CO₂ concentration distribution at the sections of y=1.4m and x=0.7m under the condition of natural infiltration. From the figure, it can be seen that some of the CO₂ generated during cooking has a significant overflow phenomenon in the range hood, flowing towards the human body. It is also affected by the gap air supply between windows and doors and windows, causing the smoke to shift towards the direction where the doors and windows are located, resulting in a high concentration of CO₂ in the human breathing area, seriously affecting the working environment of the cooking personnel in the breathing area. The average concentration of CO₂ in the kitchen during the cooking process is 1158ppm.

Analysis of simulation results under window opening conditions

Figure 10: Distributions of CO₂ concentration on the cross-sectional plane y = 1.4m and x=0.7m of case 2.

Figure 10 shows the cloud diagram of CO₂ concentration distribution at the cross sections of y=1.4m and x=0.7m when the window opening angle is 30°. The outdoor fresh air enters the room from the right window of the kitchen cooking area, and due to the influence of the introduction of fresh air, the cooking flame has a significant swing. Opening windows for ventilation has a significant effect on pollutant removal, but due to the unstable distribution of indoor airflow in a room, it can have a negative impact on the improvement of CO₂ concentration in the breathing area of personnel. Moreover, opening windows can cause pollutants to accumulate in corners, making it difficult to discharge and effectively improving indoor air quality. Therefore, it is necessary to explore the air supply methods for household kitchens in severe cold areas.
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