Study on the influence of kitchen door seam on air distribution in severe cold regions

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Abstract
In order to study the influence of different door seam settings on air distribution in residential kitchens under different ventilation modes in severe cold regions. This paper is based on CFD simulation, using existing residential kitchens as the model, and verifies the simulation results through practical tests. The results show that under the same total area of the door seam, under the two schemes of door seam air supplement and ceiling air supplement, when only the lower door seam is set, the speed of the personnel breathing area is 0.09m/s and 0.21m/s, respectively. When door gaps are set all around, the speed of the breathing area is 0.10m/s and 0.26m/s. Compared to the enclosed situation, the indoor pollutant concentration has been significantly improved under the suspended ceiling ventilation mode; Under both types of air supply methods, the pollutant concentration with gaps set all around is lower than that with only the lower door seam set. Therefore, under the two ventilation methods of door seam air replenishment and ceiling air replenishment, the impact of different door seam settings on the airflow organization of residential kitchens is as follows: the door setting around is higher than only setting the lower door seam.

Highlights
- Residential kitchen
- Numerical simulation
- Indoor airflow organization
- Door seam

Introduction
In recent years, as people's living standards have improved, more people have begun to turn their attention to indoor air quality improvement. People spend the vast majority of their lives (about 70%-90%) indoors, and the main factors affecting indoor air quality are indoor particulate matter and volatile organic compounds, which are particularly evident in residential kitchens. Currently, kitchens are still the lowest indoor air quality and comfort in residential buildings, and the high temperature grease particles generated during cooking have a significant impact on the indoor environment, where PM2.5 with small particle size easily adsorbs harmful substances such as bacteria and fungi and is deposited in the alveoli through the respiratory tract and bronchi, and enters the bloodstream through the alveoli, directly damaging the human heart and lungs and other organs and seriously endangering the life and health of cooking staff. Therefore, more and more researchers have started to study the effects of the bacteria and fungus on the human body. Therefore, researchers have started to pay attention to the concentration and distribution pattern of particulate matter in the kitchen, and control the concentration of pollutants through effective air supplementation.

Ventilation is an effective means to improve the cooking environment. Outdoor conditions in cold regions are harsh in winter, and natural ventilation is restricted, making the environmental problems in residential kitchens more severe compared to other climate zones. Opening the window during cooking will cause the room temperature to drop rapidly, greatly affecting indoor thermal comfort; and without effective make-up air, relying only on the range hood for exhaust, it will not be able to achieve the ideal smoke exhaust effect, affecting indoor air quality. Compared with only relying on seam infiltration and window ventilation, the addition of a supplementary air outlet at the ceiling can effectively improve the air quality of the kitchen and enhance the comfort of personnel.

This article takes a residential kitchen in Shenyang as the research object and conducts numerical simulations on indoor velocity and pollutant concentration. It compares and analyzes the impact of two ventilation methods, door joint air supplement and ceiling air supplement, on the indoor environment under different door joint settings. This provides a theoretical basis for the door setting form and improvement of indoor environment in residential kitchens in severe cold areas.

Methods
Based on a natural ventilation residential kitchen in Shenyang, this paper establishes a physical model as shown in Figure 1, in which the room size was 3.45m × 2.2m × 3.3m (including the ceiling height of 0.9m), the exhaust vent of the range hood was a circle with a diameter of 0.16m, and the ceiling opening was 0.3m × 0.3m rectangle, the heating type was geothermal heating, the range hood was used to exhaust air and simplify some furniture in the room during cooking. The cooking staff in the room was simplified to a number of rectangles with a height of 165cm and a distance of 0.1m from the stove. Set the door seam as a single piece with the size of 0.81m × 0.012m or four gaps with the same total area.
The proposed model is meshed by ANSYS Meshing, and the mesh is locally encrypted for the large temperature, velocity and concentration gradients. The mesh quantities of 290,000, 510,000, 700,000 and 900,000 were selected for independence verification. Figure 2 shows the velocity at the center of the door seam and finally 700,000 mesh quantities were selected for simulation.

Fig 2: Comparison of velocity at the center of door seam.

Continuous Phase Model
In this paper, ANSYS Fluent is used to solve the whole calculation domain, In the turbulence model, the RNG k-e model, which considers the rotation and rotational flow in the average flow and has stronger ability to handle flow with high strain rates and high streamline curvature, was selected for simulation. Its equation is as follows:

Continuity Equation:
\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0
\]  \hspace{1cm} (1)

Momentum Equation:
\[
\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} \right) - \frac{\partial p}{\partial x_i} + S_i
\]  \hspace{1cm} (2)

Energy Equation:
\[
\frac{\partial (\rho T)}{\partial t} + \frac{\partial (\rho u_i T)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \kappa \frac{\partial T}{\partial x_i} \right) + S_T
\]  \hspace{1cm} (3)

Component Transport Equation:
\[
\frac{\partial}{\partial t} (\rho Y_i) + \frac{\partial (\rho u_i Y_i)}{\partial x_i} = - \nabla J_i + R_i + S_i
\]  \hspace{1cm} (4)

Where i, j=1, 2, 3, ρ is the density of the fluid, kg/m^3; t is the time, s; u is the gas flow velocity, m/s; p is the pressure on the fluid unit, Pa; T represents temperature, K; Pr is the Prandtl number (dimensionless number) In addition, the standard wall function method and the implicit pressure-based format are chosen to solve and use the well-established SIMPLE algorithm, in which the pressure term is discretized by PRESTO! and the rest of the second-order windward equations are used, setting the energy residuals less than 10^{-11} and the rest of the residuals less than 10^{-5}.

Discrete Phase Model
In the simulation calculation, the particle trajectory is calculated by Lagrange method and Discrete Random Walk(DRW) model is adopted. For fine particles, the Bassett force, pressure gradient force and virtual mass force are negligible, and only the influence of gravity, Satman lift, Brownian force and fluid drag force on them is considered. In addition, the merging and breaking of particles are not considered in the calculation; All particles are particles of single diameter and the shape of particles is spherical. (Yao, 2022) The calculation formula of particle motion trajectory is as follows:

\[
\frac{du_f}{dt} = F_D(u - u_f) + \frac{g(\rho_p - \rho)}{\rho_p} + F
\]  \hspace{1cm} (5)

Where u is the fluid velocity, m/s; u_f is the particle velocity, m/s; ρ is the fluid density, kg/m^3; ρ_p is particle density, kg/m^3; g is the acceleration of gravity, m/s; F is the combined force term of the additional force, N is the additional force including thermophoresis force, lift force, etc; F_D(u - u_f) is the drag force term per unit mass of particles.

The cooking fumes generated in the kitchen are complex in composition, and the properties of the particulate matter in the discrete phase calculation are set as follows: particulate matter mass flow rate of 3×10^{-8} kg/s, density of 950 kg/m^3, and particulate matter diameter range of 1×10^{-6}~2.5×10^{-6}m.

Boundary Condition
The boundary conditions in the simulation calculation are shown in Table 1. The boundary conditions of the left boiler are set to a velocity inlet with temperature and velocity, and the cooking process is reasonably simplified as the heating process of oil. Among the conditions of particulate matter, the exhaust outlet of the range hood and the entrance of the door seam are escape conditions, and the rest of the wall conditions are set as trap
conditions because it is difficult for particulate matter to bounce back into the flow field after contact (Bin and Zhao, 2010).

Table 1 Boundary conditions

<table>
<thead>
<tr>
<th>Type</th>
<th>Parameter</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire</td>
<td>Velocity-inlet</td>
<td>1m/s</td>
</tr>
<tr>
<td>Outdoor opening</td>
<td>Pressure-inlet</td>
<td>-</td>
</tr>
<tr>
<td>Person</td>
<td>Wall</td>
<td>27.7W/m²</td>
</tr>
<tr>
<td>Door seam</td>
<td>Pressure-inlet</td>
<td>-</td>
</tr>
<tr>
<td>Wall</td>
<td>Wall</td>
<td>1.5W/m²</td>
</tr>
</tbody>
</table>

Result And Discussion

Table 2 shows the four conditions considered in this study

Table 2 Simulation case

<table>
<thead>
<tr>
<th>Cases</th>
<th>Ventilation forms</th>
<th>Door seam setting form</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Door seam infiltration</td>
<td>Only lower seam</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>All around the door</td>
</tr>
<tr>
<td>3</td>
<td>Ceiling opening</td>
<td>Only lower seam</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>All around the door</td>
</tr>
</tbody>
</table>

Figure 2 and Figure 3 show the velocity contour when the cooking time is five minutes, respectively.

In Figure 3, the velocities at the center of the chamber are 0.24 m/s and 0.23 m/s respectively. Due to the supplement of outdoor fresh air at the ceiling opening in the room, the wind speed at the opening position and the personnel working area in the room is significantly higher than that in Figure 2, and the personnel's sense of wind blowing is relatively obvious, with almost no difference in other places. When only the lower door gap is set, the speed of other areas in the room is almost zero. When gaps are set around the door, the overall speed of the room increases slightly but not significantly due to the air supplement of the left and right gaps.

Figure 2: Velocity contour of case1(left) and case2(right)

Fig 3: Velocity contour of case3(left) and case4(right)

Fig 4: Average wind velocity in personnel breathing area

Fig 5: Contour of CO2 concentration at X=-1.19m under case3(left) and case4(right)
Figure 5 and Figure 6 show the CO2 concentration contour under different ventilation modes for two working conditions. As can be seen from the figure, due to the supplement of outdoor fresh air, the CO2 concentration under the door seam air supplement condition is significantly higher than that under the ceiling air supplement condition. Due to the effect of thermal pressure, CO2 accumulates on the top of the room and does not dissipate. This situation has been improved in the ceiling ventilation mode, where CO2 only accumulates in some areas of the room. In addition, under the two air supplement modes, due to the fresh air supplement around the door of case 2 and case 4, the CO2 concentration is slightly lower than that of case 1 and case 3, the CO2 concentration in the cooking area has been improved overall.

In Figure 7, most of the PM2.5 generated by cooking has not been completely dissipated and still accumulates on the top of the working area and the breathing area, but compared with case 1, in case 3, the high concentration of particulate matter does not spread to other areas of the room due to the supplemental fresh air from outside. In case 1, the particulate matter started to make irregular vortex motion in the room, while in case 3, the particulate moved up and down along the fresh air replenished by the ceiling opening.

In Figure 8, case 3 and case 4 show similar trends, but both are lower than cases 1 and 2. It can be seen that under the suspended ceiling ventilation mode, the PM2.5 concentration in the personnel breathing area decreases significantly, and the indoor environment is significantly improved. In addition, compared to the situation where only the lower door seam is set, the concentration of pollutants is greatly alleviated when the door seam is set all around the door.

Conclusion

Through numerical simulation, this paper discusses the differences in indoor air distribution under two ventilation modes, namely, door seam air supplement and ceiling air supplement, with different door seam settings. The conclusions are as follows:

1) In both cases, CO2 and PM2.5 will accumulate on the top of the room due to the impact of heat pressure and airflow rise. However, in case 2 and case 4, due to the fresh outdoor air being replenished around the door, the concentration of pollutants in the room far from the cooking area is relatively low, and the indoor air quality and comfort level are relatively high.

2) Under the same total area of the door seam, under the two schemes of door seam air supplement and ceiling air supplement, when only the lower door seam is set, the speed of the personnel breathing area is 0.09m/s and 0.21m/s, respectively; When door gaps are set all around, the speed of the breathing area is 0.10m/s and 0.26m/s.
Compared to the enclosed situation, the indoor pollutant concentration has been significantly improved under the suspended ceiling ventilation mode; Under both types of air supply methods, the pollutant concentration with gaps set all around is lower than that with only the lower door seam set.

Therefore, under the two ventilation methods of door seam air replenishment and ceiling air replenishment, the impact of different door seam settings on the airflow organization of residential kitchens is as follows: the door seam setting around is higher than only setting the lower door seam. When residents set up kitchen doors, leaving gaps around door can provide a better indoor environment.

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References


