Indoor Ventilation Strategies Based on the Characteristics of Farmhouse Kitchens in Severe Cold Regions

Xulin Li, Shiyuan Liu*

School of Municipal and Environment Engineering, Shenyang Jianzhu University, Shenyang, China

*E-mail address: 346017194@qq.com

Abstract. Farmhouses in the cold regions of China are affected by climatic conditions, energy conditions, the building's own characteristics and farmers' living habits, and many kinds of pollutants accumulate and diffuse in the farmhouses, resulting in poor indoor air quality. Through a combination of field research and household testing, the basic characteristics of farmhouse kitchens and the current status of indoor air quality were clarified. The heat generated by fuel combustion is not fully absorbed by the stove and bed system, resulting in energy loss. The flue gas waste heat recovery device is utilized to preheat the fresh air, thus reducing the indoor fresh air load. Under these conditions, FLUENT software was used to simulate the ventilation strategies in the kitchen to verify the effects of different ventilation strategies and fresh air conditions on the removal of pollutants in the kitchen. The simulation results confirm that the heat recovery efficiency of the flue gas waste heat recovery device can reach 58.9%, and the optimized system A coupled with the fresh air condition 3 is the optimal ventilation strategy, with an exclusion efficiency of more than 90%.

Keywords: Severe cold regions; farmhouse kitchen air quality optimization; flue gas waste heat recovery.

1 Introduction

With the rapid development of the country's economic and technological level, people's living standards have been substantially improved, and the requirements for the quality of the indoor environment are becoming higher and higher. According to the data, more than 90% of our life is spent indoors[1], indoor air quality is closely related to our health. In the building, the kitchen as a building in the higher frequency of use, the use of a longer period of time in the home place, cooking process produced by the soot particles is inevitable. For farm kitchens in cold regions, the cooking activities of the residents and the use of fuel for heating produce many pollutants. Prolonged exposure to kitchens with excessive particulate matter can negatively affect the health of personnel, leading

Y. Zhang et al. (eds.), *Proceedings of the 2024 10th International Conference on Architectural, Civil and Hydraulic Engineering (ICACHE 2024)*, Advances in Engineering Research 259,
https://doi.org/10.2991/978-94-6463-658-1_65

ischemic heart disease, and lung cancer[2]. Therefore, improving ventilation efficiency and air quality is the focus of kitchen remodeling.

Most of the existing domestic studies related to the environment inside farmhouses have focused on air quality inside living rooms. For example, Ding Yong et al. found that there are obvious differences between traditional village buildings and modern buildings in towns and cities. To accurately assess the quality of the thermal environment and air quality in traditional village buildings in winter, the study was carried out by means of field tests and subjective surveys. The characteristics of indoor thermal and humid environments and air quality in winter in village buildings were quantitatively discussed, and the main points of quantitative research on indoor environmental standards for village buildings were proposed[3]. Based on the subjective questionnaire survey and theoretical research, Chen Yajing proposed a new model for characterizing the demand for the habitat of northern farmhouses[4]. Yang Yiming proposed a technical measure to effectively reduce $PM_{2.5}$ concentrations at the source through field testing and tracking records [5]. Christina Li et al. visited and investigated the indoor air quality of 180 farmhouses in the western region. Analyzing the data, it can be seen that the maximum daily average concentration of PM2.5, for example, inside the residence exceeded the national regulation by four times[6]. Ruoting Jiang et al. experimentally confirmed that rural biomass fuel combustion causes serious indoor environmental pollution, with the concentration of $PM_{2.5}$ in rural kitchens being 5.4 times higher than that in urban kitchens[7].

Some foreign scholars have also conducted experiments to analyze the current situation of air quality in farmhouses. Sumit Kumar Gautam et al. conducted a study on indoor air pollution levels in 55 farmhouses in rural India using different fuels for cooking and found that cow dung was the most pollutant-producing fuel, including CO, NO_2, $PM_{2.5}$, PM_{10}, VOCs, and benzene, followed by firewood and kerosene. The combustion of all fuels releases carcinogenic polycyclic aromatic hydrocarbons, which are extremely hazardous to human health[8].

Through literature research, it is known that the flue gas produced by biomass fuel combustion still carries more than 50% of the residual heat of combustion after passing through the stove system and heated bed system, which leads to the waste of energy[9].

According to the existing research status at home and abroad, most of the research focuses on the air quality in the living room of the farmhouse and ignores the impact of the kitchen as a source of pollution on the air quality of the farmhouse, and there are very few studies on the recovery of flue gas waste heat in the farmhouse.

2 Tests of Pollutant Concentrations in Typical Farm Dwellings

To clarify the basic conditions of kitchens within farmhouses in severe cold regions, a typical kitchen in a rural area of Shenyang, Liaoning Province, was selected for in-home testing to collect CO_2 and $PM_{2.5}$ concentrations in the kitchen, as shown in Fig. 1.

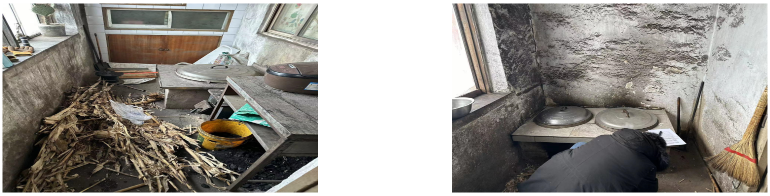


Fig. 1. Field test (source: author's own drawing)

The experimental instruments used in this experiment were TSI8530 PM analyzer and TSI7575 air quality tester. Data were recorded for the initial state of the farmhouse kitchen when no fuel was burned, as shown in Table 1.

Table 1. Initial state of the interior (source: author's own drawing)

CO_2 Initial concentration	670 ppm
$PM_{2.5}$ Initial concentration	0.13 mg/m^3
Initial room temperature	14°C

China's indoor air quality standard GB/T18883-2022 [10] provides standard values for indoor environments as well as limit values for indoor pollutants, and the instantaneous maximum value of CO_2 concentration can be up to 1527ppm, and the instantaneous maximum value of $PM_{2.5}$ concentration can be up to 4.35mg/m^3, which is a serious degree of air contamination in the kitchen of the farmhouse.

3 Modeling and Simulation Validation

3.1 Geometric Modeling of the Flue Gas Recovery Unit

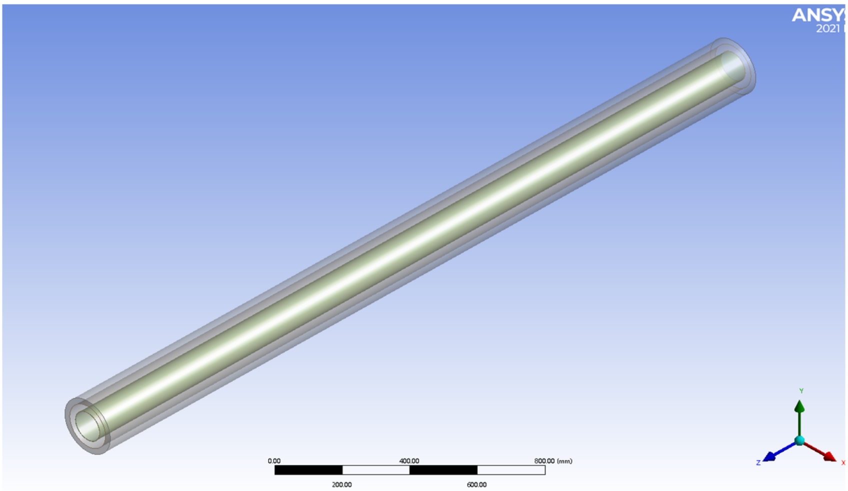


Fig. 2. Casing modeling (source: author's own drawing)

In the original flue of the farmhouse building, an external pipe is set up, relying on the wall surface of the pipe for heat exchange, to realize the use of flue gas to preheat the fresh air. Using FLUENT software to model the fresh air - flue gas waste heat recovery device, most of the chimney cross-section diameter of the farmhouse is between 10-15cm, in order to ensure the universality of the model, choose a typical farmhouse flue size for modeling, respectively, in the flue outside the additional diameter of 130mm, 150mm, 200mm external pipe, to build the fresh air - flue gas waste heat recovery device, respectively, pipe 1, pipe 2, pipe 3, casing modeling diagram outside the pipe diameter of 150 mm casing as an example, as shown in Figure 2.

To ensure the accuracy and reliability of the simulation results, the casing model is verified for mesh-independence. According to the results in Fig. 3, it is shown that the computational accuracy requirements can be met by using a medium number of meshes.

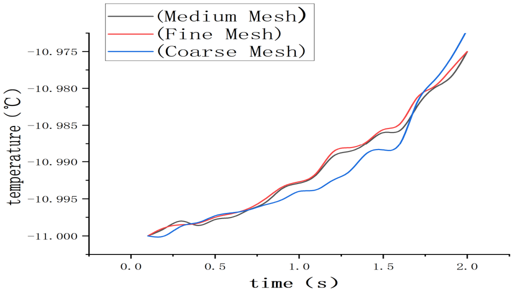


Fig. 3. Grid-independence validation (source: author's own drawing)

Simulation experiments were carried out on three kinds of casing with fresh air at speeds of 1 m/s, 2 m/s, 3 m/s, 4 m/s, and 5 m/s, respectively, to obtain different fresh air temperatures and fresh air volumes, as shown in Table 2.

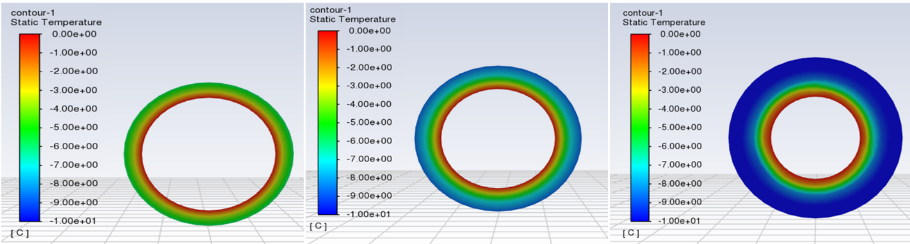
Table 2. Fresh air post-preheat data (source: author's own drawing)

Type \ velocity	Pipe1		Pipe2		Pipe3	
	temp.	air volume	temp.	air volume	temp.	air volume
1m/s	6°C	18.3672m³/h	2°C	34.2 m³/h	-4.2°C	83.682 m³/h
2m/s	1.5°C	36.7344m³/h	-3.8°C	68.4 m³/h	-6.6°C	167.364m³/h
3m/s	-2°C	55.1016m³/h	-5°C	102.6m³/h	-7.5°C	251.046m³/h
4m/s	-3.8°C	73.4688m³/h	-6.3°C	136.8m³/h	-8.1°C	334.728m³/h
5m/s	-4.6°C	91.836 m³/h	-7.4°C	171 m³/h	-8.6°C	418.41m³/h

The above 15 kinds of data were analyzed to screen the suitable fresh air working conditions as the subsequent boundary conditions. To meet the requirements of the internal environment of the kitchen, the fresh air volume is at least 72 m/h^3. To reduce the fresh air load, the fresh air temperature is required to be not lower than -7℃. Under this condition, three kinds of fresh air data with large difference in fresh air volume and from different casings are selected, and the specific data are shown in Table 3. The corresponding temperature cloud is shown in Fig. 4

Table 3. Selected fresh air data (source: authors' own drawings)

working condition	Condition 1	Condition 2	Condition 3
Casing OD Size	130 mm	150 mm	200 mm
fresh air velocity	4 m/s	3 m/s	2 m/s
fresh air volume	73.4688 m^3/h	102.6 m^3/h	167.364 m^3/h
average outlet temperature	-3.8℃	-5℃	-6.6℃



(a) Condition 1 (b) Condition 2 (c) Condition 3

Fig. 4. Fresh air outlet temperature cloud (source: author's own drawing)

The temperature range of the flue gas arriving at the flue outlet after the stove bed system is 45-110°C, which is sorted out through the existing literature, and the middle value of the temperature range is selected as the initial data of the simulation experiment to analyze the residual heat recovered by the casing under the above three working conditions. The discharge temperature at the chimney outlet decreased by 58.85℃ at most, and the heat recovery rate reached 58.9%, which proves that the flue gas-fresh air casing has a better effect on the recovery of flue gas heat, and it can realize the multi-stage utilization of heat.

3.2 Basic Modeling of the Kitchen

The kitchen was modeled according to the actual dimensions of 3.0m×2.0m×3.0m (L×W×H). The traditional earthen stove in the kitchen was simplified as a pollution source located at 0.9m×0.9m on the ground, and the smoke vent of the stove-bed system was set as an air outlet on the wall near the stove. Since insulation measures such as window sealing are used in rural areas in winter, it is considered that the external kitchen windows do not have wind penetration. The size of the inner door of the kitchen is 1m×2m (W×H), and no other air venting measures were done when modeling the kitchens. The kitchen modeling is shown in Figure 5.

In this paper, ANSYS FLUENT software was used to simulate the indoor pollutant concentration field, based on the standard k-Ɛ turbulence model, and multiple component (Species) model and DPM model were used for simulation experiments to analyze the CO_2 and $PM_{2.5}$ concentrations. Mesh division was performed using the Mesh part of Fluent software, and mesh encryption was performed at the door slits, pollutant sources, and exhaust vents. The simulation studies the diffusion of indoor pollutants and the change rule of concentration, and the system is simplified to facilitate the analysis. The following assumptions are made in this study: first, the indoor air is an incompressible fluid, and the viscous dissipation in the flow process is ignored; second, the physical parameters of the air and pollutants in the room do not change with the temperature; the Boussinesq assumption is satisfied; third, the radiative influence of the various heat-transferring surfaces in the interior is not taken into account; fourth, the temperature of the outer wall of the room is uniformly constant; and fifth, the influence of the wind pressure on the exhaust of stove-bed system is ignored.

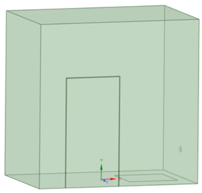
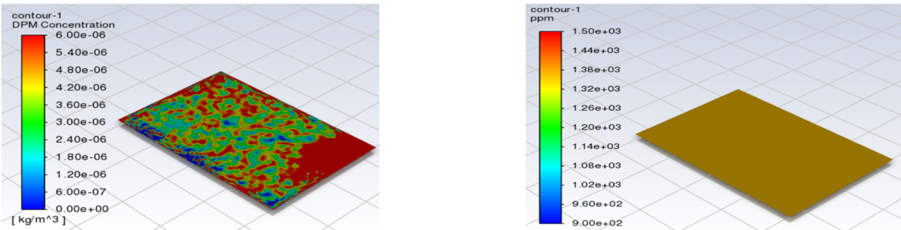


Fig. 5. Kitchen modeling (source: author's own drawing)

3.3 Simulation Validation of the Kitchen Model

Two pollutants, $PM_{2.5}$ and CO_2, were selected as the monitoring objects for model validation, and the concentration cloud at 1.2m was intercepted as shown in Fig. 6.



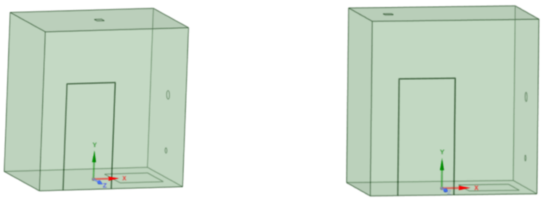
(a) Concentration field of $PM_{2.5}$ (b) Concentration field of CO_2

Fig. 6. Pollutant concentration field (source: author's own drawing)

Comparing and analyzing the experimental data with the simulated data, the error between the concentration value of $PM_{2.5}$ obtained from the simulation and the test data is within 3.4%, and the error between the concentration value of CO_2 obtained from the simulation and the measured data is between 4.7%, so it is considered that the model and the setup parameter can be used as the initial parameter of the subsequent optimization system.

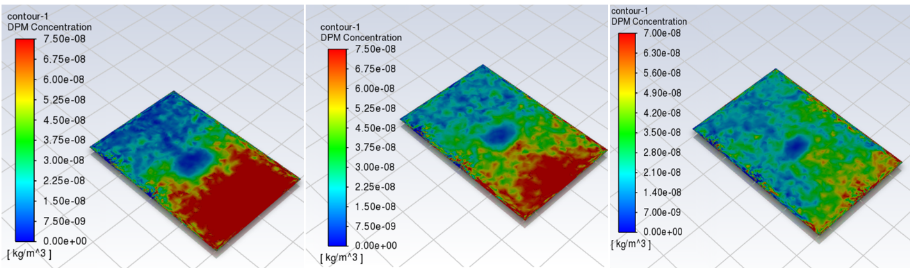
4 Simulation Results and Analysis

Residents of farmhouses in severe cold regions use external window lamination and caulking of external windows to keep warm in winter, and this behavior greatly weakens the infiltration ventilation, under which conditions it is necessary to add additional supplementary air outlets to the kitchen. Due to the poor hygienic conditions of the kitchen floor in the farmhouse, the choice was made to arrange fresh air outlets above the building. According to the survey results, nearly 80% of the kitchens are not equipped with exhaust hoods, and it is chosen to add another exhaust hood above the earthen stove as a new air vent once to ensure the balance of indoor air. Two optimization schemes with different locations of fresh air outlets are proposed, the fresh air outlet of optimization system A is arranged at the center above the building, and the fresh air outlet of optimization system B is arranged at the non-cooking area, and the optimization scheme is modeled as shown in Figure 7.



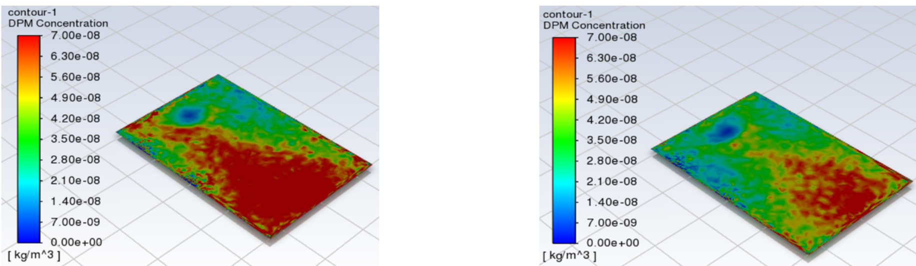
(a) optimization system A (b) optimization system B

Fig. 7. Modeling of optimization scenarios for kitchens (data source: author's own drawing)



(a) Condition 1 (b) Condition 2 (c) Condition 3

Fig. 8. system A indoor $PM_{2.5}$ concentration cloud (source: authors' own drawing)

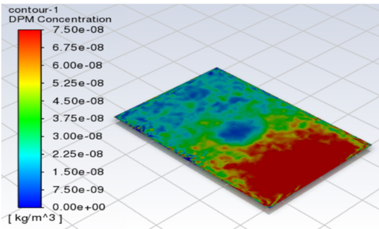


(a) Fresh air working condition 2 (b) Fresh air working condition 3

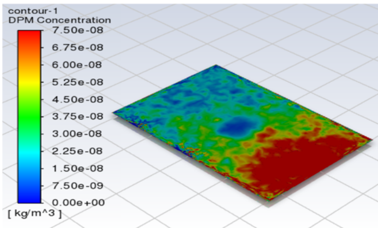
Fig. 9. system B indoor $PM_{2.5}$ concentration cloud (source: authors' own drawing)

A plane with a kitchen height of 1.2 m is intercepted as the monitoring surface to analyze the suppression effect of the two optimization schemes on $PM_{2.5}$ concentration. The $PM_{2.5}$ concentration cloud plots of Optimization Scenario A and Scenario B are shown in Fig. 8 and Fig. 9.

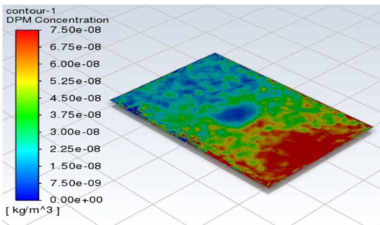
By comparing and analyzing the $PM_{2.5}$ concentration cloud diagrams of optimization systems A and B, it can be seen that the three fresh air conditions of optimization system A have a better dilution effect on indoor $PM_{2.5}$, and the average concentration of indoor $PM_{2.5}$ can be controlled within the concentration range of the national regulations, and only a small area close to the wall exists in which pollutants are aggregated. On the other hand, optimization system B has a poorer effect on the exclusion of indoor $PM_{2.5}$, and the average concentration of $PM_{2.5}$ in most of the areas in the kitchen exceeds the national limit value, which proves that optimization system A is more effective in the exclusion of $PM_{2.5}$ compared to optimization system B. The reason for this situation is that the fresh air outlet of Optimized System A is set in the middle, which is equivalent to a small air curtain when it sends air downward, blocking the diffusion of pollutants to the non-cooking area, while the fresh air outlet of Optimized System B is close to the non-cooking area, and its ventilation is in the form of comprehensive ventilation, and the amount of fresh air produced by the casing cannot meet the amount of fresh air demand for comprehensive ventilation. After comprehensive consideration, optimized system A is considered to be a more appropriate ventilation strategy.



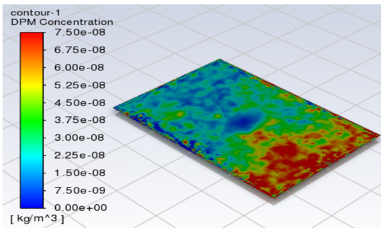
(a) $PM_{2.5}$ concentration cloud map(0.8m)



(b) $PM_{2.5}$ concentration cloud map(1.0m)



(c) $PM_{2.5}$ concentration cloud map(1.2m)



(d) $PM_{2.5}$ concentration cloud map(1.5m)

Fig. 10. PM2.5 concentration cloud of system A condition 2 (Source: Author's own drawing)

In order to analyze the height distribution of $PM_{2.5}$ in the kitchen, Condition 2 of the optimized system A was selected as the research object, and the concentration cloud diagram of $PM_{2.5}$ was intercepted according to the heights of 0.8 m, 1.0 m, 1.2 m, and 1.5 m as shown in Fig. 10. It can be seen from the figure that leads to a gradual stabilization of the average $PM_{2.5}$ concentration at 1.2-1.5 m with increasing height. This proves that the pollutants in the kitchen of the farmhouse gradually decrease with increasing height, and the concentration of pollutants is negatively correlated with height.

Comparing the simulated data with the experimental data to analyze the exclusion effect of the three fresh air conditions on $PM_{2.5}$, it can be seen in Figure 11 that under the ventilation strategy of optimized system A, the fresh air of all three conditions can make the concentration of $PM_{2.5}$ in the kitchen decrease significantly, and with the end of cooking and heating activities, the concentration of $PM_{2.5}$ gradually decreases. All three optimization methods can make the average concentration of $PM_{2.5}$ in the kitchen meet the specification requirements, so it is considered that all three fresh air conditions can effectively improve the indoor air condition. Condition 1 has the slowest dilution rate of pollutants, the worst dilution effect, and relatively unstable indoor conditions. Condition 3 has the best dilution effect, the fastest rate, and the most stable air condition in the kitchen.

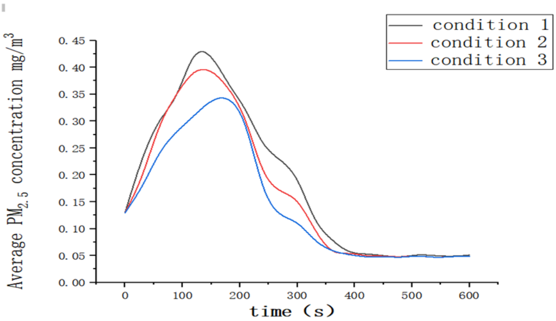
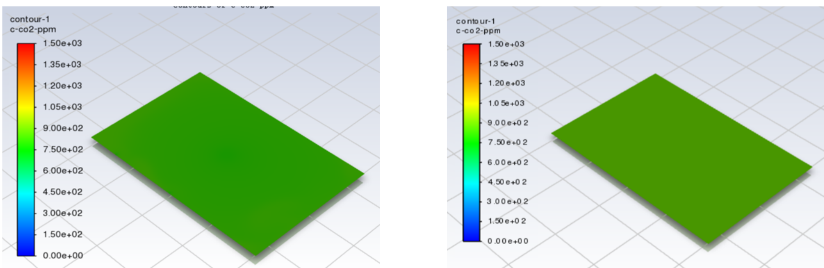
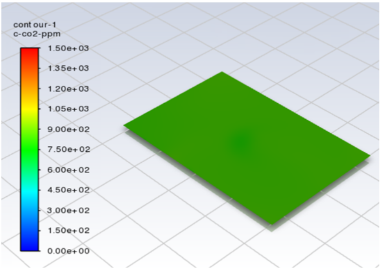


Fig. 11. Changes in average $PM_{2.5}$ concentrations for system A (Source: Author's own drawing)

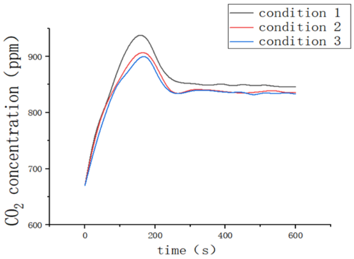
During the residents' cooking and heating activities, the instantaneous maximum CO_2 concentration in the kitchen can reach 1527 ppm, and it is much higher than the national standard. Therefore, the CO_2 concentration is used as a research object to further verify the effectiveness of optimizing the three fresh air conditions of System A to improve the air quality in the kitchen. The average indoor CO_2 concentration was calculated by intercepting the plane at 1.2m high in the kitchen, as shown in Figure 12.



(a) Fresh air working condition 1 (b) Fresh air working condition 2



(c) Fresh air working condition 3



(d) CO_2 concentration graph.

Fig. 12. Average CO_2 concentration of system A and its profile (source: resource mapping)

As can be seen in Fig. 12, all three fresh air conditions of the optimized system A have an inhibiting effect on the growth of indoor CO_2 concentration. Under the initial conditions, people's activities such as cooking over a fire will lead to a temporary increase in the indoor CO_2 concentration value, which then gradually decreases over time and remains relatively stable. Compared with the experimental data, the pollutant concentration at the same height and test position in the same period of time is greatly reduced, and the simulation results show that the highest average CO_2 concentration under the three conditions is 846 ppm, 836 ppm, and 833 ppm, which once again verifies the effectiveness of Optimization System A in improving air quality, and confirms that the pollutant elimination effect of Condition 3 is the most effective among the three working conditions.

5 Conclusion

Based on the results of the field test, FLUENT software was used to conduct simulation experiments to analyze the impact of two optimization systems and three conditions of fresh air on the pollutants in the kitchen, which proved that the optimization system A is more effective in improving the air quality in the kitchen, and under the conditions of the optimization system A, the three conditions of fresh air can ensure that the pollutant concentration in the kitchen is again within the prescribed range. Comparing the data results of the three conditions, Condition 3 has the fastest PM2.5 and CO2 rate, the highest elimination efficiency, and the most stable environment in the kitchen. Condition 1 has the highest casing waste heat recovery rate, although the elimination rate is slightly worse than that of conditions 2 and 3. In summary, the optimized system A coupled with fresh air condition three has the best exclusion efficiency for pollutants, with an exclusion efficiency of more than 90%.

References

1. Shan X, Zhou J, Chang V W C, et al. Comparing mixing and displacement ventilation in tutorial rooms: Students' thermal comfort, sick building syndromes, and short-term performance [J]. Building and Environment, 2016, 102: 128-137.

2. ZHANG Xin, LI Hong, ZHANG Chenglong, et al. Optimization and preliminary application of detection methods for aldehydes and ketones in ambient air[J], Environment Science Research,2019,32(05): 821-829.DOI: 10.13198/j.issn.1001-6929.2019.03.12.
3. DING Yong, YAO Yan. Characteristics of winter indoor thermal environment and air quality of traditional village buildings in Chongqing area[J]. Science, Technology and Engineering, 2023, 23(05):2115-2121.
4. Chen Yajing. Research on the characterization model of the demand for human habitat in northern farmhouses[D]. Dalian University of Technology, 2022.DOI: 10.26991/d.cnki.gdllu.2022.003112.
5. Yang Yiming. Winter indoor PM2.5 dispersion characteristics and health risk assessment in Liaoning farmhouses[D]. Dalian University of Technology, 2022.DOI: 10.26991/d.cnki.gdllu.2022.001490.
6. Li Xiang, Wei Quanyuan, Wei Xiuying, et al. A case study of indoor air pollution in agricultural households[J]. Journal of Agricultural Engineering, 2006(22): 231-235.
7. Jiang R, Michelle L B. A Comparison of particulate matter from biomass-burning rural and non-biomass-burning urban households in northeastern China[J]. Environmental Health Perspectives, 2008, 116(7): 907-914.
8. Sumit Kumar Gautam, R. Suresh, Ved Prakash Sharma, Meena Sehgal. Indoor air quality in the rural India[J]. Management of Environmental Quality: An International Journal, 2013(2): 244-255.
9. Cai Xianglu. Research on new winter ventilation strategies for rural houses in severe cold areas [D]. Dalian University of Technology 2022.DOI: 10.26991/d.cnki.gdllu.2022.000798.
10. General Administration of Quality Supervision, Inspection and Quarantine, Ministry of Health, State Environmental Protection Administration. Indoor air quality standards [S]. (GB/T 18883-2022).