

Optimization research on indoor ventilation mode of cave dwellings in northern Shaanxi

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Abstract: Cave dwelling is a characteristic residential building in northern Shaanxi. It is not only a masterpiece created by local residents in accordance with nature and local cases, but also meets the requirements of green ecology and sustainable development. In order to understand the influence of ventilation on the indoor environment of cave dwellings in northern Shaanxi, a representative traditional cave dwelling was selected as the research object. Based on the meteorological data in Yan'an and the actual measurement of indoor and outdoor thermal parameters, the methods of theoretical analysis, field testing and numerical simulation were adopted to study the indoor airflow distribution of cave dwellings under different ventilation methods, the results show that: the cave dwellings in northern Shaanxi have good thermal insulation performance, and the indoor temperature fluctuation is small; the relative humidity in the cave dwelling is relatively high, which is opposite to the trend of temperature change; reducing the humidity is the ventilation of the cave dwelling. The main task; the indoor wind speed is too small to form effective ventilation. Adjusting the size of the skylight can improve the natural ventilation in summer to optimize indoor ventilation. Through optimization analysis, when the size of the skylight is 0.5m*0.5m, the indoor airflow velocity changes between 0 and 0.3m/s, the ventilation efficiency is high, and the ventilation effect is high. Good, there will be no eddy current in the room, which can effectively remove moisture and enhance lighting, which can provide a basis for the opening of ventilation skylights in new local caves. Effectively improve indoor heat and humidity environment.

Key words: Northern area of Shaanxi, Cave dwelling, ventilation mode, numerical simulation

Introduction

Cave dwelling is a unique residential building in the loess Plateau of northwest China, which has a history of more than 4,000 years. According to *Mozi-Jie yong*, ancient people lived in caves dug under mounds of earth. In the Period of The Yellow Emperor, people began to dig caves to live in. Cave dwellings are still popular in the Loess Plateau because they are warm in winter and cool in summer, simple in c

onstruction and low in cost. According to statistics, there are about 40 million people living in various types of cave dwellings.

Researches on cave dwellings in different aspects have been carried out in China. Z. Yan et al. analyzed the problems caused by the structure of cave dwellings in northern Shaanxi through field investigation, and put forward suggestions for improvement from the structural system, structural requirements and construction process of cave dwellings^[1]. Y. Yan et al. established sky orientation coefficient, sky lighti

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ng correction model and comprehensive illumination formula of working face in the cave by analyzing indoor and outdoor lighting factors of the cave, and put forward renovation measures^[2]. The international joint investigation team composed of Xi'an University of Architecture and Technology and Japan University of Science and Technology, aiming at the relatively backward characteristics of cave dwellings, Traditional cave dwellings are improved by adopting passive solar heating technology and improving poor ventilation in cave dwellings through mechanical ventilation system^[3]. S. Li et al. summarized the thermal process characteristics of courtyard cave dwellings and proposed relevant measures to improve the thermal environment by analyzing the thermal environment of courtyard cave dwellings in northern Shaanxi^[4]. J. Zhao et al from Yan'an analyzed the causes of moisture in cave dwellings in northern Shaanxi through questionnaire visits and field research, and proposed a plan to transform drainage, lighting and ventilation strategies^[5]. Through literature data analysis and field research, Y. Zhu et al. proposed to improve the natural ventilation of traditional cave buildings in northern Shaanxi by using solar chimneys and sunlight beams^[6].

These studies applied a number of modern energy-saving technologies, which effectively improved the problems of insufficient ventilation in cave dwellings. However, it is still difficult to popularize among residents because of its high cost and difficulty in maintenance. Therefore, combined with economy and feasibility, this paper takes a rural household in Huangling County, Yan'an city, Shaanxi Province as the research object, and the indoor ventilation optimization scheme is comprehensively analyzed through investigation, test, and numerical simulation method.

1 Research object, research method and meteorological characteristics

1.1 Subjects

Yan'an city is located in the north of Shaanxi Province, in the middle reaches of the Yellow River and the Central South of the Loess Plateau. It is known as "military stronghold". The selected research object

is Guanzhuang village, Huangling County, Yan'an city. Huangling is located in the south of Yan'an city in central Shaanxi Province. The mausoleum of Yellow Emperor Regulus, the ancestor of the Chinese nation, is located at the top of the bridge Mountain, 1 km north of the county. Huangling governs six to seven township 4 neighborhood offices, a total of 191 administrative villages. The research object is Guanzhuang village in Longfang town. Longfang is the first demonstration town of sanitary toilet reform in Yan'an City. The cottages in the village are neat and uniform, and the roadway is clean and tidy. The folk houses in the village have long been transformed from the original mountain cave into an independent cave, and the founding major general Niu Shushen was born here.



Fig. 1. Cave model

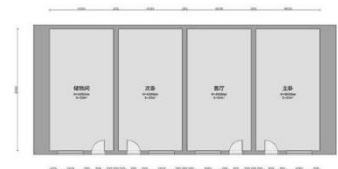


Fig. 2. Cave plan



Fig. 3. Elevation of cave Dwelling

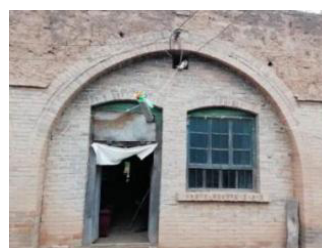


Fig. 4. Local cave dwelling

The research object is a typical representative traditional cave in the village (Fig. 1). The building faces south, with four caves arranged in a row. The ki

Ins are not connected. They are storage room, secondary bedroom, living room and master bedroom in turn (Fig. 2). Each cave is 4m wide, 8m deep and 5 m high (Fig. 3). The doors, windows and skylights are set in the south. The facade of the cave is simple without laying ceramic tiles (Fig. 4), which has a typical style of traditional cave dwellings in Northern Shaanxi.

1.2 Methods

In order to understand the influence of ventilation on the indoor environment of cave dwellings in northern Shaanxi, this paper first designs a practical measurement scheme for yan 'an meteorological data and indoor and outdoor thermal parameters, including the selection of test points and test instruments. Then the temperature and humidity in the summer cave are tested on the spot and the indoor ventilation characteristics are analyzed. Finally, combined with the ventilation theory, simulate different indoor ventilation conditions, study the indoor air distribution of cave under different ventilation modes.

1.3 Meteorological Features

Huangling County has a temperate continental climate with four distinct seasons, sufficient light, mild climate and moderate rainfall. Based on the meteorological statistics of the national basic meteorological observation station from 2011 to 2020, we found that the annual average temperature of Huangling County is 9.4 °C, the hottest average temperature in July is 21.7 °C, and the coldest average temperature in January is minus 4.5 °C. As shown in Figure 5, the annual average wind speed is 3m/s, and the southeast and northwest winds prevail.

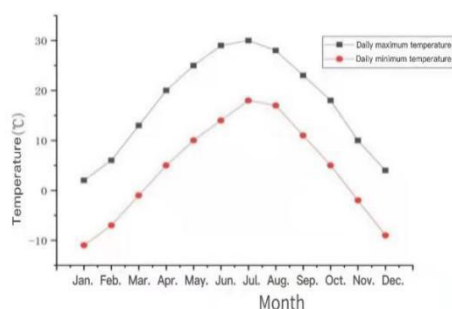


Fig. 5. Annual temperature curve in Huangling County

2 Measured analysis of indoor and outdoor wind environment

2.1 Measurement Scheme

The measurement parameters were indoor and outdoor temperatures from June 4 to June 6, 2020. In order to ensure the accuracy of the measurement data, the outdoor temperature test point is located in the small square in the center of the village; there are two indoor temperature test points, which are 1.5m high in the center of the living room and bedroom. Basic parameters of the measuring instrument are shown in Table 1. During the test, the skylight is open and the doors and Windows are closed.

Table 1. Basic parameters of the test instrument.

The measured parameters	Name and model of instrument	Measurement range and accuracy
Indoor temperature and humidity	Huayi PM 6508 digital hygograph	-20~60°C,±1.0°C;0~100%RH,±3.0%RH
Outdoor temperature and humidity	TESTO 605I temperature and humidity instrument	-20~60°C,±0.5°C;0~100%RH,±3.0%RH
Indoor wind speed	Swedish SwemaAir3000 indoor airflow meter	10~40°C,±0.1°C;0.05~3m/s,±0.03m/s
Outdoor wind speed	TESTO 405V1 thermal anemometer	-20~60°C,±0.5°C;0~30m/s,±0.3m/s

2.2 Measurement results and data analysis

In order to avoid the indoor lag reflected by temperature changes, the data measured on June 5 during the stable period from June 4 to June 6 were selected to analyze the indoor thermal environment of each room. The indoor and outdoor temperature changes on that day are shown in Fig. 6, and the indoor and outdoor relative humidity changes are shown in Fig. 7.

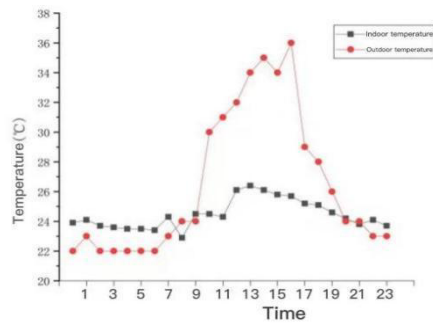


Fig. 6. Indoor and outdoor temperature change Curve

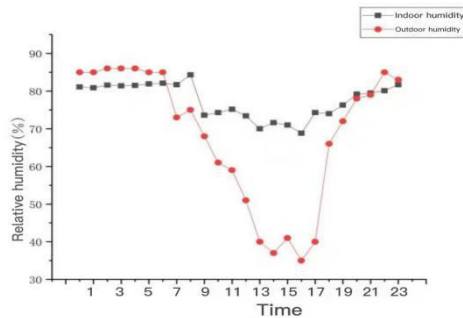


Fig. 7. Indoor and outdoor relative humidity change

As can be seen from Fig. 6, indoor and outdoor air temperature has the same trend of change, rising first and then falling with different amplitude, and outdoor temperature fluctuates greatly. During the day, the outdoor air temperature is higher under the influence of solar radiation, and the heat flow from the outdoor into the indoor, which make the indoor temperature gradually increases. At night, the outdoor temperature is low, and the heat flow from the indoor to the outdoor, which make the indoor temperature gradually decreases. During the test, the range of outdoor temperature was 22 ~ 36°C, and the daily range was 14°C. The temperature reached the peak from 14:00 to 16:00. The range of temperature inside the cave was 23.4 ~ 26.4°C, and the average temperature was 24.5°C, and the daily range was 3°C. The temperature difference between indoor and outdoor is -1.9 ~ 10.3°C. When the outdoor temperature is at its lowest, the temperature difference between indoor and outdoor is -1.9°C. When the outdoor temperature is at its highest, the temperature difference between indoor and outdoor is 10.3°C, which reflects the thermal insulation performance of the cave. Regardless of the outdoor temperature, the temperature in the cave meets the requirements of thermal comfort all day long, there is no need for other cooling measures in the cave.

It can be seen from Fig. 7 that the indoor and outdoor relative humidity changes in the same rule. The outdoor humidity ranges from 35% to 86%, and the average relative humidity is 68.4%. The minimum humidity appears at 16:00 and the maximum humidity at 4:00; The cave humidity varies from 68.8% to 82.1%, and the average relative humidity is 77.4%; The change of indoor and outdoor relative humidity is opposite to the law of temperature change, the relative humidity decreases when the temperature increases, and the relative humidity increases when the temperature decreases. According to the thermal comfort requirements recommended in the provisions on the determination of PMV and PPD indexes and thermal comfort conditions in moderate thermal environment, the indoor air relative humidity of civil buildings in China should be maintained at the limit of 30% ~ 70%. It can be seen that the humidity in cave dwellings in summer is a serious problem. In addition to regulating the temperature and humidity of the air entering the room, it can be considered to strengthen the ventilation of the inner wall of the enclosure structure to prevent condensation.

3 Ventilation simulation and ventilation mode optimization

3.1 Working condition setting

Based on the comprehensive analysis of the above test contents and results, it can be seen that the indoor temperature in Northern Shaanxi is relatively suitable in summer, and no other cooling measures are required. Only by solving the problems of insufficient ventilation and humid environment in the cave, the living comfort of residents can be improved. In order to improve the air quality inside the cave, improve the air fluidity inside the cave and solve the problem of humidity in the cave, according to the survey, 87% of the residential caves in this area use 1.5m*1.6m push-pull aluminum alloy windows, with a maximum air inlet area of 1m*0.8m and a skylight size of 0.2m*0.2m, without any shielding. The skylight size of 13% of residents' cave is 0.3m*0.3m, and there is no shelter. Based on the working conditions shown in Table 2, the ventilation simulation o

f the cave building is studied in this paper.

Table 2. Setting table of simulated working cases.

	Skylight opening size	Air intake area of window	Position of air inlet	Power of ventilation
1	0.2m*0.2m	1m*0.8m	South side of cave dwelling	Natural ventilation
2	0.3m*0.3m	1m*0.8m	South side of cave dwelling	Natural ventilation
3	0.4m*0.4m	1m*0.8m	South side of cave dwelling	Natural ventilation
4	0.5m*0.5m	1m*0.8m	South side of cave dwelling	Natural ventilation
5	Add exhaust fan	1m*0.8m	South side of cave dwelling	Mechanical ventilation

3.2 Numerical Simulation

3.2.1 Model, boundary conditions and meshing

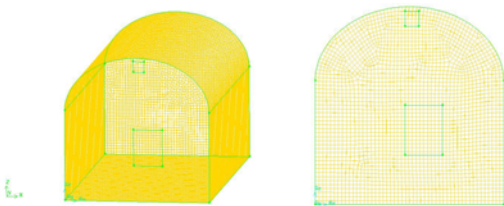


Fig. 8. Grid diagram of single cave

A 1:1 cave model is established, with the dimension s of width X=4m length Y=8m and height Z=4m.As shown in Fig. 8, Due to the irregular shape of the cave, the mesh is mainly hexahedral mesh units, a nd wedge-shaped grids at appropriate positions. The inlet is defined as the velocity inlet boundary condition, the outlet is defined as the free flow boundary condition, and the ground, roof and wall are defined as the wall without sliding. After importing the model into fluent and checking the grid information, turn on the energy equation, and the air flow state is turbulence. Therefore,the turbulence model was used in this simulation to make the calculation more accurate,and select $k-\epsilon$ equation. The setting boundary is as follows: the air inlet velocity is set as the average outdoor wind speed of 1.6m/s in summer, and the temperature is set as the calculated outdoor temperature of 28.2°C in summer. The ground is set to constant temperature and the remaining walls are

set to coupling mode.

3.2.2 Velocity vector diagram of each working case

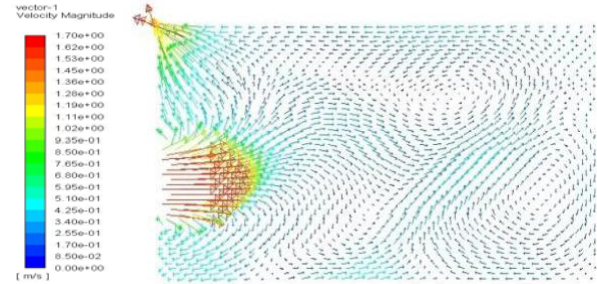


Fig. 9. Velocity vector diagram of the plane X=2 in working case 1

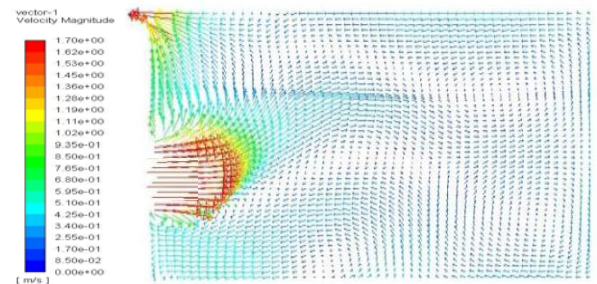


Fig. 10. Velocity vector diagram of the plane X=2 in working case 2

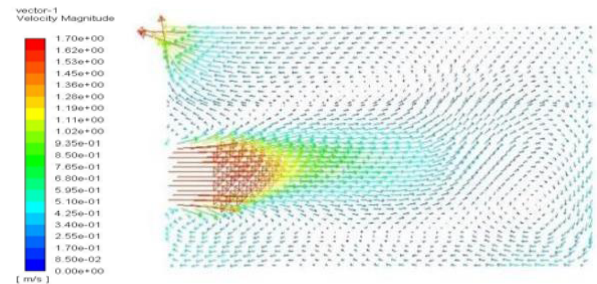


Fig. 11. Velocity vector diagram of the plane X=2 at working case 3

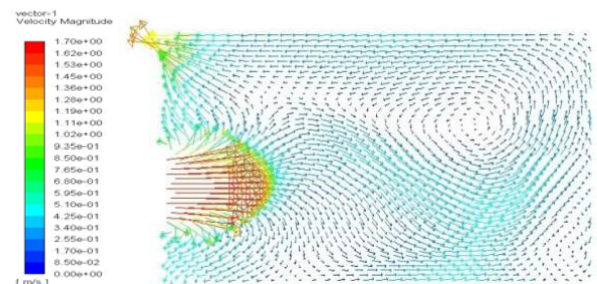


Fig. 12. Velocity vector diagram of the plane X=2 at working case 4

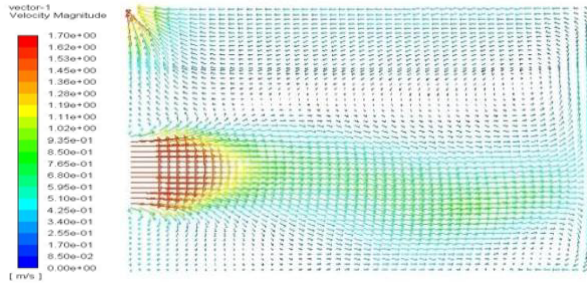


Fig. 13. Velocity vector diagram of the plane X=2 at working case 5

Fig. 9-13 shows the characteristic velocity vectors of simulation calculation for each working case.

It can be seen from Fig. 9 that the air flow distribution in the kiln is chaotic and it is difficult to form regular indoor air flow. Part of the wind coming in from the window flows to the skylight, and the rest forms multiple eddies in the middle and rear of the cave. The retention area of dirty gas in the room is large and the retention time is long, which is not conducive to the exchange of indoor and outdoor air, and the wind environment is poor.

It can be seen from Fig. 10 that the air distribution in the kiln is uneven, the vortex in the middle of the kiln is improved, and the air flow at the back of the kiln is still in circular motion which result in local turbulence in the corner, low ventilation efficiency and poor ventilation quality.

As can be seen from Fig. 11, part of the wind coming in from the window flows to the skylight, and part moves in a circular way along the back wall of the cave, forming a vortex which make people more comfortable. With the increase of depth, the wind speed decreases, and a vortex is formed at the back of the cave. The dirty gas cannot flow to the window, which can not improve the flooding at the back of the cave. Over time, bacteria will breed and affect the health of residents.

As can be seen from Fig. 12, the smooth air ventilation path is clear, the flow frequency is high and the indoor air renewal frequency is fast, which can strengthen the convection and evaporative heat dissipation of human body, enhance the thermal comfort of human body and improve the indoor air quality.

It can be seen from Fig. 13 that exhaust fans can promote the flow of the overall indoor wind field,

which has the highest ventilation efficiency and the best ventilation effect. It can not only reduce the room temperature and effectively eliminate moisture, but also ensure the normal climate conditions and fresh air.

3.2.3 Comparative analysis of results

As shown in Fig.14 and 15, take the wind speed cloud map with a height of 1.1m from the ground under various working conditions for analysis.

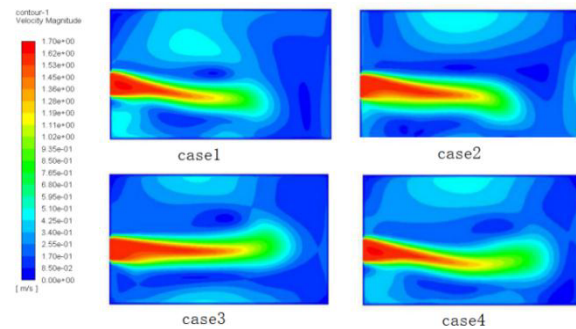


Fig. 14. Velocity distribution cloud of z=1.1 plane in working cases 1 to 4

It can be seen from Fig. 14 that the wind speed decreases gradually with the increase of depth after adjusting the skylight size. The indoor average wind speed is correlated with the size of skylight window area. When the skylight area is 0.5m*0.5m, the indoor average wind speed is 0.3m/s, which effectively solves the problems of poor ventilation, poor air quality and rear flood in cave dwellings. The ventilation efficiency of human living areas is high, which is beneficial to health.

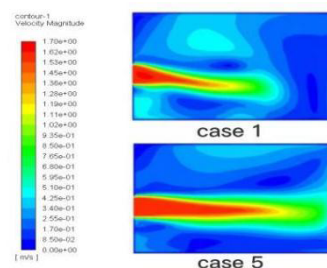


Fig. 15. Velocity distribution cloud in the plane z=1.1 under working case 1 and 5

As can be seen from Fig. 15, the air flow frequency becomes high and the indoor air renewal frequency becomes fast after the installation of exhaust fan. The calculated average indoor wind speed is 0.43 m/s, and people have a strong sense of blowing air. Therefore, the exhaust fan can be opened when neces

sary to improve the indoor air environment.

4 Conclusion

The cave in northern Shaanxi has thick walls and roofs, which can prevent hot air from entering in summer. It is warm in winter and cool in summer, giving full play to the dual functions of soil heat insulation and heat storage. However, the cave is ventilated on one side and has a long depth. The indoor daylighting is poor and the ventilation is not smooth, and the back is prone to flooding. In order to improve the living comfort, the paper analyzes the indoor ventilation characteristics through meteorological data and actual measurement, combined with the ventilation theory and simulates the indoor ventilation, and draws the main conclusions as follows:

1) For newly built caves, the skylight size can be adjusted to 0.5m*0.5m, while other structures remain unchanged, which can not only improve the indoor ventilation efficiency, improve the flood phenomenon at the back of the cave, but also strengthen the indoor lighting and improve the thermal comfort of human body.

2) For existing cave dwellings, exhaust fans can be installed in the skylight outlet, which can also improve the indoor air environment, effectively eliminate moisture and be beneficial to health.

These two methods can not only settle the problem of insufficient ventilation and damp environment in cave dwellings, but also be easy to operate and low cost. It can be promoted in the residents from the analysis of economy and feasibility.

References:

- [1] Z. Yan, H. Yang. Discussion on Problems and Solutions of Cave Dwelling in Northern Shaanxi. *LTAT*, **35**, 25-26 (2013) (in Chinese)
- [2] Y. Yan, Z. Zhao, S. Zhao. Research on Daylighting Factors of Cave Dwelling and Its Improvement Measurements. *Building science*, **27**, 33-37 (2011) (in Chinese)
- [3] Y. Wang, Q. Zhao, M. He, L. Yang, J. Liu. The Study on indoor Environment of old and New Cave Dwellings. *Journal of Xi'an University of Architecture and Technology (Natural Science Edition)*, **4**, 309-312 (2001) (in Chinese)
- [4] S. Li, Y. Fu, G. Wang, Y. Zhang. Analysis on thermal Environment characteristics of courtyard Cave dwelling in northern Shaanxi Province. *Management and Technology of Small and Medium-sized Enterprises (Mid-day)*, **4**, 165-166 (2014) (in Chinese)
- [5] J. Zhao, R. Yang, D. Li. Analysis on the causes and reform measures of cave dampness in northern Shaanxi Province. *Shanxi Architecture*, **46**, 13-14 (2020) (in Chinese)
- [6] Y. Zhu, L. Zhang, L. Xi. Exploration on the Ventilation Design Strategies of Cave Dwelling Construction in Northern Area of Shaanxi Province. *Central China Architecture*, **30**, 84-86 (2012) (in Chinese)