Optimization research on indoor ventilation mode of cave d wellings in northern Shaanxi

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Abstract: Cave dwelling is a characteristic residential building in northern Shaanxi. It is not onl y a masterpiece created by local residents in accordance with nature and local cases, but also m eets the requirements of green ecology and sustainable development. In order to understand the in fluence of ventilation on the indoor environment of cave dwellings in northern Shaanxi, a represe ntative 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 ai rflow 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 te mperature 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 ca ve dwelling. The main task; the indoor wind speed is too small to form effective ventilation. Adj usting 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 ventila tion effect is high. Good, there will be no eddy current in the room, which can effectively remov e moisture and enhance lighting, which can provide a basis for the opening of ventilation skylight s 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 hist ory of more than 4,000 years.According to *Mozi-Jie yong*,ancient people lived in caves dug under mound s of earth.In the Period of The Yellow Emperor, pe ople began to dig caves to live in. Cave dwellings are still popular in the Loess Plateau because they a re 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 t ypes of cave dwellings.

Researches on cave dwellings in different aspects have been carried out in China. Z. Yan et al. anal yzed the problems caused by the structure of cave d wellings in northern Shaanxi through field investigati on, and put forward suggestions for improvement fr om 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 i ndoor and outdoor lighting factors of the cave, and put forward renovation measures[2]. The international joint investigation team composed of Xi 'an Univer sity of Architecture and Technology and Japan Univ ersity of Science and Technology,aiming at the relati vely backward characteristics of cave dwellings, Tra ditional cave dwellings are improved by adopting pa ssive solar heating technology and improving poor v entilation in cave dwellings through mechanical venti lation system[3]. S. Li et al. summarized the thermal process characteristics of courtyard cave dwellings and proposed relevant measures to improve the ther mal environment by analyzing the thermal environm ent 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 t hrough questionnaire visits and field research, and p roposed a plan to transform drainage, lighting and v entilation strategies[5]. Through literature data analysi s and field research,Y. Zhu et al. proposed to impro ve the natural ventilation of traditional cave building s in northern Shaanxi by using solar chimneys and sunlight beams[6].

These studies applied a number of modern energ y-saving technologies, which effectively improved th e problems of insufficient ventilation in cave dwellin gs. 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 Hua ngling County, Yan 'an city, Shaanxi Province as the research object,and the indoor ventilation optimizati on scheme is comprehensively analyzed through inve stigation, 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 Prov ince, 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 cit y in central Shaanxi Province.The mausoleum of Yel low Emperor Regulus, the ancestor of the Chinese n ation, is located at the top of the bridge Mountain, 1 km north of the county. Huangling governs six to wn township 4 a neighborhood offices, a total of 19 1 administrative villages. The research object is Gua nzhuang 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 fo lk houses in the village have long been transformed from the original mountain cave into an independe nt cave, and the founding major general Niu Shushe n was born here.

Fig. 1. Cave model

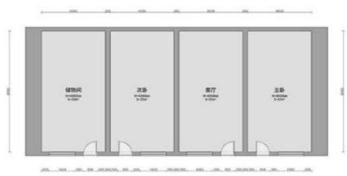

Fig.2. Cave plan

Fig. 3. Elevation of cave Dwelling

Fig. 4. Local cave dwelling

The research object is a typical representative tra ditional cave in the village(Fig. 1). The building fac es south, with four caves arranged in a row. The ki lns are not connected. They are storage room, secon dary bedroom, living room and master bedroom in t urn (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 simp le without laying ceramic tiles (Fig. 4), which has a typical style of traditional cave dwellings in Northe rn 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 climat e with four distinct seasons, sufficient light, mild cli mate and moderate rainfall. Based on the meteorolo gical statistics of the national basic meteorological o bservation station from 2011 to 2020, we found that the annual average temperature of Huangling Count y is 9.4 ℃, the hottest average temperature in July is 21.7 ℃, and the coldest average temperature in J anuary is minus 4.5 ℃. As shown in Figure 5, the annual average wind speed is 3m/s, and the southea st and northwest winds prevail.

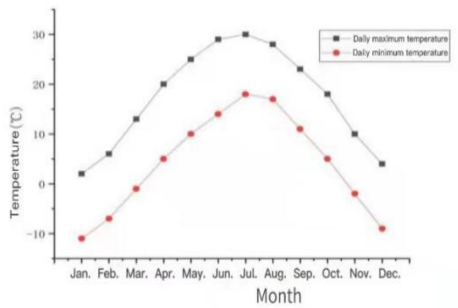

Fig. 5. Annual temperature curve in Huangling County

2 Measured analysis of indoor and o utdoor wind environment

2.1 Measurement Scheme

The measurement parameters were indoor and outdo or temperatures from June 4 to June 6, 2020.In ord er 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 t wo indoor temperature test points, which are 1.5m h igh in the center of the living room and bedroom. Basic parameters of the measuring instrument are sh own 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	Measuremet range and accuracy
Indoor temperature and humidity	Huayi PM 6508 digital hygrograph	-20~60°C,±1.0°C;0 ~100%RH,±3.0%R H
Outdoor temperature and humidity	TESTO 605I temperature and humidity instrument	-20~60°C,±0.5°C;0 ~100%RH,±3.0%R H
Indoor wind speed	Swedish SwemaAir3000 indoor airflow meter	10~40°C,±0.1°C;0.0 5~3m/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 temper ature changes, the data measured on June 5 during t he stable period from June 4 to June 6 were selecte d 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 a nd outdoor relative humidity changes are shown in Fig. 7.

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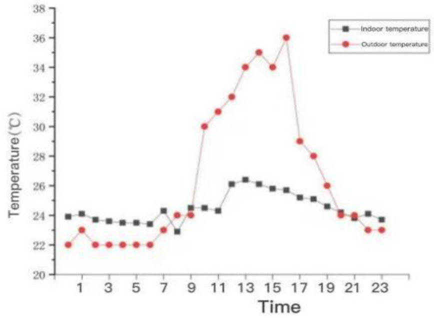

Fig. 6. Indoor and outdoor temperature change Curve

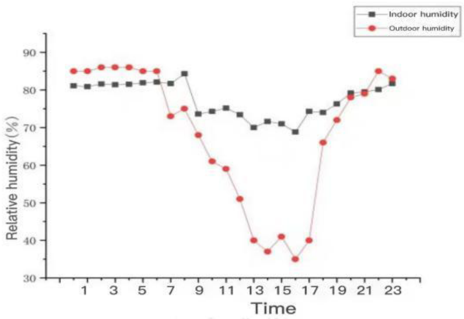

Fig. 7. Indoor and outdoor relative humidity change

As can be seen from Fig. 6, indoor and outdoor air temperature has the same trend of change, risin g first and then falling with different amplitude, and outdoor temperature fluctuates greatly.During the da y, the outdoor air temperature is higher under the in fluence of solar radiation, and the heat flow from th e outdoor into the indoor, which make the indoor te mperature gradually increases. At night, the outdoor temperature is low, and the heat flow from the indo or to the outdoor, which make the indoor temperatur e gradually decreases.During the test, the range of o utdoor temperature was 22 ~ 36℃, and the daily ra nge was 14℃. The temperature reached the peak fr om 14:00 to 16:00 . The range of temperature insid e the cave was 23.4 ~ 26.4℃, and the average tem perature was 24.5℃, and the daily range was 3℃.T he temperature difference between indoor and outdoo r is -1.9 ~ 10.3℃. When the outdoor temperature is at its lowest, the temperature difference between in door and outdoor is -1.9℃. When the outdoor temp erature is at its highest, the temperature difference b etween indoor and outdoor is 10.3℃, which reflects the thermal insulation performance of the cave.Reg ardless of the outdoor temperature, the temperature i n the cave meets the requirements of thermal comfo rt 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 o utdoor relative humidity changes in the same rule. T he outdoor humidity ranges from 35% to 86%, and the average relative humidity is 68.4%. The minimu m humidity appears at 16:00 and the maximum hum idity 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 hum idity is opposite to the law of temperature change, t he 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 provision s on the determination of PMV and PPD indexes an d thermal comfort conditions in moderate thermal en vironment, 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 i n cave dwellings in summer is a serious problem. I n addition to regulating the temperature and humidit y of the air entering the room, it can be considered to strengthen the ventilation of the inner wall of th e enclosure structure to prevent condensation.

3 Ventilation simulation and ventilatio n mode optimization

3.1 Working condition setting

Based on the comprehensive analysis of the above t est contents and results, it can be seen that the indo or temperature in Northern Shaanxi is relatively suit able in summer, and no other cooling measures are required. Only by solving the problems of insufficie nt ventilation and humid environment in the cave, t he living comfort of residents can be improved. In order to improve the air quality inside the cave, im prove the air fluidity inside the cave and solve the problem of humidity in the cave, according to the s urvey, 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 skyli ght size of 0.2m*0.2m, without any shielding. The s kylight size of 13% of residents' cave is 0.3m*0.3m, and there is no shelter. Based on the working cond itions 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 dewelling	Natural ventilation
2	0.3m*0.3m	1m*0.8m	South side of cave dewelling	Natural ventilation
3	0.4m*0.4m	1m*0.8m	South side of cave dewelling	Natural ventilation
4	0.5m*0.5m	1m*0.8m	South side of cave dewelling	Natural ventilation
5	Add exhaust fan	1m*0.8m	South side of cave dewelling	Mechanical ventilation

3.2 Numerical Simulation

3.2.1 Model, boundary conditions and meshing

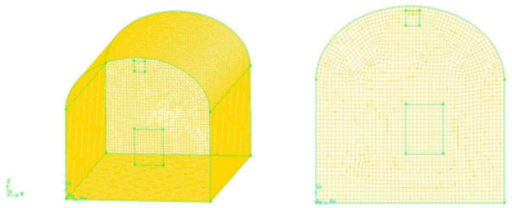

Fig. 8. Grid diagram of single cave

A 1:1 cave model is established, with the dimensions 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, and 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 $k-\varepsilon$ 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℃ 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

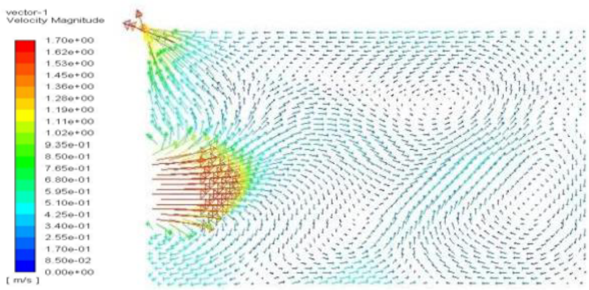

Fig. 9. Velocity vector diagram of the plane X=2 in working case 1

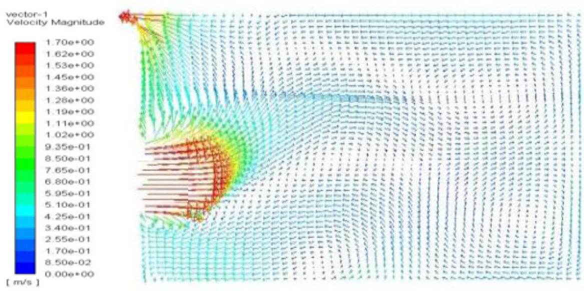

Fig. 10. Velocity vector diagram of the plane X=2 in working case 2

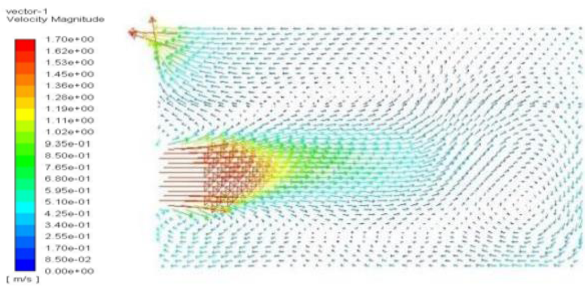

Fig. 11. Velocity vector diagram of the plane X=2 at working case 3

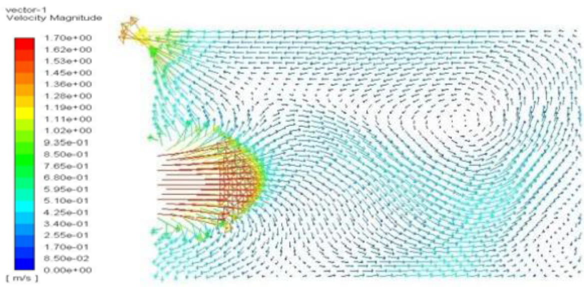

Fig. 12. Velocity vector diagram of the plane X=2 at working case 4

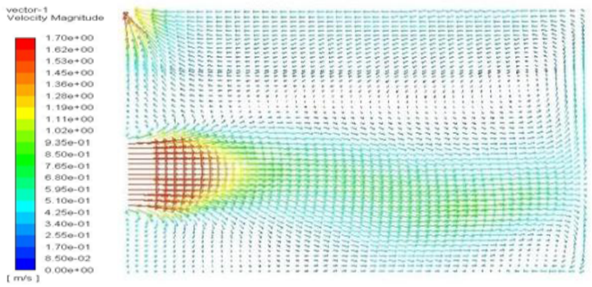

Fig. 13. Velocity vector diagram of the plane X=2 at working case 5

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 dist ribution in the kiln is chaotic and it is difficult to f orm 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 o f the cave. The retention area of dirty gas in the ro om is large and the retention time is long, which is not conducive to the exchange of indoor and outdo or air, and the wind environment is poor.

It can be seen from Fig. 10 that the air distribut ion in the kiln is uneven, the vortex in the middle of the kiln is improved, and the air flow at the bac k of the kiln is still in circular motion which result in local turbulence in the corner, low ventilation ef ficiency and poor ventilation quality.

As can be seen from Fig. 11, part of the wind c oming in from the window flows to the skylight, an d 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 w ind 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 ve ntilation path is clear, the flow frequency is high an d the indoor air renewal frequency is fast, which ca n strengthen the convection and evaporative heat dis sipation of human body, enhance the thermal comfor t of human body and improve the indoor air quality.

It can be seen from Fig. 13 that exhaust fans ca n 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 ro om temperature and effectively eliminate moisture,bu t also ensure the normal climate conditions and fres h air.

3.2.3 Comparative analysis of results

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

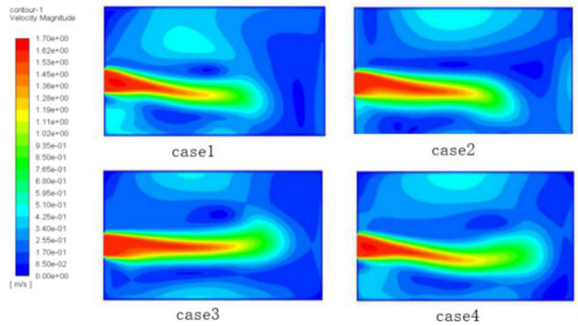

Fig. 14. Velocity distribution cloud of z=1.1 plane in working cases 1 to 4

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.

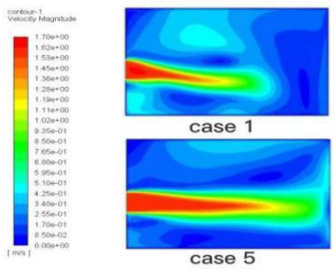

Fig. 15. Velocity distribution cloud in the plane z=1.1 under working case 1 and 5

As can be seen from Fig. 15, the air flow frequ ency becomes high and the indoor air renewal frequ ency becomes fast after the installation of exhaust f an.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 r oofs, which can prevent hot air from entering in su mmer. It is warm in winter and cool in summer, gi ving full play to the dual functions of soil heat insu lation and heat storage.However, the cave is ventilat ed on one side and has a long depth. The indoor d aylighting is poor and the ventilation is not smooth, and the back is prone to flooding. In order to imp rove the living comfort, the paper analyzes the indo or ventilation characteristics through meteorological d ata and actual measurement, combined with the vent ilation theory and simulates the indoor ventilation, a nd draws the main conclusions as follows:

1) For newly built caves, the skylight size can b e adjusted to 0.5m*0.5m, while other structures rem ain unchanged, which can not only improve the ind oor ventilation efficiency, improve the flood phenom enon at the back of the cave, but also strengthen th e indoor lighting and improve the thermal comfort o f human body.

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

These two methods can not only settle the probl em 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 t he analysis of economy and feasibility.

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