Analysis of Winter Indoor Thermal Environment of Rural Dwellings in the Areas with Rich Solar Energy

Yiyun Zhu[1,a], Miaomeng Liang[1,b], Guochen Sang[1], Qin Zhao[1], Qun Zhang[2]

[1]School of Civil Engineering and Architecture, Xi'an University of Technology , xi'an, 710048 China.

[2]School of Architecture, Xi'an University of Architecture and Technology, xi'an, 710055, China.

[a]zyyun@xaut.edu.cn, [b]13209100105@163.com

Key Words: the areas with rich solar energy, rural dwelling, indoor thermal environment, passive solar energy technology

Abstract：Taking the rural dwellings in the areas with rich solar energy in Zhongwei of Ningxia as a research example, through on-the-site survey and field-test, the paper analyzes the effects of space layout, the construction of envelope and the method of heating on winter indoor thermal environment. The results show that the solar energy resources are rich in local areas, nevertheless, the unreasonable space layout, simple construction of envelope as well as the lower solar energy utilization in existing dwellings have led poor winter indoor thermal environment. Based on the local natural conditions and climate characteristics, in consideration of full use of solar energy resources, the paper proposes the improvement of energy saving for the traditional dwellings, offers some references for the construction of local dwellings.

Introduction

With the rapid development of construction of new countryside, the total energy-using of rural buildings in China has reached to 320 million tec. The heating energy consumption per unit area of rural dwellings in northern areas has exceeded the dwellings in urban areas[1], the problem of energy consumption becomes increasingly severe. Along with the improvement of habitat and living in rural areas, the demand of rural residents for the thermal comfort of dwellings is increasing, thus, making the energy consumption of rural buildings further intense[2,3,4]. The development and utilization of renewable resources is one of the ways to resolve the energy problems, which is also the main way to realize low energy consumption of dwellings [5,6,7]. There are plentiful renewable resources in rural areas, and how to fully use the renewable resources (especially the solar energy) to meet the demand of indoor thermal environment of dwellings has been the main project in present design and research for rural dwellings, which also has significant meanings for rural dwellings to realize the sustainable development [8,9].

Zhongwei city of Ningxia Autonomous Region is located in the junction of three provinces and regions of Ningxia, Gansu and Inner Mongolia, the city neighbors the margin of Tenger desert in the north, with loess hills and gullies in the south, and in the middle it is the Weining plain where the Yellow rive flows through, the city has semi-arid climate, summer is short and hot, winter is long and cold, it also suffers the strong wind and more sand, the weather is dry and rainless, thus, the city owns the characteristics of typical continental monsoon climate as well as desert climate, also belongs to the regions in China where the economy is underdeveloped. In the region the annual average temperature is 10℃, and annual precipitation is 138mm, annual evaporation is 1729.6mm, the total amount of annual average solar radiation is 6000MJ·m^{-2}·a^{-1}, the annual sunshine is 3796.1h[10], accordingly, the solar energy resources are very rich. Influenced jointly by local historical context, residents' lifestyle and regional resources environment, the traditional civilian dwellings have its regional features. Nevertheless, along with the development of rural economy and the change of production and lifestyle, the dwellings have not adapted to the modern production and lifestyle, among the self-built dwellings the type is just a simple copy of urban buildings, leading to the increase of energy consumption and the unsatisfactory thermal environment of dwellings, the residents in the rural areas consider that in order to improve the indoor thermal environment they just need to use plenty of coal or electricity to increase the indoor temperature. They have no consciousness of energy saving, and are not aware of the utilization of renewable resources; the type of dwellings has no adaptability to the characteristics of regional climate as well as the promotion in construction with advanced building technology, which has affected seriously the development of rural construction. Through the survey and on-the-site test conducted by the research team, the paper analyzes the existing problems of Zhongwei rural dwellings in construction type, envelope, and indoor thermal environment, heating method as well as heating energy consumption. By the test and analysis of indoor thermal environment of dwellings, combing with the local climate conditions and natural recourses and on the basis of fully using solar energy resources [11,12], the paper proposes the design plan for energy saving, and provides references for the healthy development of construction in new countryside.

Survey on Dwellings Type and Subjective Thermal Sensation

The site for survey and test is located at the Heilin village 9.5 km in due west of Zhongwei city. The research team conducted questionnaires and on-the-site test for the dwellings in Heilin village in midmonth of Jan, 2015.

Dwelling Type and Wall Materials

It has been found by survey that the earth dwellings built in early 1980s, the earth-solid brick dwellings built in 1990s and the brick-concrete dwellings build presently are mainly existed in Zhongwei. The layout of villages and the shape characteristics of dwellings have been affected by the natural climate and geographic features, the dwellings are mainly the south-facing ones with one-floor and single depth, the main rooms are: hall, bedroom, kitchen, and utility room, etc., the floor height is 3.3m.

Lots of dwellings in the village are earth dwellings (as shown in Fig.1), they are saucer-shaped in plan form, and reflect unidirectional room layout and large shape coefficient. The hall is facing the south; the other rooms are facing the east or west. The exterior walls of the dwellings towards the east, west, and the north are earth walls 600mm thick, the walls facing the south are earth walls 370mm thick; the windows towards the south are wooden frame and single layer casement windows, the window size is small, which is not beneficial to obtain more solar irradiation, half of the panes of the windows are installed with glass, another half of panes are covered with plastic cloth, there are larger gaps existing between wall and the frame of windows, thus, leading to severe cold wind infiltration in winter. The roof is flat, in construction of the roof, rafters are placed directly on wood beams, reeds are laid above, yellow mud is spread on the reeds, and total thickness is smaller. The floor is built with cement, the construction of envelope is rather simple with large heat transfer coefficient. In each household, heating facilities are only installed in the hall, heating method is just to use stove and heated Kang (i.e. heated brick bed), burning materials are mainly firewood for the heated Kang and coal for the stove, as a result, the efficiency of energy utilization is lower, and energy consumption is larger, simultaneously, indoor air quality is poor. In winter the hall is a main room for family members to do some activities; including cooking, treating as dining room, therefore, its functions are too concentrated, functional partitioning is not clear and definite; the toilet is built outside of the room and in the open, frequently opening and shutting the door to go to the toilet will lead to the loss of heat, and the functions of room are not connected close.

(a) Outdoor (b) Indoor

Fig.1 Traditional earth civilian dwelling

Subjective Sensation of Indoor Thermal Comfort

The survey for subjective sensation of indoor thermal comfort is carried out separately during the day and at night, in daytime the percentages for sensation of being cold, a little cold and moderate are respectively 43.5%, 52.2%, 4.3%. at night the percentages for sensation of being cold, a little cold, and moderate are respectively 26.1%, 56.5%, 17.3%. The number of people who feel cold and a little cold accounts for the majority, which indicates that the residents have poor satisfaction to the indoor thermal environment under the local temperature and environment in winter.

Analysis of Dwellings Thermal Environment

In order to obtain further data of indoor thermal environment of local earth dwellings, the research team made the test on indoor and outdoor thermal environment for a local dwelling at 10:00 on the 16th to 10:00 on the 17th of Jan. 2015, the testing points were laid as shown in Fig.2, and then the local solar radiation was tested at 8:00 to 18:00 on the 19th of Jan. 2015.

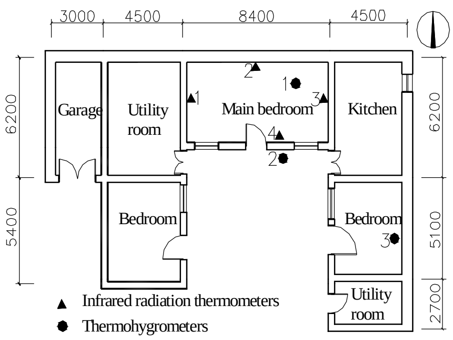

Fig.2 Floor plan of traditional civilian dwelling

Analysis of Indoor and Outdoor Air Temperature and Mean Radiation Temperature (MRT)

The high-accuracy 175-H1 thermograph and hygrograph is adopted to test the temperature and humidity of air, indoor instruments are placed above the floor 1.5m, outdoor instruments are laid in the shade with good ventilation and without effects of light and heat sources, the time interval for recording is 10min. Aged people often live in most of the local earth dwellings, the heated Kang and the stove are installed in the hall, the aged people usually receive visitors, take meals and sleep, for a occasion children of the aged people come to see them, they live in the second bedroom, therefore, the hall and the second bedrooms are chosen for test.

The test data of indoor and outdoor air temperature is shown as Fig.3, it can be found that the indoor and outdoor air temperatures have a larger wave, the average value is 1.0℃, in which the highest temperature appears at 16:00, the value is 20.2℃,the lowest temperature emerges at 6:00, the value is -5.4℃, the curve of temperature in the hall is mild comparatively, the average air temperature is 12.12℃ , the highest temperature appears at 15:00, the value is 17.1℃,the lowest temperature appears at 8:00, the value is 7.3℃, the curve of temperature in the second bedroom with out solar irradiation and heating facilities is gentle, the average temperature of air is -1.6℃, which is lower 2.6℃ than the outdoor temperature. It can be obtained from the references [13,14 , 15] that indoor temperature of earth dwelling is lower, indoor thermal environment is poorer; affected by solar irradiation, the temperature in the rooms facing the south is higher, the others is much lower, which hasn't far met the demand of human body for thermal comfort. Accordingly, the solar irradiation has a larger effect on room temperature, so the effective and reasonable utilization of solar energy can be adopted to improve the indoor thermal environment.

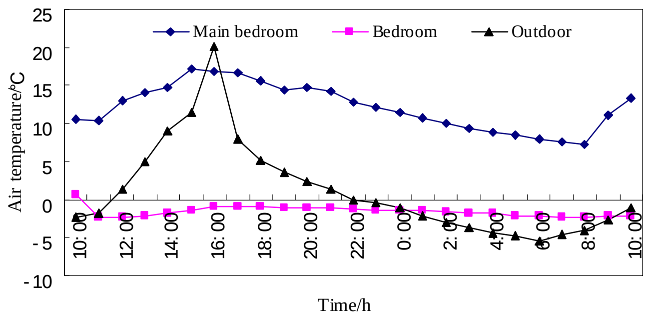

Fig.3 Air temperature of outdoor and indoor of civilian dwelling

The mean radiation temperature is calculated by wall surface temperature. The test instrument for wall surface temperature is 803-T4 infrared thermometer; testing points are set up in the middle positions of exterior and interior wall surfaces, and the middle of the roof and the floor. Three testing points around the surface geometric centre are selected separately; the average value is obtained and recorded every 1h.

The indoor MRT is the surface temperature of black body, which is measured at a certain indoor point surrounding by the wall surface around or the other emitting surfaces, and has the same amount of heat emitted by these emitting surfaces. The MRT has a very important effect on indoor thermal comfort [16], the reference [17] points out that in indoor climate when the air temperature differs greatly from the temperature of wall surfaces around, the effect of heat radiation will be much larger, then, coming out the problem of mean radiation. Thus, comparative analysis can be conducted between air temperature and MRT. The MRT can be calculated as the following formula1:

$$MRT = \frac{t_1 S_1 + t_2 S_2 + \cdots + t_n S_n}{S_1 + S_2 + \cdots + S_n} \quad (1)$$

Where: t_1、t_2、…、t_n are every surface temperatures; S_1、S_2、…、S_3 are every surface areas. Fig.4 shows the calculation results:

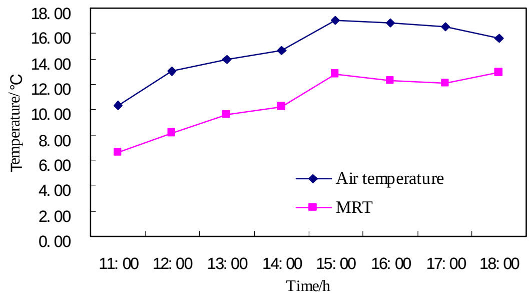

Fig.4 MRT and air temperature of civilian dwelling

It can be found from Fig.4 that the average value of MRT (11:00-18:00) is 10.59℃,the average value of indoor air temperature (11:00-18:00) is 14.78℃, obviously, both has a big difference, so in the areas of Zhongwei, the envelope has a great cold radiation to human body, the MRT reflects more effect on indoor thermal comfort, as a result, the abilities of insulation and heat storage of envelope should be strengthened.

Analysis of relative humidity of indoor and outdoor air

The change of relative humidity of indoor and outdoor air is shown as Fig.5. The average value of relative humidity of outdoor air is 33.4%, the wave amplitude is 38%. The average value of air relative humidity in the hall is 39.1%, wave amplitude is 17.6%, and in the second bedroom, the average value of air relative humidity is 38.9%, wave amplitude is 16.1%. The air relative humidity has approached to the lower limit of comfort humidity for human body[17], the air in the room is dry.

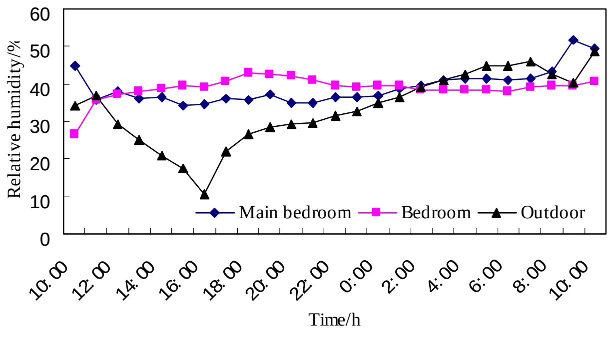

Fig.5 Relative humidity of outdoor and indoor of civilian dwelling

Analysis of Solar Radiation Intensity

The testing instrument for solar radiation intensity is JTDL-4 actinometer, the instrument is placed outside without any shielding around, channel CH4 is for total radiation intensity, sensitivity coefficient is 12.470μV/(W·m^2); channel CH3 is for scattered radiation intensity, sensitivity coefficient is 12.958μV/(W·m^2). It's sunny on testing day, the sun rose at 8:25, and set at 17:56, the time of sunshine was 11.5 hours.

The data of solar radiation are shown as Fig.6, the average value of total solar radiation in whole day is 344.8W/m^2, peak value appears at about 13:00, the value is 548.2 W/m^2. Thus, it can be explained that the solar radiation intensity is higher, and the time of sunshine is longer in winter in Zhongwei, the solar energy resources are very rich, accordingly, the passive solar energy design strategy can be more considered when designing and constructing the local dwellings. Nevertheless, the earth dwelling is usually saucer-shaped in plan form, and only the hall is designed facing the south, besides, the windows facing the south are smaller in size, which is not beneficial for solar heat gain[18]. There is only one household to install the solar water heater in the whole village, which is only one form in local areas for active utilization of solar energy, therefore, the utilization rate of solar energy is lower.

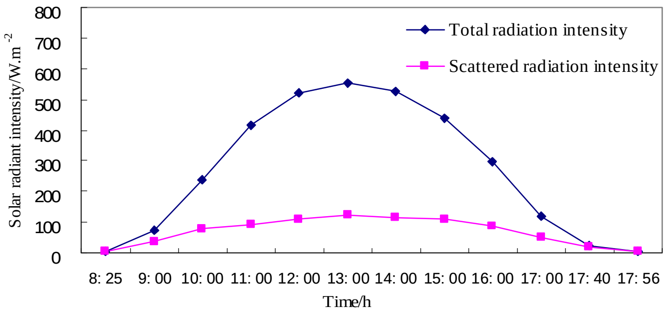

Fig.6 Outdoor solar radiation intensity

It can be obtained through the analysis of testing data above that indoor air temperature, and indoor MRT both are lower, the air is dry, indoor thermal comfort is poorer. The solar radiation intensity in local areas is higher yet, accordingly, solar energy can be fully used to improve indoor thermal environment.

Improved Strategies for New Type and Energy Saving Rural Dwellings Based on the Utilization of Solar Energy

Traditional civilian dwellings usually inherit regional culture, its architecture styles fit local natural environment and demands of function, fully using the conditions of local climate and natural resources should be inherited and developed in the process of developing modern rural dwellings. Consequently, when designing the new type rural dwellings, the advantages of traditional dwellings should be absorbed and, then the utilization of solar energy should be regarded as starting point, the principles and methods of architecture design, architecture climate and structure must be employed comprehensively, thus, new type rural dwellings which can meet the demands of contemporary village can be designed.

Through survey, on-the-site test and analysis, it has been found that local residents have had the abilities to adapt to regional climate in many aspects, but, as solar energy can not be used effectively, the plan layout of dwelling is not reasonable, the envelope has poor thermal performance either, thereby, leading to bad indoor thermal environment. It also can be obtained from the testing results given by the research team that the solar energy in local areas is plentiful and the time of sunshine is longer. As a result, the solar energy should be fully used and, advanced construction technology and design should be adopted so as to solve the problems existed in the local dwellings and, provide good ones with comfortable indoor thermal environment for local residents.

Space Layout and Passive Utilization of Solar Energy

Ningxia autonomous region is rich in solar energy, based on the local culture and climate, the space layout of existing civilian dwellings can be improved. The dwellings are built in north-south direction (as shown in Fig.7), the main bedrooms and hall which require higher thermal environment and used mainly can be placed in the south of the dwellings so as to absorb more solar radiation; in order to prevent the heat in main rooms from coming out through the northern walls, simultaneously, provide a buffer area of temperature in the north direction for the main rooms, the secondary rooms like kitchen, utility room and study which have lower demand for thermal environment can be placed in the north of dwellings. The sizes of the rooms can be determined under the conditions of considering the use function as well as obtaining more solar radiation in the south of the dwellings, the solar elevation will be calculated on local winter solstice so as to confirm more reasonable scales. The sloping roof should be adopted, the hung ceiling is installed beneath the roof, and accordingly, the vertical temperature buffer area will be formed between the roof and the ceiling (as shown in Fig.8). This layout is beneficial to indoor function partition and forming a good thermal environment.

The passive solar energy heat collecting mode can be divided into the types as direct gain, heat collecting-storage wall, attached sun room and the combined type [19]. In which the combined type has the most collecting efficiency. Thus, the type of direct gain and the attached sun room can be used together as combined one. The attached sun room can be built in the south of the hall, heat storage materials should be employed for the wall and the floor between the sun room and the hall, and these materials can absorb and store the heat of solar radiation during the day, the stored heat can release at night, at the same time, the attached sun room can be used as the temperature buffer area in the south direction (as shown in Fig.8), insulation curtain can be installed at the windows of the attached sun room so as to prevent the heat from losing. Considering to get more solar irradiation, the larger windows are set up in the walls towards the south direction, the window-wall ratio should be 0.6, the heat storage materials can be used for the walls beneath the windows and the indoor floor, thinking of the ventilation inside the room, the smaller windows are installed in the walls towards the north direction, the window-wall ration should be 0.1.

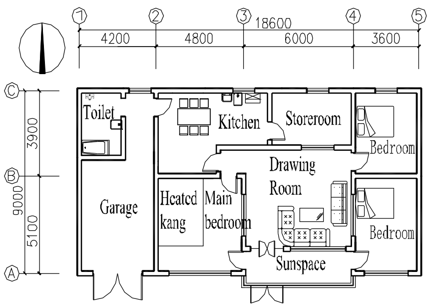

Fig.7 Floor plan of new type civilian dwelling

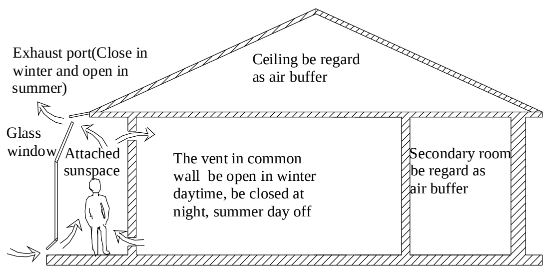

Fig.8 Thermal environment partition

Envelope Construction

The thermal performance of envelope for existing civilian dwellings is not good yet; the infiltration of cold wind is severe. The construction of envelope for new type civilian dwellings should be combined with local regional resources, making it can improve the behaviors of heat collecting and storage, the thermal performance as well.

(1) Wall

The southern walls get more heat gain, for the northern walls, since there is no solar irradiation, and heat is easy to lose, thus, the earth walls with good thermal stability can be built [20], the thickness is 600mm, the hollow brick wall in thickness 370mm should be constructed towards the south direction, the 600mm thick walls should be built in the same towards the eastern ant western directions (as shown in Fig.9).

(2) Roof

The biomass and energy saving roof is built [1], the grass shade knitted with reed or wheat straw is placed above the roof boarding, then making mud back, the waterproof components are laid; in the same, the biomass ceiling is hung, for instance, the rice hull is laid on the Gypsum board, after leveling, the thistle board is placed (as shown in Fig.10).

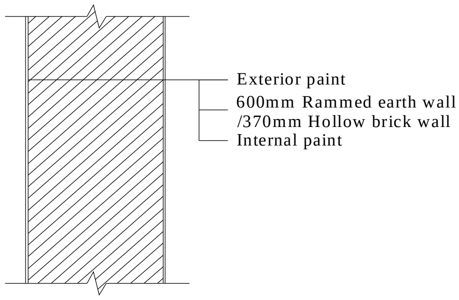

Fig.9 wall configuration

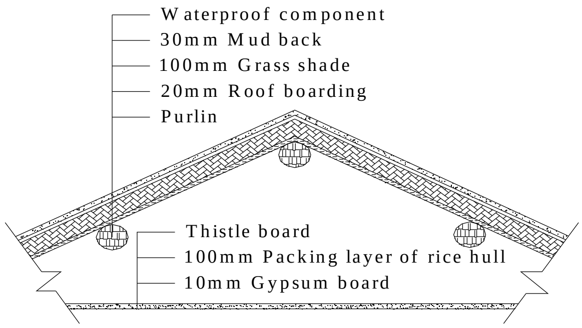

Fig.10 Structure of roof and ceiling

(3) Floor

In the range of 0.5~1m inside the exterior walls, lots of heat will transmit out from the floor in these areas, therefore, the insulation layer should be laid on the floor within this range, as each household burns coal for heating, so cinders can be used as bed course for insulation layer.

(4) Door and Window

The windows facing the south should be plastic steel and double-layer insulated glass casement window with lower heat conduction and good air tightness, meanwhile, the sealing should be done well so as to avoid the infiltration of cold wind, the window-wall ration is confirmed as 0.6; the windows facing the north should be small-sized and, plastic steel and double-layer insulated glass casement window, the window-wall ration is 0.1; insulation curtain is hung inside, in comparison with the wooden windows, insulation performance will be improved greatly.

Conclusions

Through the test and analysis of rural dwellings in Ningxia autonomous region, it can be obtained that the indoor temperature in local dwellings is lower, the thermal comfort is poorer, too, residents have lower satisfaction with the indoor thermal environment; in local areas solar energy resources are rich, but the utilization rate of solar energy is quite lower; the plan layout of dwellings is simple, the function partition is not clear and definite, thus, the practicability is not good; besides, the thermal performance of envelope is not satisfied. For these areas in rich solar energy, the design for new type civilian dwellings should be based on fully using solar energy, at the same time; the technology of passive solar energy should be integrated into the design and construction of traditional dwellings, providing a new idea for the design of rural dwellings in Ningxia. Accordingly, the conclusions are as the follows:

(1) The layout of civilian dwellings in the areas with rich solar energy resources should be on the basis that since main rooms can obtain more solar radiation, in combination with function partition and thermal environment partition, the utilization of solar energy should be strengthened so as to improve the indoor thermal environment.

(2) Adopting the attached sun room and direct gain windows, this combined passive solar energy heat collecting and heating method can fully use the solar energy resources and, increase the indoor thermal comfort, moreover, reduce the consumption and dependence on traditional energy resources, realize eventually the sustainable development of rural dwellings.

(3) The reasonable dwelling design with the utilization of solar energy at the core should be conducted, meanwhile, the properties of heat collecting and storage of dwellings, thermal performance of envelope should be increased so as to improve effectively winter indoor thermal

environment.

Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (51278419, 51278414) and Science and technology research and development program of Shaanxi Province, China (2012K12-04-01).

References

[1]Jiangyi. Research Report on Annual Report of Chinese Building Energy Saving 2013[M]Beijing: China Architecture and Building Press 2007.

[2]Ming Shan, Pengsu Wang, Jiarong Li, Guangxi Yue, Xudong Yang.Energy and environment in Chinese rural buildings: Situations,challenges, and intervention strategies[J]. Building and Environment,91(2015)271-282

[3]Ricardo Forgiarini Rupp, Natalia Giraldo Vásquez, Roberto Lamberts.A review of human thermal comfort in the built environment[J].Energy and Buildings,105(2015)178–205.

[4]Bao-jie He, Li Yang, Charla Griffy-Brown, Ben Mou, Ya-Nan Zhou,Miao Ye. The assessment of building energy efficiency in China rural society: Developing a new theoretical construct[J]. Technology in Society,38(2014)130–138.

[5]Long Shi, Michael Yit Lin Chew. A review on sustainable design of renewable energy systems[J].Renewable and Sustainable Energy Reviews,16(2012)192–207.

[6]Behnaz Rezaie, Ebrahim Esmailzadeh, Ibrahim Dincer. Renewable energy options for buildings: Case studies[J]. Energy and Buildings,43(2011)56–65.

[7]R.Cooke, A.Cripps, A.Irwin, M.Kolokotroni. Alternative energy technologies in buildings: Stakeholder perceptions[J]. Renewable Energy,32(2007)2320–2333.

[8]Bing Zhu, Wenjun Zhang, Jian Du, Wenji Zhou, Tong Qiu, Qiang Li. Adoption of renewable energy technologies (RETs): A survey on rural construction in China[J]. Technology in Society,33(2011)223–230.

[9]Liu Wei, Liu Dan, Li Baiyi, Zheng Min. Effect Analysis of a Passive Solar House in Tibet[J].AASRI Procedia, 3(2012)619–623.

[10] Sang Jianren, Liu Yulan ,Linli ,Comprehensive Evaluation on Solar Radiation Characters and Potential of Solar Energy Utilization in Ningxia. Journal of Desert Research, 2006,26(01): 122-125.

[11]Guohong Tong, David M. Christopher, Tianlai Li, Tieliang Wang. Passive solar energy utilization: A review of cross-section building parameter selection for Chinese solar greenhouses[J]. Renewable and Sustainable Energy Reviews, 26 (2013)540–548.

[12]Hussain H. Alzoubia, Amal T. Malkawi. The optimal utilization of solar energy in residential buildings in light of the Jordanian building regulations[J].Sustainable Cities and Society, 14(2014)441–448.

[13] Zhu Yiyun, Liu Jiaping. Research on Winter Indoor Thermal Environment of Rural Dwellings in Northwestern Areas [J]. Journal of Civil Engineering, 2010, 43(S2): 400-403.

[14] GB/T 50824-2013, Design Standard of Energy Efficiency for Rural Residential Buildings [S], Beijing: China Architecture and Building Press, 2014.

[15]JGJ26-2010, Design Standard for Energy Efficiency of Residential Buildings in Severe Cold and Cold Zones.[S]Beijing: China Architecture and Building Press .2010.

[16]Francesca Romana d' Ambrosio Alfano, Marco Dell'Isola, Boris Igor Palella,Giuseppe Riccio, Aldo Russi. On the measurement of the mean radiant temperature and its influence on the indoor thermal environment assessment[J]. Building and Environment,63(2013)79-88.

[17]Liu Jiaping, Yang Liu .Design on Indoor Thermal Environment[M].Beijing : China Machine Press,2005.4.

[18]K.J.Kontoleon. Glazing solar heat gain analysis and optimization at varying orientations and placements in aspect of distributed radiation at the interior surfaces[J]. Applied Energy,144(2015)152–164.

[19] Li Yuanzhe, Thermal Design Manual on Passive Sunroom [M].Beijing: Tsinghua University Press 1993.

[20] Xiang Dong, Veronica Soebarto, Michael Griffith. Achieving thermal comfort in naturally ventilated rammed earth houses[J]. Building and Environment,82(2014)588-598.