Thermal Studies of Suitable Ecological Building in China's Loess Plateau Region

Mu Jun and Edward Ng Yan-yung

Department of Architecture, The Chinese University of Hong Kong, Hong Kong SAR, P.R.China

ABSTRACT: Aiming to minimize fossil fuel use and environmental impacts caused by buildings, thermal design is one of the most effective approaches of ecological architecture to reduce these impacts. For any given regions, ecologically thermal design has to follow the principles of the ecological design, which are needed to be conditioned in the local situation. In this context, under the poor conditions of China's Loess Plateau region, the feasibility limited by the lacks of budget and conventional resources for construction is the main challenge to the ecologically thermal design for local buildings. Under this background, the methodology based on condition analyses and computer simulation experiments with TAS is involved in this study. As a result, based on the building elements and technologies available locally, this paper will present a series of alternative techniques and feasible thermal design strategies for this region so as to reach the most effectively ecological approach. This not only paves a way for ecological architecture to suit of the situation of China's Loess Plateau region with its cold climate, but is also beneficial to the tropical regions with similar conditions.

Keywords: Suitable ecological architecture, thermal design, experimental simulation, TAS, China's Loess Plateau

1. INTRODUCTION

In terms of considerable environmental and social problems caused by fossil fuel use [1], it is necessary and imperative to minimize human's dependence on fossil fuels, such as coal, oil and gas. In vies of this,, building is playing a vital role in solving these problems since it has become a significant fossil fuel consumer and producer of different environmental impacts. [2] This can be addressed by adopting a holistic approach of ecological architecture. [3] In current buildings, energy which needs thermal requirements, i.e. heating and cooling, is one of the biggest sources of fossil fuel consumption. [4, 5] Accordingly, aiming to minimize fossil fuel use and environmental impacts caused by buildings, thermal design is one of the most effective ways of ecological architecture to reduce the adverse effects.. In addition to the basic strategies in conventional way, ecologically thermal design has to follow the principles of the ecological design which show that any given regions need to be conditioned to suit the local situation so as to achieve the most effective ecological approach.

Under this background, the paper focuses on China's Loess Plateau region located in north-west China. (Figure 1) It is characterized by the largest deposit of loess. However, environmental degradation, low economic level, lack of resources and technologies for buildings are the problems of this region. Under such poor conditions, the feasibility limited by the lacks of budget and conventional resources for construction is the main challenge to the ecologically thermal design and local buildings. In this context, based on the ecologically theoretical strategies and principles concluded from the analyses of the local conditions, as well as computer thermal simulation studies with TAS (EDSL) [6] this paper will show a series of feasible thermal design strategies for this region so as to reach the most effectively ecological approach. It illustrates a feasible way which the thermal design is considered the suitable ecological architecture to deal with the problems happened in China's Loess Plateau.

Figure 1: Xifeng and China's Loess Plateau region

2. METHODOLOGY

The methodology of the study is based on the condition analysis and computer simulation experiment, and is composed of three steps. Since the thermal design study here is aiming at achieving ecological architecture, the first step is to outline what suitable ecological architecture in the case of the Loess Plateau region would be, and to highlight the principles which ecologically thermal design should follow. Therefore, in the first step, the current conditions of Loess Plateau should be studied. According to the analysis of the local conditions and relevant literature, a series of theoretical strategies and principles of ecologically thermal design for local buildings are concluded.

In the second step, thermal simulation with software TAS is employed in the thermal design study for a prototype, a classroom designed in Xifeng, which is the representative region of Loess Plateau. Based on the theoretical strategies and principles concluded before, building elements and technologies available locally are filtered and optimized thermally by using the simulation experiments. The aim is to get sustainable, effective and feasible solutions by using ecologically thermal design. Accordingly, the simulation study shows a series of feasible techniques, which can effectively improve the thermal performance of the building with optimal sustainability and practical feasibility.

Finally, according to the thermal performances and the cost efficiency of these techniques, the thermal design strategies of the suitable ecological architecture in the Loess Plateau areas can be concluded.

3. DEFINING THE LOCAL SUITABLE ECOLOGICAL ARCHITECTURE

In order to define the suitable ecological architecture in the Loess Plateau region and highlight the theoretical strategies and principles that ecologically thermal design for the local buildings needs to follow, three aspects about the local conditions, which generally influence the building design, should be studied. They include the economic level of the building and resources of the building, climate, and vernacular architecture.

The Loess Plateau region is one of the poorest parts of China. Especially in the rural areas, the mean of the per capital annual net income is as low as 228USD. [7] However, the cost of the local construction is comparatively higher than that in other parts of China. It is because there is lacking sufficient conventional resources for building. Under such poor conditions, the guideline of any other alternative technology for building should be found in this region in order to reach the effective approach of ecological architecture. In comparison with the conventional building technology, an alternative technological method put strong emphasis on the minimum use of non-renewable resources, and stress minimizing the environmental impacts as well as regional or sub-regional self-sufficiency in material and technologies. [8] It is evident that this kind of technology is helpful because it not only can reach the maximum ecological approach, but also can enhance efficiency and feasibility of construction. In view of this, ecological design for the local buildings has to attain high efficiency by utilizing any local technology and materials obtained locally.

For the local climate, the Loess Plateau region has cold winter and comparatively moderate summer. Taking Xifeng as an example, the mean of the monthly air temperature in winter is as cold as -8.8°C. In summer, it is below 25°C in average. It also has daily and seasonal large temperature swings. (Figure 2) It is noted that fossil fuel consumption in the existing local buildings mainly results from heating in winter. Correspondingly, the thermal performances of the buildings in winter need to be emphasized by the thermal design. According to the basic thermal design strategies [9], fossil fuel consumption for heating in winter can be reduced by two methods. The first one is to minimize heat loss whereas the second one is to use natural energy. In fact, thermal performances of the buildings can be upgraded by insulation & thermal mass, natural ventilation systems with heat exchanger and passive solar systems.

From studying the existing local buildings, it is found that there are some useful ecological elements embodied in the local vernacular architecture. It is characterized by earth-based dwellings. Earth-based dwellings can be classified into three types. They are hill-side caves, sunken caves and earth-vaulted houses. (Figure 3) According to the data obtained from field investigation and measurement, it is found that the earth-based dwellings have desirable thermal performances when compared with the conventional buildings. Besides, they are really environmental friendly. Furthermore, they are much cheaper and can be constructed by the locals very easily. In winter, the hill-side cave, for instance, only needs 10% of fuels for heating of the conventional buildings because of its more stable and warmer indoor thermal ambience. However, its construction cost is only around 20% of the latter since it relies on the simple techniques that occupants can build it by themselves with raw materials. The advantages brought by this local building technology are resulted from using earth materials and natural products, such as adobe, rammed earth, straw etc. Especially, when comparing with the conventional building materials, such as fired bricks and concrete, the earth-based materials have more advantages in thermal property, environmental performance and cost efficiency. Therefore, it is better to use the local earth-based technology in the study of ecological architecture. According to the literature [10], the earth-based technology can be utilized in the building envelope based on different natural products, and can be used to measure the ground temperature effect.

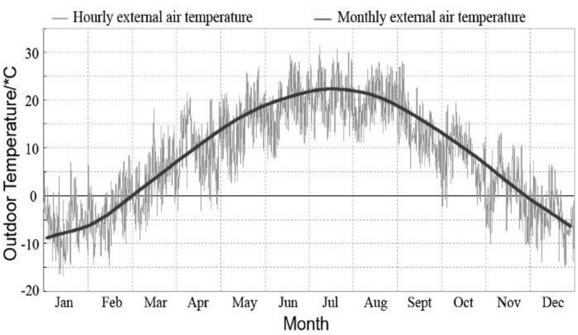

Figure 2: Hourly and monthly air temperatures in Xifeng (Source: MeteoNorm V5.0)

It can be said that the theoretical strategies concluded from this study can basically outline what the suitable ecological architecture would be. It can be summarized by the hypothesis that when earth-based buildings combine with the passive systems which utilize natural energy, as an alternative technology, they could achieve an optimal thermal performance like minimizing fossil fuel use and other environmental impacts. In this process, ecological thermal design should follow the principles of the comfortable indoor temperature, high cost-effectiveness, minimum energy embodied in the building and construction ease.

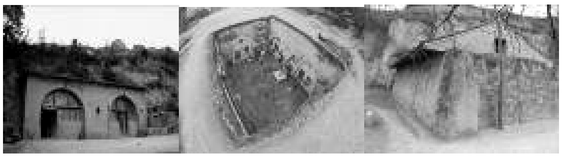

Figure 3: Hill-side cave (left), sunken cave (middle, Source: [11]) and earth-vaulted houses (right)

4. THERMAL STUDY BY SIMULATION EXPERIMENT

4.1 Prototype Selection for Thermal Simulation Study

Before going through the steps of the thermal simulation, the prototype of this study needs to be determined in the beginning. In this study, a classroom in a real project is employed as a prototype and basic model of all simulation series. It will be built in Maosi village near Xifeng city.

The reason for selecting a classroom because it generally has more complex thermal and technical challenges that the thermal design may encounter, such as larger space dimensions, bigger internal volume to be operated and higher standard of indoor ventilation. If these challenges could be conquered, the relevant experiences would be significant to most of the conventional buildings.

The classroom will be built at several levels of terraces, surrounded by hills from northwest to east. The opening faces to the south. The primary design is as follows: 12 classrooms are constructed into 6 units at two different levels, facing the south and spreading along the west-east contour lines. Each classroom can accommodate at least 40 students. According to the local codes, if the area of the classroom is around $54m^2$-floor (6×9m on plan) and 3.2m-height, it will be appropriate. The classroom, together with its dimensions and surrounding environment, will act as the basic model for the coming simulation experiments.

4.2 Model Setup of Experiment Series and Analysis

Based on the principles and theoretical thermal design strategies mentioned before, the simulation study aims to improve the thermal performance of the classroom by using a maximum ecological approach like filtering and optimizing the natural materials obtained locally, building technologies and the incorporations of the classroom design.

In this study, the software TAS is used for thermal simulation. By comparing the measured data with the simulated results of an existing local classroom, it is validated that the software can basically predict the dynamic indoor temperature in the simulated building models by inputting the relevant component parameters and weather data (Figure 4).

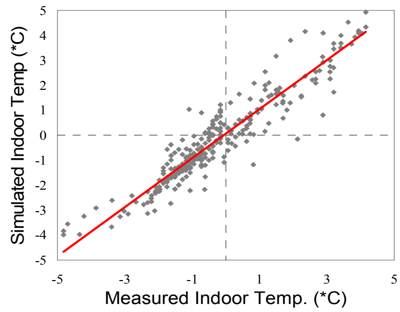

Figure 4: Validation of simulation software

After getting validation, a series of simulation experiments will be set up with a two-phase study and then verify the technical possibilities which can improve the thermal performance of the classroom. In this process, the hourly climatic data in TMY (typical meteorological year), 1995, obtained from the program, MeteoNorm V5.0 by METEOTEST, is employed. When it comes to the cold winter and moderate summer in the local area, the winter environment (the coldest two weeks are in January) is focused on all simulation series. The indoor air temperature is emphasized in order access the building thermal performance.

The two phases of the simulation experiments are illustrated in Figure 5. In the first phase, according to the two basic strategies of the thermal design, i.e. minimizing heat loss and utilizing natural energy, the

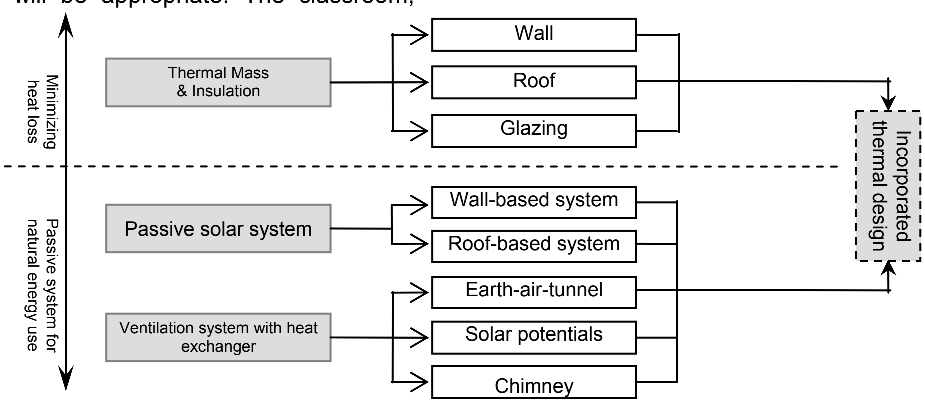

Figure 5: The experimental series of thermal simulation

simulation experiments are grouped into three parts: thermal mass & insulation, passive solar system and natural ventilation system with heat exchanger. Among them, based on the basic classroom model, locally available materials, building elements and their incorporations can get filtered and optimized thermally by simulation, and reach a higher thermal performance and cost efficiency.

For thermal mass and insulation, locally available materials are examined for the building envelope in the form of wall, roof and glazing. It is found that local earth-based materials and natural products are the optimal options for thermal mass and insulation. With a small increase in cost and lease of embodied energy, heat loss through the building fabric can be greatly reduced by employing this natural thermal mass and insulation, such as the thick adobe wall and additive straw layer on the local conventional pitched roof. To maximize the utilization of solar energy for heating, a series of conventional passive solar systems are tested from the solar collector's positions of the southern wall and roof. After optimizing their components and spatial elements, it is noted that the sunspace and roof sunspace (the local pitched roof with a suspended ceiling straw-based-insulated, and with the southern sloping side glazed) can effectively increase indoor air temperature of the classroom, for they function not only as a solar heater but also a thermal buffer.

In addition, to reach the healthy indoor air quality for 40 students, according to ASHRAE Standard [12], an air exchange rate has to reach at least 3.5L/s. In order to minimize heat loss by using such ventilation system, the natural ventilation system with heat exchanger is studied. It is noted that the passive solar system modified in the air circulation mode may pre-warm or sometimes even heat fresh air from outside. Due to the terraces in the school site, the dug tunnel with 2.8-m-depth and 1.2m thick sheltered-earth is available to attach to the north side of the classroom. By studying the relevant tunnel elements, such as length, section area, air flow rate, etc., the optimized earth-air-exchange tunnel can effectively moderate fresh air passing through it. Parts of the experiments showed that the earth-air-exchange tunnel could comparatively be the most effective and steady heat exchanger to reduce indoor heat loss by using the ventilation system in a large extent and by incorporating with the chimney. In addition, except the overcast days, the roof sunspace has potential to be a heater especially in the afternoon if it is powered by a small fan. Thus, this will further enhance the indoor temperature.

In the second phase, in order to optimize the incorporated thermal performance and then thermally improve the classroom design, these techniques, which are obtained in the last phase, are incorporated in forms of several incorporated system models. Based on thermal mass and insulation, extra components, such as Trombe wall, sunspace and tunnels, are incorporated in several ways with different internal air circulation (Figure 6). In operation, occupants can control the indoor thermal ambience only by adjusting relevant components, such as the tunnel door and fan speed. It is found that this incorporated system can make the indoor thermal environment of the classroom achieve a desirable comfort level without any extra fossil fuel consumption.

After finishing these two phases, together with the basis on earth-based materials and natural products, the result of this study showed that using a series of feasible techniques can effectively upgrade the thermal performance of the classroom. The construction means and costs can be grouped into three aspects: thermal mass and insulation; extra components and incorporated system. (Some of them are shown in Figure 7)

5. THERMAL PERFORMANCE PREDICTION

To further predict the thermal performance and cost effectiveness of each optimized technical option, simulation is extended for the whole heating season (Mid Nov to Mid Feb) based on the classroom model. Three cases of the ventilation modes are simulated. The first one is ventilated at 3.5L/s (6.1 ACH) and occupied by 40 students. The second is only ventilated and the last one is simulated only by infiltration without any occupant. The first and the last one can basically illustrate the thermal effects of these techniques on two types of buildings respectively, including those being able to fulfil and those not being able to fulfil the ventilation requirement. The sky condition is taken into consideration. According to the local weather record, during the heating season, fine, cloudy and overcast days account for 25%, 37% and 38% respectively. Based on the setup above, these techniques are gradually employed in the basic classroom model and simulation.

By simulation, the mean of the daily operation indoor temperatures during the heating season can be obtained from each simulation case. To compare with the thermal performance in the conventional classroom, the differences of the indoor temperature between each simulation case and conventional case are sorted out and generate in Figure 7. In this figure, the absolute indoor temperatures of the conventional classroom acting as the base line are shown by the black solid line in Y axis. The color lines illustrate the increase in indoor temperature resulting from the employed techniques. Meanwhile, based on the local experiences and observations, the lowest acceptable air temperature for local villagers in this season is taken as 4.3℃. Compared with the temperature in the conventional classroom, the difference in the lowest acceptable temperature is marked with black dotted line.

As the blue line showing in the figure, it is evident that during the fine and cloudy days,, the indoor thermal environment may reach the lowest acceptable level only by employing thermal mass and insulation in both ventilated and not ventilated cases, . In overcast days the indoor temperature is still colder than the acceptable range. However, in addition to thermal mass and insulation, the employment of 'extra component' can make the indoor temperature higher than the acceptable level.

For example, for the ventilated case, the green line simply shows that as long as the earth-air tunnels are added, and then an acceptable indoor temperature can be obtained. In this case, the indoor temperature is much higher than the lowest acceptable level.

The sunspace can also bring a similar effect on the un-ventilated classroom. If the extra components with the incorporated system are replaced, the thermal performance of the classroom in any cases could be greatly improved to a desirable level.

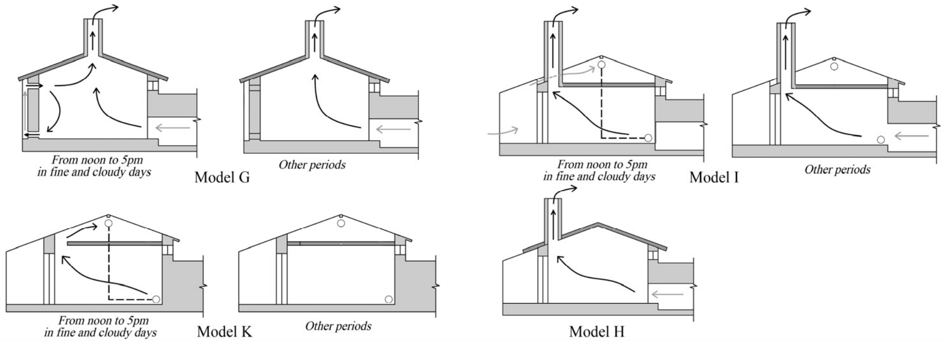

Figure 6: Incorporated system models as optimized

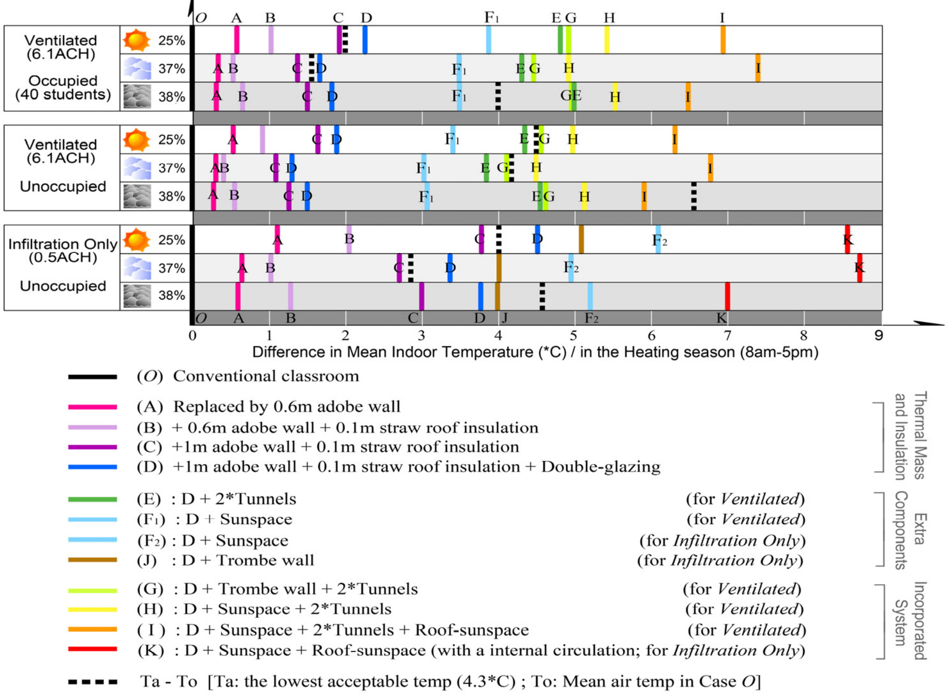

Figure 7: Comparison of the thermal contributions from the developed techniques, based on mean indoor temperatures in different sky conditions

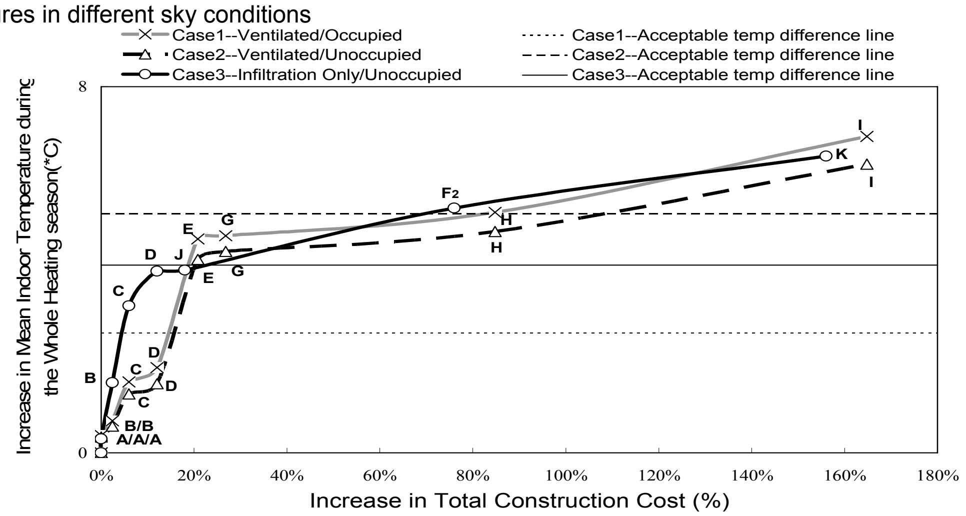

Figure 8: Relationship between construction cost and thermal performance of the developed techniques

To further illustrate the relationship between the increase in cost and improvement of the building thermal performance resulting from each technique, Figure 8 is generated based on the mean of the indoor temperature during the whole heating season. Y axis shows the increase in indoor temperature compared with the conventional classroom. X axis is the increase in total construction cost. The grey curve shows the ventilated and occupied case, and the dotted one shows the ventilated case only, and the solid curve shows the infiltration case.

From the figure, it is obvious that thermal performances of these techniques are proportional to their construction costs. Meanwhile, the most basic techniques, such as earth-based thermal mass and insulation, tunnels, are most effective in cost and thermal performance. They may increase the mean of the indoor temperature of the ventilated building and the building which only uses infiltration to the level near or even higher than the acceptable range. Beyond that, further improvement of the thermal performance would cost much more and be less effective, though a more advanced incorporated system can give a better thermal performance.

6. CONCLUSION

Since the thermal prediction derived from two simulated cases above, one with ventilation and another with infiltration only, can basically illustrate the types of buildings with different ventilation requirements, the following ecological thermal design strategies can be concluded according to the performances of these optimized techniques in thermal effect and cost-efficiency.

For most types of buildings in the Loess Plateau region, thermal mass and insulation are necessary, They are also the most effective way to improve the thermal performances of buildings; For buildings which require a low ventilation rate, such as dwellings and offices, thermal mass and insulation could help the buildings attain to an acceptable thermal comfort level during most time of the heating season without any fossil fuel consumption for heating; For buildings which require a high ventilation rate, such as classrooms, thermal mass, insulation and the earth-air-exchange tunnel are highly recommended because they all can significantly improve the indoor thermal environment and help it attain to a comfortable level with only a small increase in budget. However, to meet a higher thermal performance, the incorporations of passive solar system are also appreciable in spite of its higher construction cost. Hence, they can be selectively employed.

Based on this strategy and relevant optimized techniques for the thermal design, in practice, local builders may use Figure 7 and 8 as references. Moreover, in order to achieve the most effective ecological approach, they can depend on their personal economic situation, resources, functions and the site conditions to decide which techniques are most suitable for them.. In this case, indoor comfort could be achieved by consuming least fossil fuel and money on heating. Moreover, since most materials recommended in these strategies are earth and natural products. They not only have much lower embodied energy than the conventional materials, but also are easily afforded by most local villagers. Meanwhile, since these techniques are derived from the local vernacular or conventional architecture, they could be manipulated easily by local builders or even inhabitants. Therefore, it can be concluded that the developed architecture would be economical with desirable sustainability and constructional ease, as well as be feasible and suitable for the conditions in Xifeng areas and the whole Loess Plateau region if it employs these optimized techniques and strategies. ., However some other considerations still need to be addressed in future studies, such as thermal performance in summer, further detailed techniques in practice and feasibility of other types of buildings. After all, the developed strategies of ecologically thermal design from this study still give the inspirations to the ecological architecture to suit the case of the Loess Plateau areas in China. And they are worth further developing. More importantly, though this study focuses only on the severe climate zone, the methodology based on condition analyses and simulation experiments is significant to the tropical regions with similar conditions.

REFERENCES

[1] IPCC, Climate Change 2001: the Scientific Basis. Cambridge University Press, 2001, 152-155

[2] E Iain McCreary, Alan Y Gu, Verne W Loose and Joseph M Roop. 1996. China's Energy: a Forecast to 2015. The Los Alamos National Laboratory for the U.S. Department of Energy.

[3] Brenda and Robert Vale, The new autonomous house: design and planning for sustainability. London: Thames & Hudson, 2000.

[4] D&R International Ltd. 2004 Buildings Energy Databook. DOE's Office of Energy Efficiency and Renewable Energy, 2005.

[5] Steven Blanchard and Peter Reppe, Life Cycle Analysis of a Residential Home in Michigan. School of Natural Resources and Environment, University of Michigan,1998.

[6] Environmental Design Solutions Limited, http://www.edsl.net/

[7] National Bureau of Statistics of China (NBSC), Construction statistical yearbook of China, 2004.

[8] Dickson David, Alternative technology and the politics of technical change. London : Fontana, 1974.

[9] Baruch Givoni, Climate considerations in building and urban design. New York: Van Nostrand Reinhold, 1998.

[10] Louis Bourgeois, Spectacular vernacular: a new appreciation of traditional desert architecture. Salt Lake City: Peregrine Smith Books, 1983.

[11] Committee for the International Symposium on Earth Architecture (CISEA), Report on the International Symposium on Earth Architecture, 1986.

[12] Ventilation for acceptable indoor air quality, ASHRAE standard 62.1-2004. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2004.