

Design Strategies on Heat Recovery of Cooking Stove in Rural Houses of China

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ABSTRACT

Wulong County is a high altitude mountainous region located in the southeast of Chongqing Province, included in the hot summer and cold winter (HSCW) climate zone of China. The indoor and outdoor temperatures are quite low during the winter and sometimes are intolerant for local occupants. The percentage of possible sunshine is only 13% in winter according to meteorological data, which makes it nearly impossible to use solar energy for space heating. Other ways of heat gaining without extra energy consumption should be explored for the rural houses of this area. This paper analyzed impacts of cooking activities on indoor environmental quality, and estimated the potential of heat recovery of cooking stove for space heating. We conducted in-depth observations of occupants' behavior (including life patterns and cooking activities) and field investigations on thermal environment and indoor air quality. A series of design strategies were proposed based on these survey results. The strategies emphasized the utilization of heated walls and a proper room layout.

INTRODUCTION

The hot summer and cold winter (HSCW) climate zone, with 0.55 billion people living there, covers a grand area of the central China. The climate is far harsher than any other places of the same latitude. Wulong County located in Chongqing Province with an average altitude of over 1,000 meters above sea level, is a representative area of the HSCW zone. The annual average temperature is 15-18°C. The extreme minimum temperature can reach as low as -3.5°C, while the highest temperature is 41.7°C, with high humidity all year round. The annual precipitation is 1000-1200mm. Most precipitation is April to June for four months, accounting for 39% of annual precipitation. People live in this remote mountainous area suffer from both extreme hot summer and cold, wet winter. The present existing rural houses fail to achieve thermal comfort especially in winter. According to the field measurements performed in February, 2012, the average indoor air temperature of a traditional timberwork house is 2.45°C. The indoor temperature even falls below zero sometimes. The situation with the modern concrete house is no better. The average indoor air temperature is 4.59°C with the minimum value of 1.4°C, which are far below the thermal comfort zone. The heating season is up to six months from October to the following March.

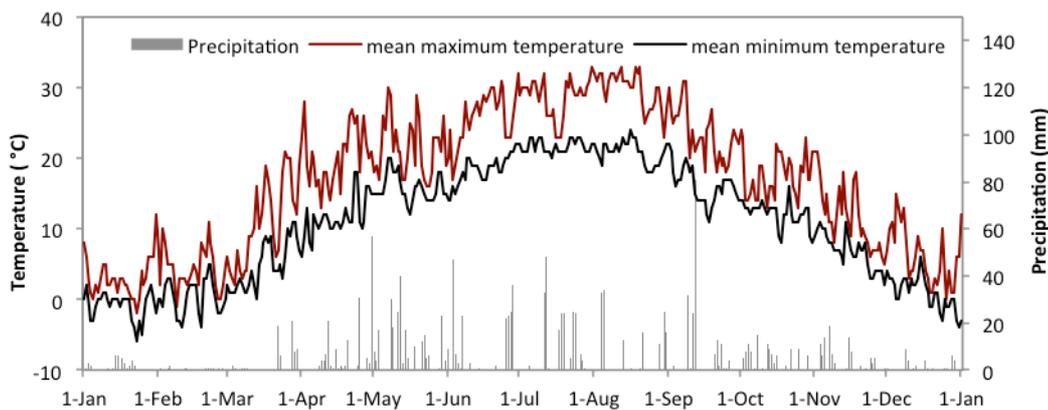


Figure 1 The climate condition of Wulong during a typical year. (Data sources, www.accuweather.com)

An in-depth study has been conducted since 2011. Based on long-term field measurements and investigations, a number of low-tech and lowcost strategies have been proposed to improve the indoor environment quality. We found the potential of heat recovery from cooking activities and upgraded traditional heated-wall system as the heat source. In this paper, the present conditions of thermal environment, indoor air quality, energy consumption and occupancy schedule have been discussed in detail. And the innovative heated-wall system and a possible house layout are introduced. The design intends to rediscover localization by using locallyavailable materials and traditional building technologies in an innovative way. The indoor thermal comfort and indoor air quality can be improved and comply with the features of occupants' life pattern. The strategies and techniques we proposed have broad-range applicability in HSCW zone. Community discussions were held during the whole design process and a pilot building is to be built there for future assessments.

METHODS

Respectively, four field investigations on indoor environment quality (IEQ) were conducted in August 2011, April 2012, January 2013 and February 2014, in a remote village of Wulong County, Chongqing Province, China. Both questionnaire interviews and quantified measurements were applied. A total of 105 households participated in the questionnaire surveys, which includes 47 valid questionnaires in summer and 58 valid questionnaires in winter. The investigation included energy consumption of the household, heating method, health condition and 24-hour occupancy schedule. The subjective thermal comfort questionnaire survey was also carried out, including thermal comfort vote (TCV), thermal sensation vote (TSV), thermal satisfaction and expectation. Certain scales and remarks are attached to these votes. TCV has a five-point scale from 0 to 4 (0 represents comfortable and 4 is limited tolerance); TSV has a seven-point scale from -3 to +3 (-3 is very cold and +3 is very hot); Thermal satisfaction has four remarks from unsatisfied to satisfied valued -1, -0, +0 and +1, respectively (-0 means “just unsatisfied” while +0 means “just satisfied”).

Mean while, the thermal environment measurements were carried out during these four surveys, indoor and outdoor environment parameters were recorded by auto-loggers for at least 72 hours each time. The thermal and luminous performances of rural houses in different seasons have been discussed and presented in our former papers. For more detailed information please refer to those previous studies. Field measurements of indoor air quality (IAQ) were only performed in February 2014. The indoor CO concentration, CO₂ concentration and particle matter in four typical kitchens were monitored for 24 hours. Detailed Information of the Instruments **are shown in Table 1**.

Table 1. Detailed Information of the Instruments

Physical Quantity	Instrument	Accuracy	Data Intervals
PM2.5	Dust Trak8520	± 0.001mg/ m3	1 minute
CO	Q-Trak 7565-X	±3% or ±50 ppm	5 seconds
CO ₂	EZY-1	±75ppm	5 minutes

OBSERVATIONS AND RESULTS

Energy Sources and Consumption

According to survey, wood and liquefied petroleum gas (LPG) are the main energy sources for cooking while wood, charcoal and electricity are used for heating. On average, 16.7% of the household income is spent on energy. During heating season, the average energy consumption of wood and charcoal are 536kg and 126kg per household respectively. And due to the increasing heating demand, the monthly average energy consumption of electricity is 305kWh per household while the amount is only 178kWh in summer. The energy price of wood is 0.25 RMB/kg and charcoal is 2.8 RMB/kg. Residential electricity price is 0.55 RMB/kWh.

Figure2 is composed of photos and thermographs of traditional heating and cooking methods. The locals adhere the concept of ‘interval heating and spot heating’. Instead of heating the whole room, families or neighbours gather around a basin of charcoal or an open fire pit. High efficiency biomass stove are also applied in recent years. The traditional cooking stoves are widely used, burning woods and agricultural wastes. These inefficiency stoves cause the indoor air pollution. To make it worse, people often use part of the kitchen as living room in a traditional house, which leads to higher exposure to particle matters and harmful gases. As for concrete house occupants who usually have better incomes, using electric stoves and electric heating lamps is a common choice. Although it is less polluted, it significantly increases the energy consumption.



Figure 2 Traditional heating and cooking methods used by local residents.

Subjective Votes

About 34.5% of the respondents were dissatisfied with the present heating methods for hygiene problems or high levels of consumption. 96.6% of the respondents expected their houses to be warmer during the winter. TSVs for indoor thermal environment were -1.76 and -1.78 (close to cold) for winter daytime and nighttime, respectively. TCV was 1.18 (between slightly uncomfortable and uncomfortable) and the result of thermal satisfaction vote was -0.38 (between unsatisfied and just unsatisfied). These results illustrate the necessity of improve the thermal conditions in winter. Low temperature and high humidity lead to higher risk of rheumatic disease and even higher mortality rate in elderly during the winter. About 47.4% of the respondents had arthritis or rheumatism disease. The prevalence rate increased with age. This rate increased to 66.7% in the age group of over 60 years old.

Indoor Air Quality

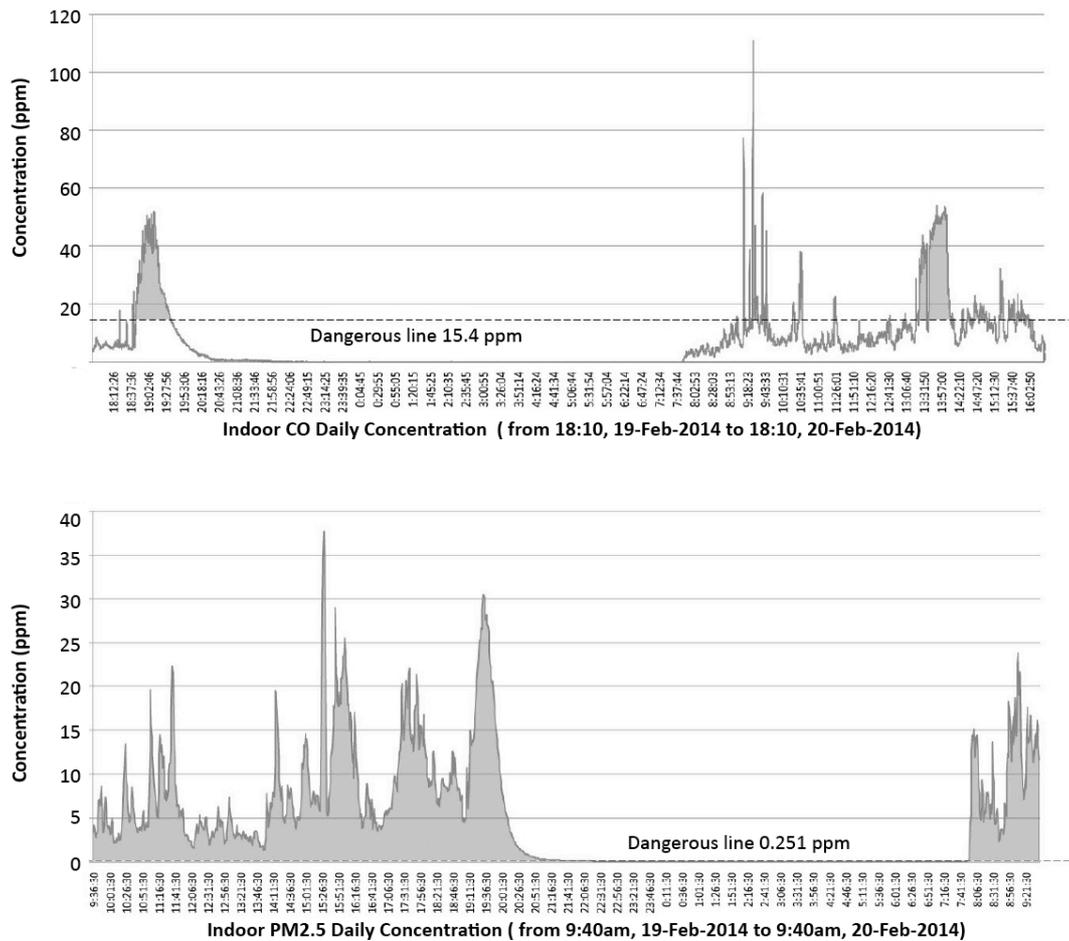


Figure 3 Daily concentration of PM2.5 and CO of a vernacular house with traditional cooking stoves.

The indoor air pollution is quite serious due to the lack of ventilation design and incomplete combustion, particularly for traditional houses. As shown in Figure 3, the peak value of PM2.5 concentration in a traditional house was 48.055 mg/m³ while cooking which was ten times higher than that of the concrete house. The peak value of CO concentration was 28.3ppm, which was eight times higher than that of the concrete house. The peak value of CO₂ concentration reached 662ppm in daytime while the valley value was 423 ppm in nighttime. These air quality indicators overrun the limitation of national standard thus increase the risk of hypertensive disease.

Life Patterns

A 24-hour occupancy schedule was formed based on questionnaire survey and observational survey, as shown in Figure 4. It illustrates the potential of using the afterheat of cooking activities as heat source for living room and bedrooms. The activities in living room and bedroom peaked right after cookings.

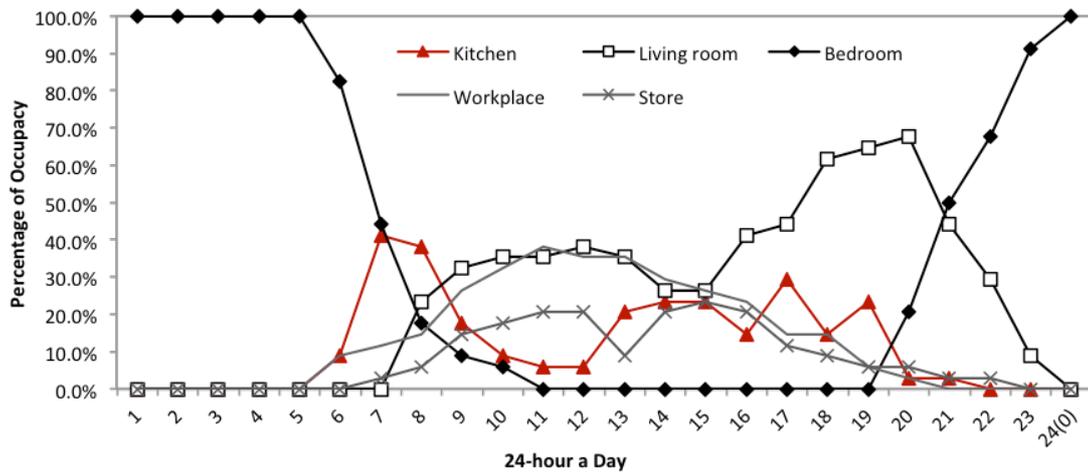


Figure 4 24-hour occupancy schedule in winter based on field survey.

DESIGN STRATEGIES

Design Intends

The design aims to support a more comfortable and healthier living condition without extra energy consumption and investments, by the properly building layouts and the innovative heated-wall system. It also takes the unique life patterns of local occupants into account, making efforts to minimize the total heating demand by continuing the concept of ‘interval heating and spot heating’. A house menu is provided to maximize the flexibility and personalization. The economic cycles of households are also considered. Occupants can run small business, keeping rural livestock, or processing farm products at home. Several design strategies and techniques have been applied as follows.

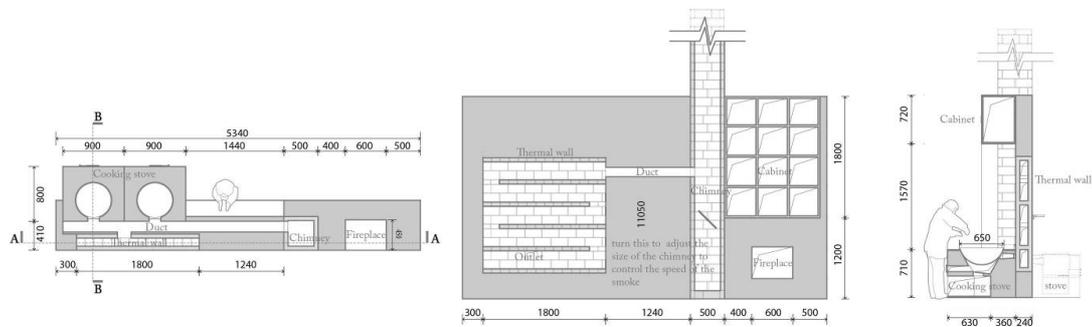


Figure 5 Detailed drawings of the heated-wall system

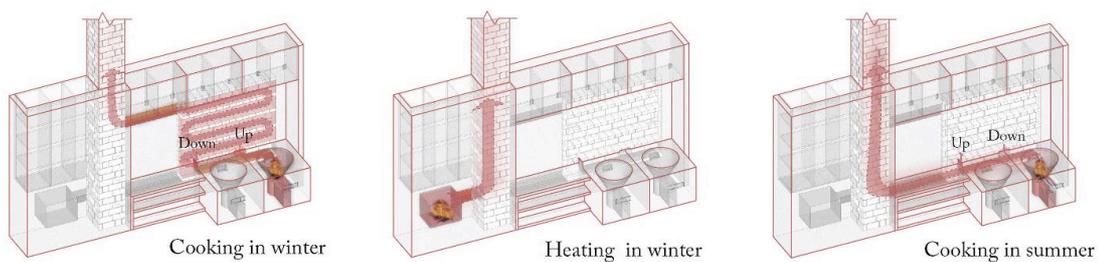


Figure 6 Running modes of the heated-wall system

Innovated Heated-wall System

Heated-wall system is a traditional technique for heating in the northeast of China but rarely known by southerners. The cooking stove is connected to a hollow wall, letting the hot smoke exhausted from the wall cavity. In this way, the wall is heated during cooking and radiant heat to adjoining rooms. The wall is usually located between kitchen and bedroom. According to the study held by Tsinghua University in 2008, the heated wall can maintain a relatively comfortable temperature for about two hours after the stove stops burning. The innovated heated-wall system we proposed here adds a fireplace on the other side, sharing chimney with the hollow wall, **As shown in Figure 5 and Figure 6**. The cooking stove uses biomass instead of coal, reducing the reliance on fossil fuels. The fireplace can be alternated by a high-efficiency biomass stove.

Buffer zone

With a proper layout, we can optimize the use of heated-wall system (see **Figure 8**). The concept of "buffer zone" is applied to resolve the paradox of cooling in summer and heating in winter (see **Figure 7**). The core zone of the plan is composed of four spaces surrounding the heated-wall system. Insulation layers are only used around the core zone which is the main living area in winter. The core zone is surrounded by a buffer zone, which is semi-open space buffering the core from cold outdoors and playing the main living area in summer. In this way, the indoor environment quality is improved without extra energy consumption and little investments.

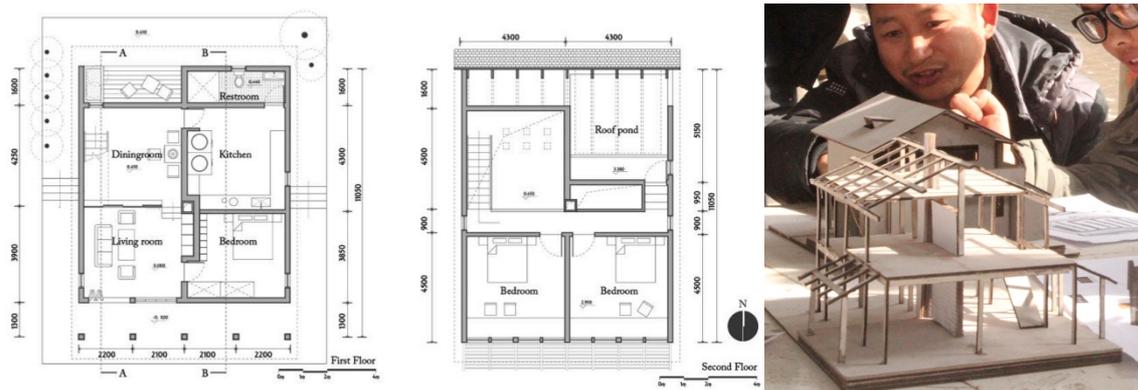


Figure 7 Plans and working model of design proposal

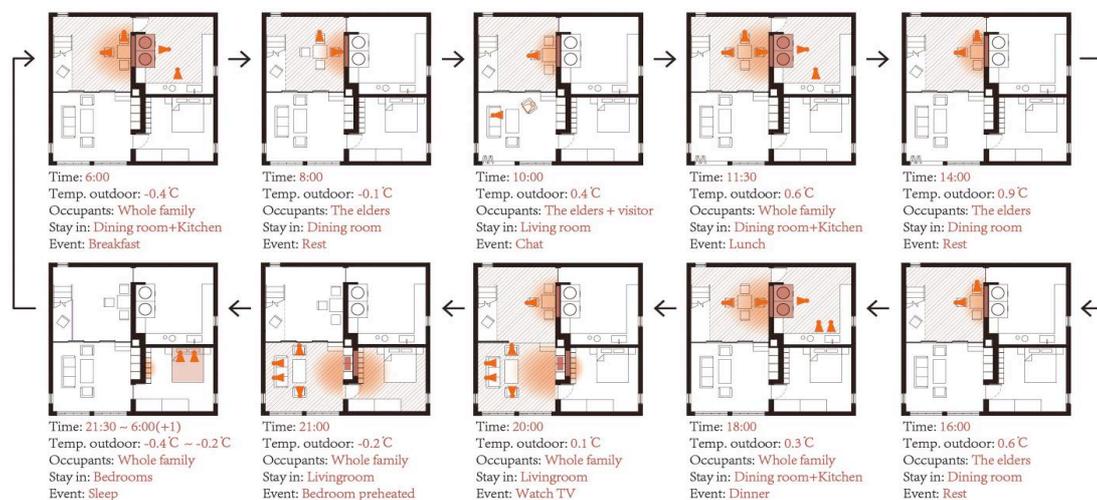


Figure 8 Routine of the operation of heated-wall system harmonizing with daily life

Localization

The construction can be performed by local labours, and the new building technique can be passed on and as a means of livelihood for them. All strategies are affordable, using locally available materials, and cost efficient even for people in less affluent area. Community discussions were held during the whole design process and a pilot building is to be built there for future assessments.

CONCLUSIONS

In this paper, based on in-depth field investigations and measurements, the thermal environment and indoor air quality of rural houses in southwest of China were analyzed. The authors discussed the impacts of cooking activities on indoor environmental quality and the potential of heat recovery through occupant's life patterns. A series of low-tech and low-cost design strategies were proposed based on survey results. The strategies emphasized the utilization of an innovated heated-wall system for space heating, locally available materials and a proper room layout to optimize the benefits.

ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China (NSFC), Design Strategies of Chinese Vernacular House in Hot-summer and Cold-winter Climate Zone (Grant No. 51278262) and State Key Laboratory of Subtropical Building Science, South China University of Technology, Research on Ecological Strategy and Technology of Livable Environment in Subtropical Area.

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