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Energy demand for rural household heating to suitable levels in the Loess Hilly Region, Gansu Province, China

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A B S T R A C T

This study was conducted to analyze the status of energy use for heating in rural areas and the energy demands required by rural households to maintain temperatures suitable for the residents to live comfortably. In addition, suggestions to improve the thermal comfort of such families are put forward. In this study, we obtained data regarding temperature changes and energy consumption in two villages in the region through field observations and recorded records, after which we set up trend surface models and calculated the accumulated temperature differences and actual energy consumption for the heating period. We then compared the actual thermal efficiency and the theoretic thermal efficiency in the case of energy-saving technology based on relevant national standards. Although large amounts of fuels were consumed by households for heating, they only met 39.6% and 46.6% of the energy required to maintain a suitable living standard in Zhangguan Village and Hepan Village respectively. However, the current integrated thermal efficiency of energy consumption for household heating is only about 17%. These findings indicate that the inadequate heating in the area is not due to inadequate energy, but to inadequate technology. Therefore, the potential for improving integrated thermal efficiency by the application of energy-saving technologies is enormous.

1. Introduction

Having adequate food and warmth have been considered the most basic needs for human existence since ancient times. In Chinese culture, there are many expressions about human existence conditions that are associated with food and warmth, such as living in hunger and cold and having rags on one's back and little in one's belly. People require clothing, shelter and fuel to remain warm. Since the Paleolithic age, firewood has been used as an energy source for cooking, resisting cold, lighting and defense [1]. Although bio-energy is still the primary source of energy for heating in rural areas, the use of firewood in the study area has decreased due to deforestation. Remaining warm has also been one of the primary motivations for improvements in shelter by humans. Additionally, according to the archaeological discoveries in Qin'an Dadi-Bay ruins of Gansu province, the use of fire has long played a vital role in the everyday life of people in the region [2].

It is difficult for humans to tolerate ambient temperatures below 0 °C. In middle and high latitude and altitude regions on the earth, low temperatures during winter are not suitable for humans. Therefore, improving the habitation environment and increasing the indoor temperature during winter have been one of the important aspects of human survival and development. The Chinese government has established comparatively good heating systems in urban areas and provided urban citizens with heating subsidies, but the heating needs of rural citizens have not been included in the scope of the government's public expenditure. In the last 30 years, the Chinese economy has developed rapidly, which has led to great improvements in the living standards of urban and rural residents. However, energy shortages still exist, especially with respect to household heating. Despite these shortages, there is currently no heating indicator in the target system of China's rural construction regulations designed to ensure suitable living conditions, in which only the per capita housing area relates to warmth [3,4]. Accordingly, it is necessary to improve construction to better meet the demand of rural residents for indoor heating.

Internationally, there have been numerous studies conducted to evaluate household heating in winter from different points of view. Particularly, the results and findings in papers published in the international journal ENERGY in recent years reflected the progress in this field of study. For example, Haralambopoulos et al. [5] investigated the structure of residential energy consumption in the capital of a relatively large Aegean island and proposed remedial actions in order to reduce consumption and avoid environmental pressures. Chen et al. [6] studied the energy embodied in the residential building envelope of Hong Kong, their results

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Nomenclature

ΔT_1	cumulative temperature difference of indoor and outdoor temperature (h °C)
ΔT_2	cumulative temperature difference of 16 °C and outdoor temperature (h °C)
W_1	actual consumption of fuel (kgce)
W_2	the amount of fuel consumed to maintain indoor temperature of 16 °C (kgce)
q_H	heat loss per unit building area (W/m^2)
K_i	heat transfer coefficient of the *i*th type of enclosure structure (W/m^2 °C)
q_c	the consumption of standard coal per unit building area (kgce/m^2)
p	the number of heating days
H_e	the calorific value of standard coal (8140 W h/kg)
η	integrated thermal efficiency (%)
R^2	the fitting degrees
$F_{0.01}$	the critical value for a test with $\alpha = 0.01$
F	the test statistic values

revealed those building components with significant potential for reduction in embodied energy demand. Sarmah et al. [7] presented a comparative analysis of the household energy consumption patterns and available biomass energy in six un-electrified villages of the Jorhat district of Assam, they found that fuel wood was preferred for domestic energy consumption and 21.5–42% more energy was consumed in winter than in summer for meeting cooking, water heating and space heating needs. Emery and Kippenhan [8] conducted a long-term study of residential home heating consumption in the Pacific Northwest, they found that the space conditioning energy needs were strongly affected by occupant behavior, and suggested that estimates of energy savings can be based upon envelope thermal resistance for moderate occupant behavior. Mikkel et al. [9] analyzed the relative competitive positions of the alternative means for domestic heating in Denmark, and thought that district heating should be advocated only for areas with a high concentration of heat demand. Murat and Kamola [10] evaluated the energy-saving potential in the residential sector of Uzbekistan, and suggested to use the heating degree-day method for determining the natural gas consumption norms for residential heating. Dejan and Toma [11] investigated the systematic approach to natural gas usage for domestic heating in urban areas of Serbia, and established a general model to achieve coordinated development of centralized energy supply systems fueled. Gugliermetti and Bisegna [12] analyzed the energy savings connected to the potential use of reversible windows and found that new double-glazed window systems were very helpful for buildings with no-prevalent cooling or heating requirements. Otherwise, the study reports on home heating and cooling increased evidently since 2008. For example, Peeters et al. [13] evaluated the control of heating systems in residential buildings in Belgium and found that the primary energy consumption of a heating system is determined by the net energy demand of the building, but also by the efficiency of the equipment and the way it is used by the inhabitants, which indicated great potential for energy savings. Matteo et al. [14] evaluated the relationships between the age of a building in Italy and its main geometric and thermophysical properties through a statistical approach and found a way to simplify the energy balance, making the calculation easier and faster. Manuel et al. [15] evaluated the thermal comfort criteria and building design in Portugal. Jamal et al. [16] evaluated space heating systems used in Jordan and found that fossil fuels contributed significantly to air pollution and the build-up of carbon dioxide in the atmosphere. He also confirmed that residential space heating accounted for about two thirds of the total residential energy consumption. Sardianou [17] estimated the main determinants of household residential energy consumption for space heating in Greece employing cross-sectional data for 2003. Philippa et al. [18] analyzed drivers of the demand for heating in the residential sector of New Zealand. Sung et al. [19] conducted a field study of thermal comfort in low-income dwellings in England before and after energy efficient refurbishment. Singh et al. [20] investigated thermal performance and comfort temperatures in vernacular buildings in northeast India and attempted to determine the range of comfort in these buildings for different seasons. James et al. [21] investigated traditional high altitude Nepali homes and provided simple and low cost strategies to improve their comfort levels. Zhu et al. [22] carried out actual energy performance measurements on a zero energy house versus a conventional house in suburban Las Vegas of US, and found that four items have a low equivalent cost of electricity compared to the commercial rate, namely the high performance windows, the compact fluorescent lights, the air conditioner with a water-cooled condenser, and the highly insulated roof. Popescu et al. [23] developed and analyzed an original methodology for the simulation and prediction of space heating energy consumption in buildings connected to a district heating system, and their results shown that climate and human behavior are two main factors playing important roles in the model. Lam et al. [24] analyzed future building energy use in subtropical Hong Kong, and proposed a new climatic index *Z* determined for past (1979–2008, measurements made at local meteorological station) and future (2009–2100, predictions from general circulation models) years.

Chinese studies of household heating conducted to date have primarily focused on aspects such as architectural design and heating appliances and their benefits. The Chinese kang is an ancient integrated home heating system; however, these systems differ among regions. Bin et al. [25] investigated the thermal environments of rural residences that contained a coupled Chinese elevated kang and passive solar collecting wall heating system in northeast China and provided preliminary information regarding the indoor thermal environment of new rural energy-saving residences in winter. Zhi et al. [26] evaluated the thermal performance of Chinese kangs as a rural home heating system in Northern China. Jing et al. [27] introduced technology and case analysis of heat metering and energy efficiency retrofitting of existing residential buildings in northern areas of China. Yun et al. [28] designed an incentive mechanism for improvement of the energy efficiency of residential buildings in northern China. Jie et al. [29] compared urban and rural residential thermal comfort under natural ventilation conditions through a field survey conducted in Hunan Province and found that rural occupants had relatively lower thermal expectations than urban occupants, and that this was likely because fewer air-conditioners were used in the rural area evaluated.

Based on field observation data, this study establishes a mathematical model that simulates temperature changes and analyzes energy associated with household heating during winter in the loess hilly area. According to the relative national standard, we issued a heating energy indicator that adapts to the suitable living construction requirements of rural China, and estimated the potential for thermal efficiency of household heating to be improved by the application of energy-saving technologies. The goal of this study is to put forward policy suggestions to ameliorate rural energy construction, and to provide a scientific basis to strengthen rural public services and improve the livelihood of rural residents.