Renewable Energy 87 (2016) 1059–1066

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Assessment of an integrated active solar and air-source heat pump water heating system operated within a passive house in a cold climate zone

M. Shan [a], T. Yu [b], X. Yang [a, *]

[a] Department of Building Science, Tsinghua University, Beijing 100084, China
[b] Qingdao Hongrui Electric Power Engineering Consulting Co., Ltd, Shandong 266100, China

ARTICLE INFO

Article history:
Received 28 March 2015
Received in revised form
7 September 2015
Accepted 9 September 2015
Available online 29 September 2015

Keywords:
Energy saving
Passive solar
Active solar
Air-source heat pump
Overheating

ABSTRACT

In the pursuit of energy savings and emission reductions, solar energy heating systems have been promoted in China. However, there still exist many barriers to the operation of solar heating systems, in combination with other systems, under realistic conditions. In order to investigate this further, an integrated space heating system including passive sunspace, active solar water heating, and air-source heat pump (ASHP) was built. The detailed running performance of each subsystem was comparatively analyzed in a full-scale test house in a cold climate zone. This integrated system showed many encouraging results in terms of the maintenance of a stable and comfortable indoor thermal environment during the winter season. The study building consumed electricity as convectional energy, which only accounted for about one-third of the total energy supplied for heating. However, our study also found some shortcomings in the system design. Feasible suggestions regarding the running procedures aimed at a more optimal and effective design were proposed. The systems proposed in this study could be used as a promising future technology for energy savings and emission reductions in rural buildings. The study could also help achieve targets for energy savings and renewable energy utilization in China and other countries.

1. Introduction

With the development of the Chinese economy, energy consumption in the residential sector of rural areas has increased greatly over the last several decades. A recent large-scale national survey on energy consumption and indoor environmental quality in Chinese rural houses showed that the total energy consumption in this sector had reached 317 million tons of coal equivalents (tce) (9.3×10^9 GJ) per year [1]. I The widespread use of solid fuels (e.g. coal, wood, and straw) for space heating and cooking leads to negative impacts such as shortages in national energy supply, indoor and outdoor air pollution [2], and human health threats [3]. A recent study [4] indicated that in Beijing, soil dust, coal combustion, biomass burning, traffic emissions, industrial pollution, and secondary inorganic aerosols were the main sources of the identified $PM_{2.5}$. Coal and biomass burning in rural areas may contribute 15–20% of primary $PM_{2.5}$ emissions. Therefore, an increased utilization of clean renewable energy is important.

Solar energy technologies show much promise, considering their ever-increasing output efficiencies and adaptability to a variety of regions. The use of solar energy has experienced rapid growth in recent years due to both cost reductions resulting from technological improvements, and the support in the form of government policies. Solar energy usage has been emphasized in the National Guideline on Medium- and Long-Term Program for Science and Technology Development of China 2006–2020 [5]. Solar water heating is one of the most popular solar thermal systems, and accounts for 80% of the solar thermal market worldwide [6]. Over the past four decades, solar water heating systems have gained a wide application in the building sector on a global scale [7–11]. China has also experienced a strong growth in the solar water heater industry. The production of domestic solar water heaters increased from 3.5 million m^2 in 1998 to 125 million m^2 in 2008, with an annual average growth rate of 25% [12].

Most areas within the cold climate zone in China have 3000–3200 annual hours of sunshine, and 5860–6670 MJ/m^2 of

* Corresponding author.
E-mail address: xyang@tsinghua.edu.cn (X. Yang).

http://dx.doi.org/10.1016/j.renene.2015.09.024
0960-1481/

annual solar radiation [13]. The utilization of solar energy for heating has the advantages of higher heat collecting efficiency and less possibility of freezing of water pipes and collectors [14]. A few demonstration projects have shown ways to utilize solar water heating systems in different types of building in China [15–18]. However, these systems encountered such problems as high initial cost, low average room temperatures, and excessive auxiliary energy consumption.

Due to its unstable nature, solar energy alone cannot provide adequate heating in buildings, and auxiliary heat sources are needed. Most rural houses in the cold climate zone of China have south-facing windows or attached sunspaces that can provide passive solar heating in winter [19,20]. Consequently, when various sub-systems (e.g. passive solar, active-solar, heat pumps, etc.) are integrated, additional challenges concerning both design and optimal operation can emerge. Although previous work on each individual application can be found in the literature, there remains a general lack of knowledge and ambiguity regarding several technological aspects that should be addressed [21,22]. These are: (1) design principles; (2) comprehensive field data and improved results; (3) performance evaluation of multiple sub-systems based on detailed measurements; (4) reasonable and effective running procedures with different systems.

To provide clarity on the integrated system, a comprehensive experimental analysis of passive solar, active solar, and auxiliary heating systems was conducted in this study. The findings could further the understanding of technical features, identify barriers to effective operation, and propose suggestions to improve the performance of the overall integration system.

2. Study building and system design

2.1. Study building

The study building is a single-story house at the Rural Energy and Environment Laboratory of Tsinghua University, located in Beijing, China (40°23′9.10″N; 116°31′19.28″E). The building is located in a cold climate zone, with average temperatures of 26.5 °C in July and −4.6 °C in January, respectively. This laboratory enables researchers to use an iterative "practical engineering" process to develop and rigorously test new energy technologies in a setting similar to actual rural conditions, as compared to a traditional engineering laboratory.

The house was constructed in imitation of common rural houses in Northern China, and comprised of a bedroom, a living room, and a storage room. The total floor area was around 60 m^2. The house floor was supported by four concrete pillars and suspended 50 cm above the ground to prevent heat transfer to the soil. Hence, the heat transfer boundary condition of the floor is simplified and similar to other external walls. The layout of the study house is presented in Fig. 1, and detailed information on the building envelopes is given in Table 1.

2.2. Integration of system components

The integrated heating system of the study house comprised an attached sunspace as the passive solar energy system, an active solar water heater, and an air-source heat pump (ASHP) as the auxiliary heating source.

The sunspace had a depth of 0.9 m, and the south-oriented internal and external windows both consisted of monolayer glass with plastic-steel frame. The total areas of the internal windows and wall were 6.4 m^2 and 27 m^2, respectively. The external window had a glass to window ratio of 0.78 (18.2 m^2 glass and 23.3 m^2 window). A two-layer curtain was added to improve external window insulation performance, and it consisted of a thin layer coated with radiation reduction material and a thick cotton layer. The curtain was open during the daytime to ensure that sunshine could easily enter the room, and it was closed during the night to reduce heat loss. The thin layer acted to reduce heat loss from radiation, while the thick layer and the air between the two layers acted to reduce heat loss from conduction.

The use of an evacuated tubular collector is ideal for active solar systems, having the advantages of relatively low cost, high efficiency, improved anti-freezing performance, and technological maturity [23]. Three sets of solar water heaters with a total area of 10 m^2 were installed on the roof. Each set contained 26 evacuated glass tubes with a length of 1.8 m, and external and internal diameters of 58 mm and 47 mm, respectively. All evacuated glass tubes were oriented to the south with a 45° inclination angle, and the tubes had a single opening on the top end connected to three stainless steel water tanks (capacity 240 L × 3) which was surrounded by a 10 cm expanded polystyrene (EPS) insulation layer. The main advantage of directly adopting a solar water heater as an active solar energy system is the reduction in the energy consumption of water pumps, due to the combination of collection tubes and water tanks, along with natural circulation.

The air-source heat pump (ASHP) had a scroll compressor with 1840 W of input power. An 800 L stainless steel water tank with a 6 cm rubber plastic insulation layer was used to store the heat generated by the heat pump. The heat was exchanged by a plate heat exchanger connecting the water tank and air-source heat pump. The thermal performance of ASHP under low temperature conditions has been greatly improved in recent years. The primary advantage of adopting ASHP as an auxiliary energy system is the elimination of pollution from coal and biomass stoves, and the avoidance of high running costs from direct electric heating devices. In order to avoid the supplied hot water being mixed with the returning cool water, all hot water tanks were specially designed to connect the heat source loop with the floor-heating loop. Considering the influence of buoyancy, the hot water was pumped from the top of the water tank to the radiant floor, and the water returning from the floor heating system flowed to the bottom section.

Radiant floor heating was adopted as a terminal device due to its increasing popularity in China. It can provide a more comfortable indoor thermal environment as compared to convective heating systems. Furthermore, floor-heating systems provide an optimal compromise between energy consumption and thermal comfort [24]. The configuration of the radiant floor adopted in this study is shown in Fig. 2. From the bottom to the top, the floor was composed of an insulating layer (30 mm), circulation water pipes (Φ20 mm/16 mm) with surrounding concrete (30 mm), a screed coat (~20 mm), and a surface layer of ceramic tile (8 mm). The water pipe spacing was 150 mm.

The entire system schematic is shown in Fig. 3.

2.3. System running procedure

The common temperature priority mode of active solar system and ASHP was designed to study and compare system performance.

The solar collectors operated through natural circulation within the hot water tank. As illustrated in Fig. 3, the ASHP, pump 3, and electromagnetic valves M5 and M6 were simultaneously controlled by the thermometer T2, which regulated the average temperature of the hot water tank connected to the heat pump. When T2 was lower than the set value (35 °C), the heat pump system would run until T2 reached a set value (38 °C). The room heating system could be operated automatically via a comprehensive controller. The room temperature T0 had the highest priority in order to control the operation of the entire space heating system. When T0 was