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The field test and optimization of a solar assisted heat pump system for space heating in extremely cold area

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ABSTRACT

As a kind of sustainable energy source, solar energy is becoming highly valued. Especially in extremely cold areas, the amount of energy consumed for space heating is huge, and the conventional coal heating has polluted the environment seriously, therefore solar heating is significant on both energy and environment conservation. In this study, a solar assisted heat pump (SAHP) system was investigated for space heating under extremely cold climatic condition. The system principle and operation modes was presented, and then the project profile and design procedure were introduced, and finally the system performance was evaluated by field test on typical winter days and modeling via TRNSYS simulation environment. The results show that the solar collector efficiency was 51%, and the solar fraction can reach 66% in December. Economic analysis was also performed and the heating expenses for the present SAHP system was 18 RMB/m^2. Finally, the temperatures of solar energy for both direct heating and storage and only for direct heating (T_{1A} and T_{1B}) were simulated and optimized, which have important significance on the operation time of different operation modes.

1. Introduction

With the aggravating shortage of energy over the world, solar energy is being paid more attention by researchers due to its renewability and sufficiency. Especially in severe cold areas, the conventional district heating not only pollutes the environment but also consumes a lot of un-renewable energy. Therefore, it is significant to use solar energy to replace fossil fuels for heating on both energy saving and environment conservation. However, the available solar energy is intermittent due to the alternating of daytime and nighttime, sunny days and overcast days. For example, the peak of the heating load is in nighttime at which time no solar energy could be used. On the contrary, the solar energy is abundant while the demand of heating is low in daytime. In addition, the thermal heat collected by solar energy usually cannot be used for direct heating because the temperature was not high enough. However, heat pump is an energy-efficient and environment-friendly apparatus, which can effectively utilize a low-temperature heat source for space heating. Therefore, a combination of solar energy and heat pump (solar assisted heat pump) system can improve the quality of the energy available and shows potential for different applications due to its higher energy utilization efficiencies compared to the conventional heating and cooling systems (Kaygusuz, 2000).

A number of investigations have been conducted by researchers in the design, modeling and testing of solar assisted heat pump (SAHP) systems for heating. The studies included the system performances and technical feasibilities for various types, such as SAHP systems for water heating, SAHP systems for space heating (with storage or direct expansion) (Ozgener & Hepbasli, 2007). Hawlader developed a solar assisted heat pump water heating system to research the thermal performance by simulation (Hawlader, Chou, & Ullah, 2001). It is found that the thermal performance of the system is affected significantly by speed of the compressor, solar irradiation, collector area and storage volume, and the matching of solar collector and compressor speed was also important. The effect of the thermal storage device on the performance of the SAHP system was analyzed experimentally and theoretically (Han et al., 2008; Wang, Zheng, Zhang, Zhang, & Yang, 2010). Kaygusuz investigated the performance of the combined solar heat pump system with energy storage in encapsulated phase change material (PCM) packing for residential heating (Kaygusuz & Ayhan, 1999). The average seasonal storage efficiencies of the series, parallel and dual source heat pump systems, the effects of various system parameters were all analyzed. A direct-expansion solar assisted heat pump system, which could realize space heating in winter, air conditioning in summer and supply hot water throughout whole year, was also evaluated (Kuang & Wang, 2006). Based on experimental test, the effects of environmental and structural parameters on the performance of a solar assisted heat pump heating system were also investigated (Kuang, Sumathy, & Wang, 2003).

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Nomenclature

A_S	collector area, m^2
Q_H	heating load, W
J_T	average solar radiation, J/m^2 day
f	solar fraction, %
η_{cd}	average collector efficiency, %
η_L	heat loss factor of piping and thermal storage, %
Q_C	useful gain energy of solar collector, kW
Q_S	energy supplied by solar energy and heat pump, kW
$c_{\rho,C}$	specific heat of collector fluid, kJ/kg K
$c_{\rho,H}$	specific heat of heating fluid, kJ/kg K
$\dot{m}_c$	flowrate of collector fluid, kg/s
ρ_g	ground reflectance
β	slope of surface from horizontal,°
γ	azimuth of surface,°
U_A	overall conductance of house, kJ/(h K)
CAP	house thermal capacitance, kJ/K
C_{min}	effectiveness-C_{min} product, kJ/(h K)
α_0	intercept of the collector efficiency
α_1	negative of the first-order coefficient, kJ/(h m^2 K)
α_2	negative of the second-order coefficient, kJ/(h m^2 K^2)

Symbols

T_1	the fluid temperature at solar collector outlet, °C
T_{1A}	the set value of solar energy for both direct heating and storage, °C
T_{1B}	the set value of solar energy for only direct heating, °C
T_{1C}	the set value of auxiliary energy for freeze protection, °C
T_{22}	the set temperature of solar energy for storage, °C
T_{22A}	the set value when the mode of storage energy for direct heating will operate, °C
T_{22B}	the upper temperature of heat pump for heating, °C
T_{22C}	the lower temperature of heat pump for heating, °C
T_{22D}	the set value at which point the thermal heat in thermal storage tank can be used for anti-freezing, °C
T_S	the set value of solar energy for storage, °C
V	the volume of thermal storage tank, m^3
H	the height of thermal storage tank, m
N	number of nodes
N_1	the top node
N_5	the bottom node

In addition, a series of solar assisted ground-source heat pump was performed by many researchers (Bi, Guo, Zhang, & Chen, 2004; Kaygusuz, 2000; Ozgener & Hepbasli, 2005). They analyzed the influence of solar collector area and total borehole length on system performances using the software of Transient Systems Simulation TRNSYS (Chen & Yang, 2012). Raab et al. validated the model for the calculation of the thermal behavior of ground buried hot water heat stores and found that the deviations between measured and calculated heat quantities do not exceed 5% (Raab, Mangold, & Müller-Steinhagen, 2005). Typically, Ozgener and Hepbasli conducted a comprehensive review on the energy and exergy analysis of solar assisted heat pump systems, especially for ground-source heat pumps (Ozgener & Hepbasli, 2007). The heating efficiency of the system as well as its applicability in residential heating were performed experimentally on a solar-ground source heat pump system during the heating period of a cold region in Turkey (Bakirci, Ozyurt, Comakli, & Comakli, 2011).

SAHP for space heating is a mature technology and has reliable design methods. The size and cost of an active solar heating system affect its successful utilization on a large scale, which depend not only on the heat collected and storage facilities but also on the parameter setting, operation modes, and control methods. However, the studies on system performance were few when all-glass evacuated tube collector and water source heat pump were coupled for space heating. Therefore, the purpose of the study was conducted to present a new SAHP system, which was confirmed in an actual project in extremely cold areas in China. The operation modes and parameter setting were investigated by field test and simulation. The parameter setting was optimized to analyze the operation time of different heat source. Besides, the economy and operation expense of the system were also discussed on the bases of actual operation condition. The study has a certain reference for the design and building of SAHP systems in actual project, especially in extremely cold areas.

2. Description of the system

2.1. System principle

As shown in Fig. 1, the SAHP system consists of solar collector, thermal storage tank, and water source heat pump, auxiliary boiler, heating terminal, heat exchangers, and water pumps. The hot fluid flowing out from the solar collector can be used directly for heating through heat exchanger 1, and also can release heat to the water in the storage tank via heat exchanger 2. The water in the thermal storage tank can be used directly for heating through heat exchanger 3 either. Actually, the water in the thermal storage tank is mostly used as a heat source for the heat pump because its temperature is not high enough for heating directly. An auxiliary gas-boiler is employed in this system, which will be used when the solar energy is not enough to meet the demand of heating load, as well as supplies heat to both solar collector and thermal storage tank to avoid freezing when it is necessary.

In this system, 23 temperature sensors (T_1 to T_{22}, and the ambient air temperature T_a) and 6 solenoid valves (valves 1–6) were employed. The measuring points are shown in Fig. 1. Some of the sensors were set to ensure the stable operation of the system and the switching of different operation modes. The others were set to analysis the parameter changing and the system performance in different conditions.

2.2. Operation modes

As the solar irradiation varies along with the time and weather, different operation modes were designed to improve the system stability in different conditions. The collected solar energy can be used for direct heating or storage, and the thermal energy stored in storage tank can also be used for heating directly or to promote to a higher-level temperature by heat pump. Totally, there are 7 operation modes on the basis of water temperatures at collector's outlet and in storage tank. The preset control values are shown in Table 1.

Mode 1: Solar energy for both direct heating and storage

When the fluid temperature at the outlet of collector reaches the set value of T_{1A} (it is surely higher than the water temperature in storage tank), pumps 1, 2, and 4 will be tuned on and valve 1 will be opened. The hot water from the collector first flows into heat exchanger 1 for direct heating. Afterwards, it goes to heat exchanger 2, where the released heat is then stored.

Mode 2: Solar energy for only direct heating

When the fluid temperature at the outlet of collector reaches the set value of T_{1B}, or it is lower than the temperature in storage tank,