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Performance Analysis of Solar and Air Source Heat Pump Hybrid Heating Systems applied in Shandong Rural Area

H Du[1], X L Zhou[1], L X He[1], D Zhao[1], S Wang[1], N L Liu[1] and P Cui[1]

[1]School of Thermal Engineering, Shandong Jianzhu University, Jinan, Shandong

E-mail: sdcuiping@sdjzu.edu.cn

Abstract. Due to the low efficiency and frosting of the air source heat pump (ASHP) in extreme cold climates, the use of existing solar water heaters or dedicated solar collectors as auxiliary heat sources can further improve the overall operating efficiency of ASHPs. Based on the case study of a typical rural building in Shandong, the simulation models of the solar-air source heat pump (SASHP) systems connected respectively in series and in parallel have been established under the TRNSYS platform. The operating performance and the solar fraction of the two systems have been simulated under different conditions. The results show that the performance of the parallel SASHP system is higher than that of the series SASHP system. The research results can provide certain guideline for the clean heating in rural areas of Shandong province in China.

1. Introduction

The solar-air source heat pump hybrid heating system (SASHP) can provide a better heat source for rural buildings in northern China and also reach a higher operating performance compared to the single air source heat pump (ASHP) system (Poppi et al. 2016, Wu et al. 2018). Recently some researchers have conducted a lot of work on theoretical and experimental studies in terms of solar heating technology. Kaygusuz and Ayhan (1999) developed a solar and heat pump coupling system to provide space heating for a building and the system COP reached 3.0. S. Ghafghazi, Sowlati et al. (2010) designed several solar energy heating systems coupled with biomass energy, industrial waste heat and a boiler, respectively. The results showed that the performance of the solar heating system combined with biomass energy had the highest value among those systems. Hewitt and Huanget al. (2011) designed a solar energy heat pump system and investigated the influences of the parameters (such as the solar collector area, working fluid, supply water temperature and compressor capacity) on the system performance. It was found that under the same conditions, the well-matched parameters of the solar collector area and the heat pump capacity were beneficial to improve the operating performance of the system.

According to the literature review aforementioned, a number of studies on SASHP systems have been well conducted, whereas, few studies have been carried out on the performance simulation of a SAHSP system applied for a rural building in China. In recent years, clean energy heating technologies have been advocated in rural areas under government incentives in China. ASHP systems have been applied to provide space heating for rural buildings. However it has a quite low COP value in lower outdoor air temperature. Therefore, the SASHP hybrid heating system can improve the COP and release the air pollution problem in rural areas. It is highly significant to investigate the feasibility of SASHP systems applied in rural buildings. In this study, a typical rural building in Shandong province is selected as an example to develop the simulation models of different SASHP systems including the building loads, solar collector, thermal storage tank, ASHP and control modules in TRNSYS platform.

2. Building heating load simulation

In this study, a two-story house in a village in the suburb of Jinan City, Shandong province is selected as the case study. The building is located in the cold zone with a moderate solar energy resource. The house was built in 2006, with a total floor area of 220m^2 and a floor height of 3.6 m. The thickness of external wall with a brick-concrete structure is 240 mm. There is no external wall insulation and the window is a single layer glass with aluminum alloy frame. The ground floor layout is shown in Figure 1.

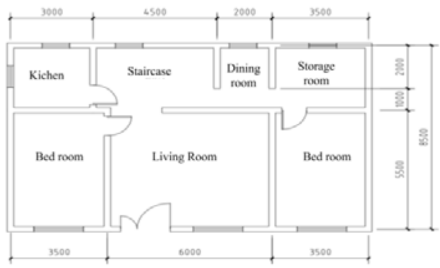

Figure 1. The ground floor layout of the rural building

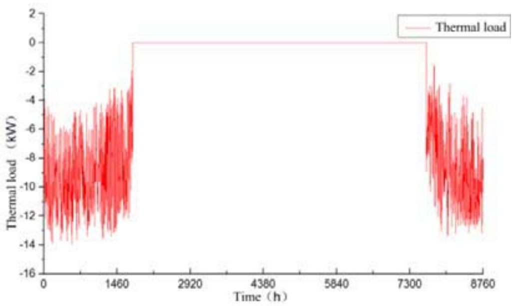

Figure 2. Building hourly heating load

According to the design standard in Shandong province, the design temperatures of the main functional room and the auxiliary function room are set to be 18℃ and 15℃, respectively. Heating period is set up from November 15 to March 15, with 24 hours of continuous heating. In this study, the building hourly heating load is simulated by means of DeST-h software, as shown in Figure 2. It can be seen from Figure 2 that the peak heating load is 14.5 kW in January, and the accumulated heating load is 23268kWh in the whole heating period.

3. Configuration design of SASHP systems

The SASHP heating system consists of two parts: solar collector system and ASHP system, which are coupled by a thermal storage tank or a plate heat exchanger. In this study, two kinds of system configurations are proposed:

No. 1: parallel SASHP hybrid system in which the solar energy is connected with the ASHP in parallel, as shown in Figure 3.

No. 2: series SASHP hybrid system in which the solar energy is connected with the ASHP in series, as shown in Figure 4.

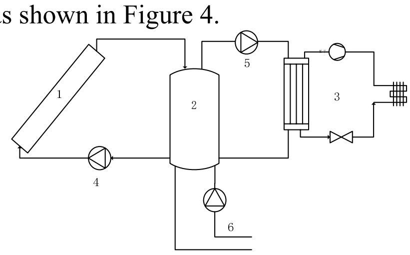

Figure 3. Parallel SASHP system

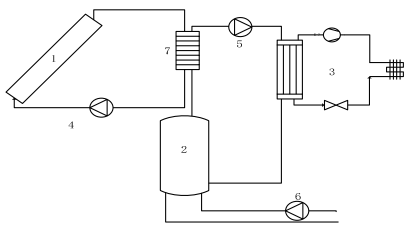

Figure 4. Series SASHP system

1-solar collector; 2-storage tank; 3-heat pump; 4- solar circulating pump 5-circulating pump of the heat pump; 6-load side circulating pump; 7-plate heat exchanger

As shown in Figure 3 and Figure 4, in the parallel system, the water in the storage tank for space heating is heated by the solar collector and ASHP simultaneously; while in the series system, the solar collector takes part in the heating system by heating the return water of the ASHP. In this simulation, the optimal control methods are used to realize the automatic switch of the two heating sources.

4. Simulation and analysis of the SASHP heating systems

4.1. Simulation and analysis of the series SASHP heating system

The simulation model of the series SASHP hybrid heating system is based on a single ASHP system. The basic parameters of the main components are listed in Table 1.

Table 1. Parameters of main components in the series SASHP heating system

Components	Parameters	Quantity
ASHP	LPR-19ID(CL) Heating capacity：16kW Heating power：4.6kW Cooling capacity：13kW Cooling power：4.2kW	1
Storage tank	1m×2m×1m	1
Circulating pump	Flow rate：3500kg/h Pumping head：20mH_2O	2
Solar collector	Area：40m^2	40
Buffer tank	Size：1m×0.5m×1m	1
Circulating pump	Flow rate：1500kg/h Pumping head：20mH_2O	2
Plate heat exchanger	Heat transfer area: 2m^2	1

According to the above information, the parameters of the components in TRNSYS are set and the series SASHP heating system model is built as shown in Figure 5.

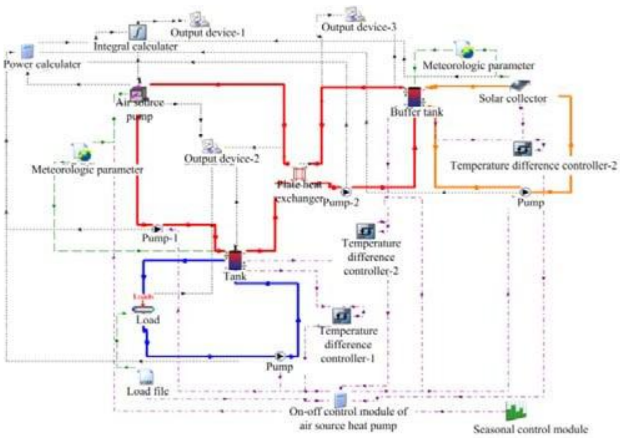

Figure 5. Dynamic simulation diagram of the series SASHP system

The heating system can operate under three different modes. During the daytime, when it is sunny and the collected solar energy is rich enough to provide heating, the solar collector is set to work alone; when the system work at nights or rainy days, the ASHP operates separately; and in other situations, the two parts of the system can work together to provide space heating. The system simulation results are shown in Figures 6-8.

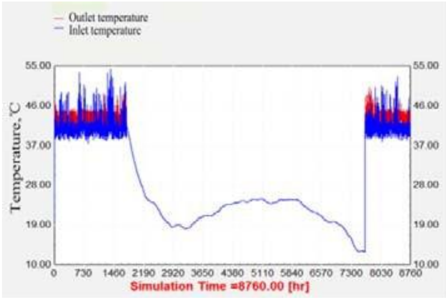

Figure 6. Hourly inlet and outlet water temperature of the heat pump

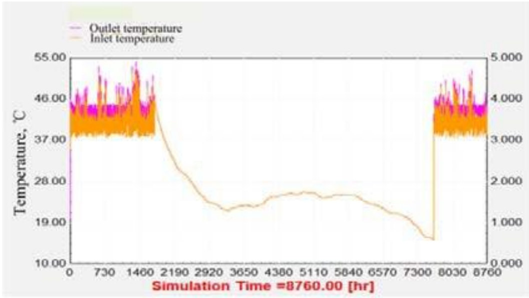

Figure 7. Hourly inlet and outlet water temperature of the storage tank

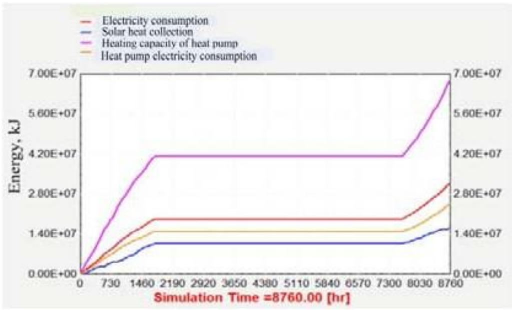

Figure 8. System accumulative heating capacity and energy consumption

As can be seen from Figure 6, when the solar radiation is significantly high, the solar collector system can raise the temperature of return water of heat pump to 45℃. In this case, the ASHP will automatically stop. It should be noticed that the supply water to the space may be higher than 45℃ when the solar radiation is strong. In general, the water supply temperature does not exceed 55℃, which guarantees a relatively comfortable indoor environment.

The efficiency of the solar collector is not only related to the solar collector characteristics, but also to the system configurations. In the series system, the solar collector system does not heat the building directly, which causes a relatively lower value of solar collector efficiency with only 40% during the whole heating season. The solar energy guarantee rate is 20.88%.

4.2. Simulation and analysis of the parallel SASHP system

The development of this system configuration is to combine the ASHP and solar collector in the parallel way to provide the space heating. The parameters of the main components are shown in Table 1. According to the component information, the parameters of the components in TRNSYS are set, and the simulation model of a parallel SASHP heating system is built as shown in Figure 9. In this simulation model, as long as the collector side circulating pump starts to work, the three-way valve will be open according to a preset ratio. Otherwise, the ASHP system works alone.

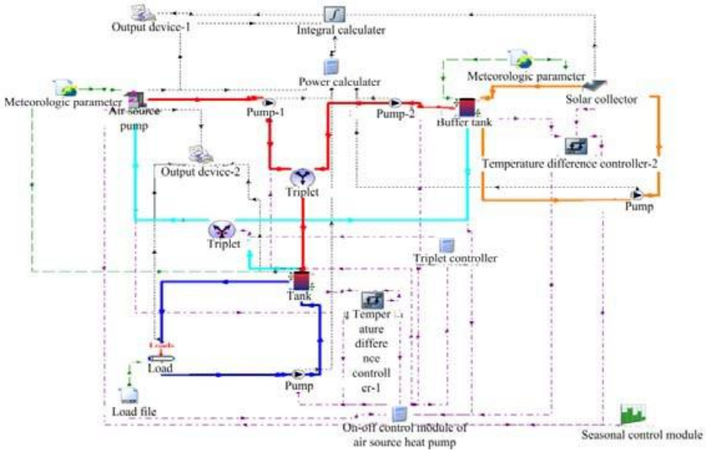

Figure 9. Dynamic simulation diagram of the parallel SASHP heating system

The simulation results are shown in Figures 10-12.

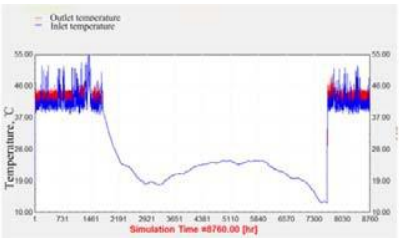

Figure 10. Hourly inlet and outlet water temperature of the heat pump

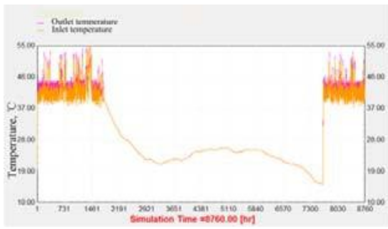

Figure 11. Hourly inlet and outlet water temperature of the storage tank

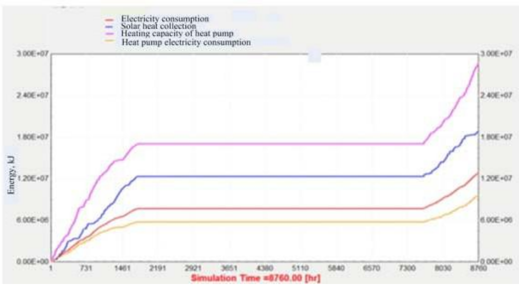

Figure 12. System accumulative heating capacity and energy consumption

It can be seen from Figure 10 that there are three operation modes of the system. The supply water temperature and return water temperature in the heat pump keep the same during a period of time, which indicates the solar collector system works alone. In this period, the solar collector system can satisfy the building load independently because of the rich solar radiation. It can be seen from Figure 11 that the water supply temperature of the system is almost constant between 40℃ and 45℃ during the ASHP working time.

5. Comparisons of simulation results between different systems

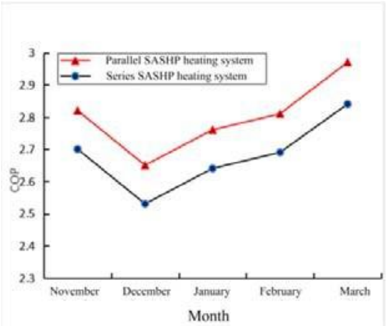

Figure 13. Variation of system COP of SASHP heating systems

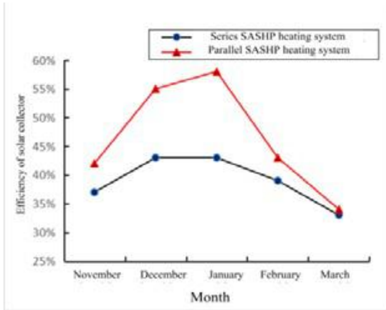

Figure 14. Variation of solar collector efficiency of SASHP heating systems

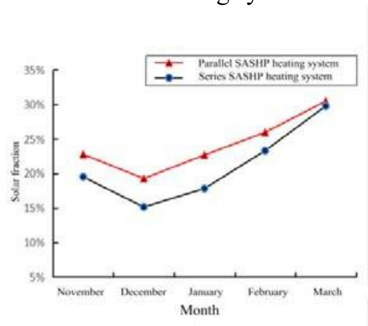

Figure 15. Variation of solar guarantee rate of SASHP heating systems

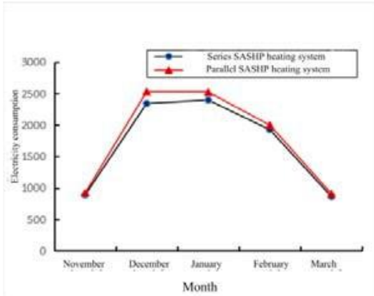

Figure 16. Variation of system power of SASHP heating systems

It can be seen from Figure 13 to Figure 16 that the parallel SASHP heating system shows obvious advantages compared to the series SASHP system. The average COP of parallel system is 2.77, and the average solar collector efficiency and the average solar guarantee rate are 46% and 24.2%, respectively. Although the total power consumption of the parallel hybrid system is reduced by only 459 kWh compared to the series hybrid system, the efficiency of the solar collector system in parallel system is 17% higher than that of series system. In addition, if the solar collector and the ASHP connect in series, the heated water from the solar collector enters the condenser of the ASHP, which would result in a higher temperature of the return water and the decrease of the system COP. Therefore, the parallel SASHP heating system is more suitable for rural residential heating in Shandong province.

6. Conclusions

In this study, two kinds of SASHP heating systems are proposed which are series and parallel hybrid heating systems and their simulation models have been developed in the TRNSYS platform based on a real rural building located in Shandong province. According to the analysis of the annual energy consumption, the annual average efficiency of the solar collector and the solar fraction, it is concluded that the performance of the parallel SASHP heating system is better than that of the series SASHP system.

7. Acknowledge

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