Energy-saving Design and Operation Strategy of Solar Water Heating System Assisted with Air-source Heat Pump

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Abstract. At present, the widely combined use of air-source heat pump and solar water heating system have improved the energy utilization efficiency of the whole hot water system. However, the best combination of the two has not been found, and the original combination has not maximized the utilization of solar energy and precise control of water supply. In order to solve this problem, we established a solar-air source heat pump water heater by taking the domestic hot water system in a college dormitory in Hengyang area. The Transient System Simulation Tool (TRNYSY) was used to build a simulation model. We proved the feasibility of the system by its heat transfer rate and performance parameter. And we numerically analyzed the monthly total electricity consumption and total annual electricity consumption of the system equipment to verify its economy. The simulation results showed that the solar-air source heat pump water heater could effectively improve the problem of low joint efficiency of hot water system, avoid energy waste, and verify the correctness and effectiveness of the established system.

1. Introduction
With the rapid development of the social economy, the air-source heat pump assisted solar heating technology is quite mature. The combination of the two as the heat source of the centralized hot water system can complement each other and is an ideal heating method. However, if the overall system energy consumption is to be further reduced, the system should be optimized with appropriate control strategies. There are three different control methods at present: time control method, double water tank control method, single water tank plus water level control method [1]. Among them, the advantages of the double tank control method are more prominent. Banister et al. [2] studied the two-tank system of solar-assisted heat pump, and the results showed that the two-tank system had higher energy saving rate than the single-tank system. Xiaodan Wang et al. [3] also found that the energy consumption of the two-tank system could be reduced by 45% in summer and 9.5% in winter.

However, the above control schemes cannot properly adjust the control strategy according to the current water consumption situation [4]. They cannot effectively calculate the opening time of the heat pump [5] and accurately control the water volume and water temperature. They do not maximize the use of solar energy, and the system still has a lot of energy saving space.

In this paper, the air-source heat pump assisted solar water heating system was used as the object, and the control modes under different weather conditions and water working conditions were studied by
using the double water tank control method. We maximized the use of solar energy while it met the demand for water. The following is a schematic diagram of the system water supply.

![Schematic diagram of solar water heating system](image)

1. Control system 2. Large tank 3. Small tank 4. Solar energy collector 5. Air-source heat pump 6. Water pump 7. Temperature sensor 8. Water level gauge 9. Inlet valve 10. Outlet valve 11. Solar radiation sensor 12. Hot water circulating pump 13. Check valve 14. Return pipe temperature sensor 15. Internet

Figure 1. Schematic diagram of solar water heating system assisted with air-source heat pump

2. Design of combined heating water system

2.1. Determination of basic parameters

We took the hot water system of a school dormitory in Hengyang City as an example, which is used for bathing hot water for 300 students. With reference to the Code for Design of Building Water Supply and Drainage [6], the monthly water consumption is designed as shown in the following table. The daily concentrated water time is from 18:00 to 23:30, the heat pump opening time is 14:00, the hot water consumption is 12.25 t/d, the hot water temperature is 45°C, and the design cold water temperature is 15 °C [7].

| Month | Property                  | Daily water consumption of 300 people (t) |
|-------|---------------------------|------------------------------------------|
| 2、7、8| College vacation          | 0                                        |
| 5、6、9| Summer                    | 12                                       |
| 4、10  | Transition season         | 18                                       |
| 11、12、1、3| Winter     | 24                                       |

2.2. Design and calculation of solar collector

The solar collector uses forced circulation, the collector is consistent with the local latitude, and the inclination is set to 20° [8]. With reference to the Selection and Installation of Solar Centralized Hot Water System [9], the total area of the direct system collector can be directly calculated from the daily average water consumption, temperature and other known variables. In this project, the area of the solar collector is 140m². In this project, the collecting water tank is 9.8 m³, and the collecting water tank is 2m³.

2.3. Calculation of hot water load value

Daily hot water load value is [10]:

$$q_r = \frac{q_1 (60 - T_1)}{(T_e - T_r)}$$

(1)

In this formula: $q_r$ is the per capita daily hot water consumption corresponding to the mixed hot water temperature. $q_1 = 30 \text{ L per person per day}$[8]. $T_e$ is the mixed hot water temperature used by the user. $T_e=45^\circ \text{C}$. $T_r$ is the daily tap water temperature, $T_r=15 ^\circ \text{C}$. 


The hot water quota at 60° C recommended by the Standard for Water Saving Design in Civil Buildings \[1\] is converted by the formula (1). In this paper, the daily hot water consumption period is distributed from 18:00 to 23:30, and the water consumption time is 5.5h.

2.4. Air-source heat pump

In this paper, the air-source heat pump was operated in a heating condition. And the heating capacity, power, output heat pump COP, evaporator side air outlet temperature, and condenser side fluid outlet temperature were calculated according to the evaporator side air and the condenser side fluid inlet temperature conditions. With reference to the standard Selection and Installation of Solar Centralized Hot Water System \[9\], Standard for Water Saving Design in Civil Buildings \[11\], and Specification of Solar Water Heating System Assisted with Air-source Heat Pump (for capacity of water tank more than 0.6m\(^3\)) \[12\], we conducted a preliminary design through the above calculation, the initial parameters of the system components were shown in Table 2.

| Component                  | Parameter | Value       | Component                  | Parameter | Value |
|----------------------------|-----------|-------------|----------------------------|-----------|-------|
| Heat collector             | Area/m\(^2\) | 140         | Heat collecting small tank | Heat loss coefficient /kJ.h\(^{-1}\).m\(^{-2}\).K\(^{-1}\) | 0.8    |
| Hot water circulating pump | Rated flow / (kg.h\(^{-1}\)) | 10200 | Air-source heat pump       | Rated heat output/kW | 46.3   |
|                           | Rated power /W | 400         |                            | Rate power/kW | 10.4   |
| Heat collecting large tank| Volume/m\(^3\) | 9.8         | Heat circulating pump      | Rated heat output /(kg/h) | 9500   |
|                           | Heat loss coefficient /kJ.h\(^{-1}\).m\(^{-2}\).K\(^{-1}\) | 2.5          |                            | Rate power/W | 400    |

3. System simulation based on TRNSYS

3.1. Establishment and operation strategy of TRNSYS model

We established a simulation model of solar air-source heat pump combined heating water system for college student apartment based on TRNSYS software.

| System parts                  | Parts code | Parameter setting                                                   |
|-------------------------------|------------|---------------------------------------------------------------------|
| Solar collector               | Type1b     | Collector area: 140m\(^2\)                                          |
| Air-source heat pump          | Type941    | Instantaneous efficiency intercept: 0.8                            |
| Water pump                    | Type114    | First order heat loss coefficient: 13kJ/(hm\(^2\).K)                |
| Seasonal water consumption    | Type14b    | Second order heat loss coefficient: 0.05kJ/(hm\(^2\).K)              |
| Temperature controller        | Type2b     | Heat output: 230kW, Rated power: 71.8kW                             |
| Heat collecting large tank    | Type4      | Set according to different purposes of the pump                     |
| Heat collecting small tank    | Type4      | Set according to the daily water usage time                         |
| Weather parameters            | Type15-2   | Set according to seasonal water consumption                         |
| Integrator                    | Type24     | Set according to the control requirements of the collector         |
| Output display                | Type65a    | circulating pump and the auxiliary heat collector of the heat pump units |

3
According to the weather conditions or the sunshine radiation, the solar water heating system is operated separately, the air-source heat pump and the solar energy are operated together, and the air-source heat pump unit is separately operated. The small tank is used to replenish water to the large tank. We proposed that when the water volume of the large tank is one quarter of the full volume, the small tank is selected to replenish the water volume of the large tank.

3.2. System simulation model based on TRNSYS
We set the model parameters and the control running strategy in the TRNSYS software and got the simulation model diagram as shown in Figure 2. The simulation time is one year. The heat-collecting capacity, auxiliary heating amount and other data need to be accumulated. And we calculated the system performance parameter.

![Figure 2. Schematic diagram of air-source heat pump assisted solar water heating system model](image)

3.3. Analysis of simulation results
The heat sources of the system are solar energy and air source heat pump. The output component is connected with the meteorological component and the heat storage tank, etc. The output is shown below.

3.3.1. Analysis of heat transfer rate.

![Figure 3. Solar radiation and other heat transfer rate](image)

As we can see from the above figure, the total monthly radiation amount of solar energy varies greatly during the year. In January, the total monthly radiation amount was 8621 kWh for the whole year and reached a maximum value of 17612 kWh in September. The available energy curve absorbed by the collector showed that the available energy absorbed by the solar collector reached a maximum of 7261 kWh in September and a minimum of 2763 kWh in January. According to the heat curve provided by the air source heat pump, the air-source heat pump assisted heat quantity reached a maximum of 25664 kWh in January and a minimum of 1472 kWh in September. Overall, the total monthly solar radiation in summer was significantly higher than that in winter, while the available energy absorbed by the
The collector and the heat supply of the air-source heat pump showed opposite trends, both of which showed that the winter value was higher than the summer value.

3.3.2. *Performance of air-source heat pump*

![Figure 4. Solar collecting efficiency and COP](image)

The figure 4 showed that the solar heat collection efficiency $\eta$ was about 40%, which reached a maximum of 43% in October and a minimum of 32% in January. The COP of the air source heat pump system was about 4. The COP of the air source heat pump system is 0 in February, July and August, which reached a maximum of 4.7 in June and a minimum of 3.3 in January. In general, the COP of the transitional air-source heat pump is slightly larger than that of spring. The annual heat collection efficiency can reach more than 38%. The overall efficiency is higher. The heat pump units have better performance. The air source provides 73% of the heat. Therefore, this system has high energy utilization rate of heat pump.

3.3.3. *System power consumption.*

Taking month and year as the integration time, we analyzed the monthly and annual data of each device. The monthly power consumption and total power consumption of each device are shown in Figures 5. and 6. The total annual power consumption data of each equipment is shown in Table 4.

![Figure 5. Monthly consumption of each device](image)

![Figure 6. Total consumption of all devices](image)

**Table 4. Annual power consumption of each device**

| Device                     | Energy consumption (kWh) |
|----------------------------|--------------------------|
| Heat pump                  | 178.9                    |
| Heat circulating pump      | 545.1                    |
| Air source heat pump       | 31841.6                  |
The monthly total energy consumption of air-source heat pump and the monthly total energy consumption of heat collecting pump had the same change trend, which was higher in winter than that in summer. In January, they reached the maximum value. In September, they reached the minimum value. In contrast, the energy consumption of circulating heat pump in summer was higher than that in winter. It reached a maximum of 77.2kWh in June and a minimum of 39.5kWh in January.

The total monthly power consumption of the system equipment varies significantly from month to month. It was much higher in winter than that in summer, and it reached a maximum of 7731kWh in January and only 398kWh in September. Combined with the total annual power consumption of each equipment, it can be known that the air-source heat pump consumes the largest amount of electricity, accounting for more than 97%, with a total annual power consumption of 32565kWh.

4. Conclusion

The analysis results were summarized as follows:

1. In this paper, the simulation model of air-source heat pump assisted solar water heating system was built by TRNSYS. Combining the simulation results, we analyzed the heat exchange capacity, heat pump performance and power consumption of the system. The comparative analysis of various factors showed that the combined hot water supply system was more energy-efficient than the traditional solar water heating system and the air-source heat pump water supply system. The system has certain guiding significance for engineering optimization design.

2. When simulating the school hot water system in Hengyang area, we found that the working efficiency of the system varied with the seasons. In winter, the solar heat collecting efficiency was the highest. In the transitional season, the air-source heat pump had the highest heat collecting efficiency. We can reasonably optimize the system through the change of system work efficiency caused by seasons, which can provide some guidance for the optimization design of air-source heat pump assisted solar water heating system.

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