Simulation on Solar assisted Air Source Heat Pump Heating System in Rural House by Using TRNSYS

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Abstract. According to the simulation software TRNSYS to simulate the Solar assisted Air Source Heat Pump Heating System in a multilayer rural houses in Lanzhou area. By analysis simulation data on solar and air source heat pump as the heat source, providing energy for the low-temperature radiant floor heating, the paper discusses the feasibility and comfort of this system. Based on the solar radiation characteristics, the advantages of this system was given out, developing the building energy efficiency.

1. Introduction
Under the dual pressure of energy demand and environmental protection, solar energy is a kind of sustainable clean energy, which is inexhaustible, and will inevitably become one of the main energy for human use in the future. Wang Lipu and Li Jinping [1] pointed out that solar energy is the most convenient, promising and renewable building energy in the world. In the three coldest months (December, January and February) of heating season, the daily average solar radiation in Northwest and North China is 9000-15000kJ/m². According to the calculation of using full glass vacuum tube solar collector, the daily heat collection time is considered as 8 hours, the building area heat index is calculated as 50W/m², the water temperature difference between heating supply and return is 15°C, and the daily heating time is 8h, so the required collector area per unit of building area is between 0.21-0.37m² [2].

According to different low-temperature heat sources, heat pumps can be divided into the following five types: water source heat pump, air source heat pump, ground source heat pump, solar energy heat pump, etc. [3]. Air source heat pump is a kind of heat pump system which transfers the heat energy in the air from low-grade energy to high-grade energy by inputting a small amount of high-grade energy (such as electric energy). It is convenient and practical, and can be used throughout the year without the influence of weather factors. But because the temperature of the low-temperature heat source of air source heat pump will change with the outdoor temperature, when the outdoor temperature drops, the efficiency of the heat pump will decrease. Therefore, the air source heat pump heating hot water system has certain requirements on the ambient temperature when it is used in winter [4].

According to the advantages and disadvantages of solar water heating system, using the characteristics of air source heat pump as auxiliary heating, the solar auxiliary air source heat pump heating system is composed of two systems organically. In most cases, most of the buildings in rural areas are single story and two story below. There is enough space to install heat collection system and air source heat pump hot water system. According to this area ratio, it can be fully realized. Therefore, it is feasible to use solar energy for heating in rural areas. In this paper, TRNSYS software is used to
simulate the two-story residence in Lanzhou area. The temperature change, load change, solar fraction change with outdoor solar radiation, water temperature at the outlet of air source heat pump water heater and water temperature of water storage tank are analyzed during the heating period. Thus the feasibility and superiority of solar auxiliary air source heat pump heating system in rural areas of Lanzhou are obtained.

2. Overview of simulation building
The two-story rural residence in Lanzhou area is selected as the simulation building. According to the building thermal zone prescribed by *Thermal design code for civil building* (GB 50176-1993), Lanzhou is a cold area, which needs heating because of its cold and long winter. The outdoor calculated (dry bulb) temperature for heating in winter is -11℃, and the coldest month is January. Lanzhou area is rich in solar energy resources. In the coldest month in winter, the average monthly solar radiation on the horizontal surface in January is 8.178MJ/m²·d, the average monthly solar radiation on the inclined surface is 11.312MJ/m²·d, and the monthly sunshine hours can reach 162 hours [5]. The simulated building plan is shown in Figure 1 and Figure 2.

![Figure 1. The architectural plan 1 floor of simulation](image1)

![Figure 2. The architectural plan 2 floor of simulation](image2)

The total building area of this simulation is 190.84m². According to the *Energy conservation design standard for heating residential building* DB62/T25-3033-2006 in Lanzhou area, the building shape coefficient should not exceed 0.3, and when it exceeds 0.3, the thermal insulation performance should be strengthened. Therefore, according to the above requirements, the thermal parameters of building envelope structure are shown in Table 1.
Table 1 Thermal parameter of building palisade structure

| Building palisade structure | Materials                                                                 | The heat transfer coefficient of the enclosure structure [W/(m²·k)] |
|-----------------------------|---------------------------------------------------------------------------|---------------------------------------------------------------|
| Exterior wall               | 20mm cement mortar + 50mm polystyrene composite plate + 10mm air layer + 240mm porous brick + 20mm cement mortar | 0.38                                                          |
| Roof                        | 4mm waterproof layer + 10mm plasterboard + 112mm fiberglass + 19mm roof structure | 0.316                                                         |
| Floor                       | Under the concrete base along the outer wall 2 m of the 150 mm thick 2.8 plaster benzene board insulation layer | 0.497                                                         |
| Window                      | Single frame insulating glass window                                       | 1.3                                                           |
| Exterior door               | Insulated exterior door                                                    | 2                                                             |

The heating system of the building is solar energy low temperature floor radiation heating, the surface is wooden floor, the filling layer is light cement, the coil spacing is 200mm, the pipe diameter is DN20, and the insulation layer is 60mm thick benzene plate. The solar low temperature floor radiant heating system is composed of flat-plate collector, collecting thermal cycling water pump, heat storage water tank, auxiliary heat source and heating coil.

3. Main calculation basis and equipment parameters

3.1. Heating load calculation

According to the regulation of literature [5], the heating load of solar energy collection system is the building heat consumption under the condition of calculating the outdoor average temperature during the heating period. The heat consumption of the building is calculated according to the following formula [6]:

\[
q_H = q_{HT} + q_{INF} - q_{IN}
\]  (1)

In the formula, \(q_H\) is the heat consumption of the building per unit building area, W/m²; \(q_{HT}\) is the heat consumption of heat transfer through the enclosure structure per unit building area, W/m²; \(q_{INF}\) is the heat consumption of air infiltration per unit building area, W/m²; \(q_{IN}\) is the heat gain in the building per unit building area, W/m².

The heat consumption of heat transfer through the enclosure structure is calculated as follows:

\[
q_{HT} = (t_i - t_c) \sum_{i=1}^{N} \varepsilon_i K_i F_i / A_o
\]  (2)

In the formula, \(t_i\) is the calculated temperature of indoor air. According to the Code for design of heating, ventilation and air conditioning, the indoor design temperature of civil residential buildings is generally 16-20°C. The Code for low temperature radiant floor heating system stipulates that "for the calculation of the heating load of radiant floor heating, the indoor calculated temperature should be 2°C lower than the conventional calculated temperature", and the indoor design temperature is 16°C; \(t_c\) is the outdoor average temperature, °C, and the outdoor average temperature for the calculation of heating is -11°C; \(\varepsilon_i\) is the correction coefficient of the heat transfer coefficient of the enclosure structure; \(K_i\) is the heat transfer coefficient of the enclosure structure, W/(m²·°C); \(F_i\) is the area of the enclosure structure, m²; \(A_o\) is the building area, m².

The heat consumption of air infiltration is calculated as follows:

\[
q_{INF} = (t_i - t_c) (C_p \rho N V) / A_o
\]  (3)

In the formula, \(q_{INF}\) is the heat consumption of air infiltration, W; \(C_p\) is the specific heat capacity of air, taking 0.28 (W·h)/(kg·°C); \(\rho\) is the air density, taking the value under the condition of \(t_c\), kg/m³; \(N\) is the number of air changes, times/h, and the number of ventilation in the heating room in winter is
not less than 0.5 times/h; $V$ is the volume of air changes, m$^3$.

3.2. Calculation of collector area

The determination of collector area is based on the characteristic monthly solar radiation and heating load in winter, which is calculated according to the following formula:

$$ A_c = \frac{86400 Q_H f}{J_f \eta_{cd} (1 - \eta_L)} $$

In the formula, $A_c$ is the total area of the collector of the direct solar heating system, m$^2$; $Q_H$ is the daily average heating load, W; $J_f$ is the average daily solar radiation on the inclined surface of the collector installation during the local heating period, J/m$^2$; $f$ is the solar fraction, which shall be determined based on the comprehensive consideration of solar radiation conditions, system economy and user requirements during the service life of the system, generally taking the value of 0.3-0.8; $\eta_{cd}$ is the average heat collection efficiency during the service life of the system, which is 0.42 this time; $\eta_L$ is the heat loss rate of the pipeline and water storage tank, which is 0.2 this time.

3.3. Calculation of auxiliary heating capacity

The calculation of the heating capacity of the auxiliary heat source is based on the most extreme case, that is, in the hot water system, the heat is provided by the auxiliary heat source, and the solar radiation provided by the sun is 0. According to the hot water supply load, it can be calculated according to the following formula:

$$ P = \frac{24 Q_d}{\eta_a (1 - \eta_L) T} $$

In the formula, $P$ is the power of auxiliary heat source, W; $Q_d$ is the daily average hot water load, W; $\eta_a$ is the thermal efficiency of auxiliary heat source heating equipment, %; $\eta_L$ is the heat loss rate of pipeline and water storage tank, which is 0.1 this time; $T$ is the daily heating time of designed auxiliary heat source, h, which is 24h this time.

3.4. Main equipment parameters

The selected equipment parameters are as follows. For the collector side of the solar collector, the collector bears the building load, and the collector is calculated by formula (4). In case of bad outdoor sunshine or rainy weather, there is electrical heating to bear the load. For the load side, the flow rate in the indoor floor heating pipe is calculated according to the water temperature difference between the supply and return of about 10°C, and the flow rate in the pipe is guaranteed to be within the scope of the national design standard. The heating capacity and heat loss of the heat storage tank are not considered in this paper. This simulation building is a single story building, so the downward heat transfer of the floor radiation heating system is not considered. See Table 2 for the parameters of each component of the heating system.

| Component Parameters | Parameters |
|----------------------|------------|
| Collector area (m$^2$) | 14         |
| Heat collecting circulating pump flow (m$^3$/h) | 1.008 |
| Heat storage tank cubage (L) | 1400 |
| Air source heat pump hot water unit (KW) | 3.8-30.1 |

4. System simulation and analysis of simulation results

TRNSYS software, that is, A Transient System Simulation Program, now widely used as a kind of computer program code. TRNSYS uses a system specific language, allowing users to program components. Users can use C language, FORTRAN language and other programs to write their own components. These components constitute different systems through configuration and connection. TRNSYS component is a modular design software, which is composed of modules with different
functions according to requirements. All modules in the system have their own unique functions, so that the thermal system required by user modeling has great flexibility. Each component is assigned a specific type. By building a model of multi area building components (type56a) according to the actual building situation, and selecting components for connection according to the system needs, the connection mode of the solar low-temperature floor radiation heating system constructed in this paper on the TRNSYS platform is shown in Figure 3.

![Figure 3. The simulation diagram of system](image)

4.1. Relevant data analysis of simulation room

The simulation time is the whole heating period, from November 1 to March 31 of the next year, totaling 151 days. The weather data adopts the time-by-time data of China's typical weather, which can be set by the component Type 109 in TRNSYS. TRNSYS software is used to simulate the main room temperature and outdoor temperature of the experimental room during the heating period. The simulation curve is shown in Figure 4.

![Figure 4. The variation of indoor and outdoor hourly temperature in heating period](image)
bedroom, the second floor bedroom 1 and the bedroom 2, respectively. It can be seen from Fig. 4 that through the energy-saving design of the enclosure structure and the heating of the room, the indoor temperature of the living room 101 on the first floor, the living room 105 for the elderly, the bedroom 201 on the second floor and the bedroom 204 are all maintained between 10℃ and 25℃. The temperature of the three bedrooms is above 16℃, which can meet the requirements of the indoor heating design temperature of 16℃, and the indoor thermal environment is better. The living room has a large area relative to the bedroom, and has an external door and three external windows, with large heat dissipation, so the indoor temperature is relatively low, between 10℃ ~ 20℃, which can meet the requirements of indoor thermal comfort. In the temperature curve of three bedrooms, the temperature of bedroom 105 is higher than that of 204, because 105 has less exterior wall than 204.

Through the change of indoor temperature, the change of indoor heating load in the whole heating period can be simulated. Take the coldest month January as an example to illustrate the change of indoor heat load with temperature, as shown in Figure 5. From Figure 5, it can be seen that the indoor heating load is inversely proportional to the outdoor temperature, and the indoor heating load decreases with the increase of outdoor temperature, and vice versa. We take the living room 101, the elderly bedroom 105, the bedroom 201 and the bedroom 204 as the typical rooms to study the heating load. The living room is located in the upper part of Fig. 5 due to the large area of the room enclosure structure, one external door and three external windows, which consume a lot of heat due to the infiltration of cold air and need a lot of heating load to maintain the indoor temperature. Due to the small area of the other three rooms, the required heating load is located below Q101. The structure of bedroom 105 and bedroom 204 is roughly the same, but bedroom 204 has one more exterior wall than 105, so the heating load of 204 is greater than 105.

![Figure 5. The hourly heat load of typical room changes with ambient temperature in January](image)

**4.2. Correlation analysis of solar collector system**

Figure 6 shows the variation curve of solar fraction and inclined plane solar radiation quantity during heating period. It can be seen from the figure that the daily solar fraction f is not the same in the simulation time. In some days, the solar fraction is close to 0%, indicating that the solar effective heat gain in these days is almost 0; in some days, the solar fraction is more than 100%, indicating that the average solar effective heat gain is greater than that required by the laboratory. It can also be seen from the figure that the solar fraction increases with the increase of solar radiation. From the formula of solar fraction, it can be seen that solar fraction = solar effective heat gain/heat required by buildings, so solar radiation is one of the factors affecting solar fraction. In the whole heating period, the solar radiation of inclined plane exceeds 5000KJ/hr.m² in most cases, which indicates that the solar energy resources in Lanzhou area are rich and the potential of light energy is great, which is very suitable for the development of solar heating.
Figure 6. The variation curve from solar fraction to total radiation on titled surface in heating period

Figure 7. The variation curve from the inclined plane of solar radiation and solar heat collector average daily efficiency in January

Figure 7 shows the daily average efficiency of the solar collector and the variation curve of the solar radiation on the inclined plane in January. The figure shows that the efficiency of the solar collector increases with the increase of the solar radiation, and the efficiency of the solar collector is maintained between 0.1 and 0.4 in the coldest month.

4.3. Analysis of hot water temperature of air source heat pump hot water unit

When the weather is bad in the daytime or at night, the solar radiation is insufficient, the water temperature in the heat storage tank cannot reach the set water supply temperature, the air source heat pump is started, and the water in the heat storage tank is heated, so that the water temperature rises, and the hot water temperature required for heating is reached. As an auxiliary heat source, the opening of air source heat pump hot water unit is affected by the water temperature of the heat storage tank. Figure 8 shows the variation curve of the hot water temperature at the outlet of the air source heat pump hot water unit and the outdoor temperature in January. The figure shows that the water temperature at the outlet of the air source heat pump hot water unit changes at about 60°C, which does not reach the maximum set water temperature of 70°C. After heating, the hot water enters the heat storage water tank and enters the room through the coil, which meets the water supply temperature requirements of floor radiation heating.
4.4. Temperature analysis of the heat storage tank
According to the document [5] of solar heating system with short-term heat storage, the volume of the storage water tank corresponding to the solar collector per square meter is 50~150L. Increasing the volume of the heat storage tank can improve the solar fraction of the solar heating system, but increasing the volume of the water tank will increase the heat dissipation capacity of the water tank. Therefore, the heat storage tank of the short-term heat storage system should consider the heat preservation cost of the water tank according to the heat preservation situation of the water tank. For the low-temperature floor radiant heating system, because the floor has certain heat storage function, the volume of the heat storage tank can be appropriately reduced, but in order to ensure the uniformity of heating, the allocation of the heat storage tank shall not be less than 20L/m² [7]. According to various factors, the volume of the heat storage tank is calculated as 100L/m², the area of the solar collector is 14m², so the volume of the heat storage tank is 1400L.

5. Conclusion
Using TRNSYS software, according to the solar auxiliary air source heat pump heating system of this residence, the change of indoor temperature and hourly heating load during heating is studied, and the relationship between the change of building heating load and the change of relevant factors in the whole heating period is obtained. From the simulation, the solar auxiliary air source heat pump heating system can meet the requirements of rural residential heating in Lanzhou in winter, and the indoor thermal comfort can meet the requirements. The research on the characteristics of solar radiation and solar fraction in Lanzhou area shows that the use of solar energy and air energy further proves the feasibility and advantages of solar auxiliary air source heat pump heating, and gives full play to the characteristics of building energy saving.

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