Preliminary Analysis of a Solar Heat Pump System with Seasonal Storage for Heating and Cooling

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Abstract: For higher solar fraction and suitability for both heating and cooling, a solar heat pump system with seasonal storage was studied in this paper.

The system scheme and control strategy of a solar heat pump system with seasonal storage for heating and cooling were set up, which is responsible for the space heating and cooling and domestic hot water for a residential block. Through hourly simulation, the performance and the economics of such systems were analyzed, for the different tank volumes, operating modes and weather conditions.

The results show that 1) for most areas of China, the solar systems with seasonal storage can save energy; 2) for areas with cold winter and hot summer, it is suitable to store heat from summer to winter and store cold energy from winter to summer, but for chilly areas, it is suitable to only store heat from summer to winter; 3) when the ratio of volume of seasonal storage tank to collector areas is 2~3, the system performance is optimal and the payback period is shortest for most areas of north China; and 4) if cooling storage is needed, the seasonal storage coupled with short-term storage may raise the solar fraction largely.

Key words: Solar heating, Seasonal Storage, Heat pump

In most area of China, it is cold in winter and hot in summer. There are about 2/3 areas with annual total horizontal irradiation above 5000MJ/m^2 in China. The resources of solar energy are abundant and they have large potential for solar heating and cooling in these areas.

In order to increase the solar fraction of solar heating systems, the concept of seasonal storage was put forward and some demonstration projects have been built in Europe since 1980's [1]. Seasonal storage charges solar heat collected in summer and discharge heat in winter. To increase the available temperature differences of the seasonal storage and hence reduce the storage size, some solar heating projects introduces heat pumps

1. INTRODUCTION TO THE SOLAR HEAT PUMP SYSTEM WITH SEASONAL STORAGE

1.1 Schematic Diagram and Operating Strategies of Solar Heat Pump System with Seasonal Storage

In order to meet the requirement of heating in winter and cooling in summer, the schematic of solar heat pump system with seasonal storage was put forward, as in Fig. 1[2].

The system includes collector arrays (A), a seasonal storage water tank (B), a domestic hot water tank (D), heat pumps (E), boilers(F,H), cooling towers(G), and some pumps.

In this system, it uses Domestic Hot Water (DHW) priority strategy, that is, the collected solar energy is stored in the storage first, after its temperature is greater than the set temperature (such as 60℃), the solar energy is stored in the seasonal storage.

The space heating and cooling operation model during a whole year are as below:

(1) Operation mode in winter

If the temperature in the seasonal storage is greater than the heating supply temperature (such as 60℃), the water in the seasonal storage is used to meet the heating demand directly. When the temperature is between 50 ℃ and 60 ℃, the temperature of the supply water from seasonal tank is raised to 60℃ by boiler and then sent to the load. When the tank water temperature is 10℃ to 50℃, the heat pumps extracts heat from the seasonal storage and heat the return water form the load side. If the temperature is below 10℃, heat pumps stops and seasonal storage are bypassed, while boilers are used to direct heating. Since then the seasonal storage was used to store cold energy for summer cooling.

(2) Operation mode in spring

The seasonal storage is used to store cooling energy. The tank water temperature increases gradually because of heat gains from ambient. The collected solar energy only stored in the DHW tank.

(3) Operation model in summer

In this season, the cooling demand is met by the heat pump or the seasonal storage. When the temperature in the seasonal storage is below 15℃, the water in it is supplied as chilled water to the load. When the temperature is 15℃ to 40℃, the heat pump begin to work as chillier and seasonal tank water is

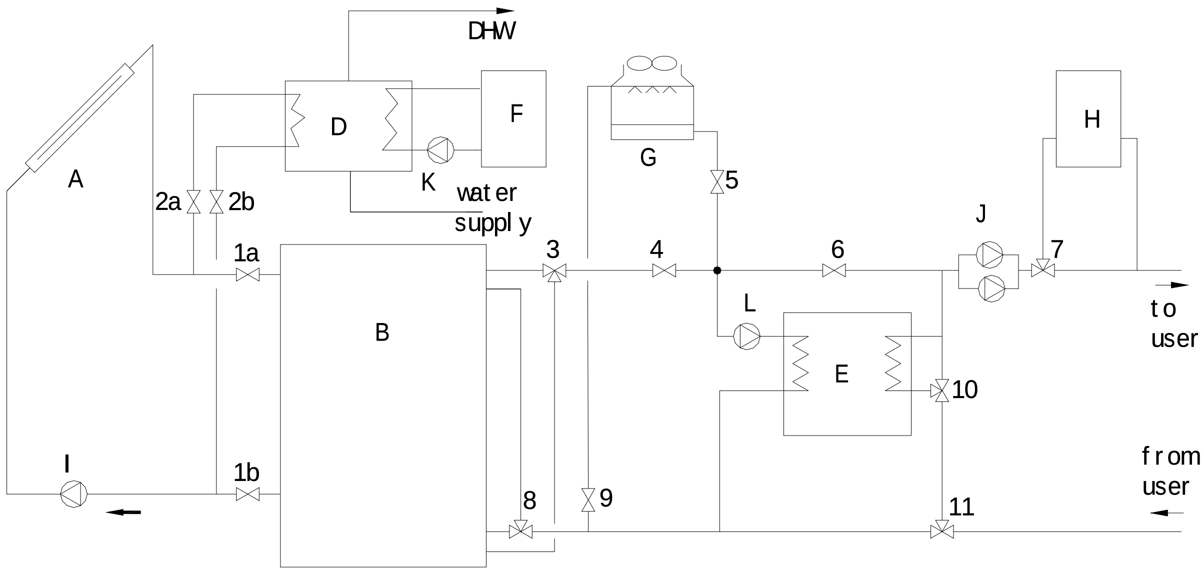

Fig. 1 Schematic of solar heat pump systems with seasonal storage

used to cool the condenser of the heat pumps. If the temperature is greater than 40℃, the cooling tower is started and the seasonal storage begin to store solar energy for winter heating.

(4) Operation model in autumn

The task of this season is to discharge as much heat as possible into the seasonal tank for winter use.

1.2 Overview of the Virtual Case

In order to study the characteristics of such systems and the feasibility of applying them to China, a virtual residential district in the suburb of Beijing was assumed, then a solar heat pump system with seasonal storage was designed. This system is responsible for the heating and cooling of the virtual residential district of floor area of 23000m^2. The design space heating load is 1124kW, design space cooling load is 390kW, 60^{o}C DHW 60m^3 per day.

The collectors is stalled on the building roof and inclined 30° to the horizontal plane, facing north. The total collector area is 2900m^2 or so.

The seasonal storage is hot water storage and stands above ground. The ratio of volume of seasonal tank to the collector area (it will be reduced to Rv in the following sections) is 2. That means the volume of seasonal storage tank is 5800m^3.

After all main features of this system was determined, some computer routines were made, and many simulations were conducted hour by hour for many different parameters and conditions based on

TMY weather data within the life cycle. Some important results will be discussed in the following sections.

2. ANALYSES OF THE BASE CASE

For the DHW load, from the Fig. 2, we can see that the domestic hot water load can be met mostly by solar energy and the solar fraction achieves 87.5% in a whole year.

For the space heating load, the thermal energy in the seasonal storage tank can be extracted directly or by heat pump to meet the load. The total thermal energy stored by the seasonal storage can meet the total space heating load about 17.1%, as in Table 1.

For space cooling load, the water in the seasonal storage tank can be used as direct cooling when its temperature is below 15℃. If the temperature is higher, it can be used as the condenser cooling water of heat pumps, it's useful for reducing the energy consumption of the cooling tower and charging heat into seasonal tank quickly. The total cooling load met by seasonal storage tank is about 29.7% directly or indirectly as in Table 2. If the terminals of air conditioning system can tolerate higher chilled water temperature, it will be able to use more free cooling.

Tab.1 Space heating load met by storage (GJ)

Month	Total heating load	Direct heating	Heating by heat pump
1	3550	0	0
2	2710	0	0
3	1170	0	0
11	1820	1000	660
12	3130	0	460

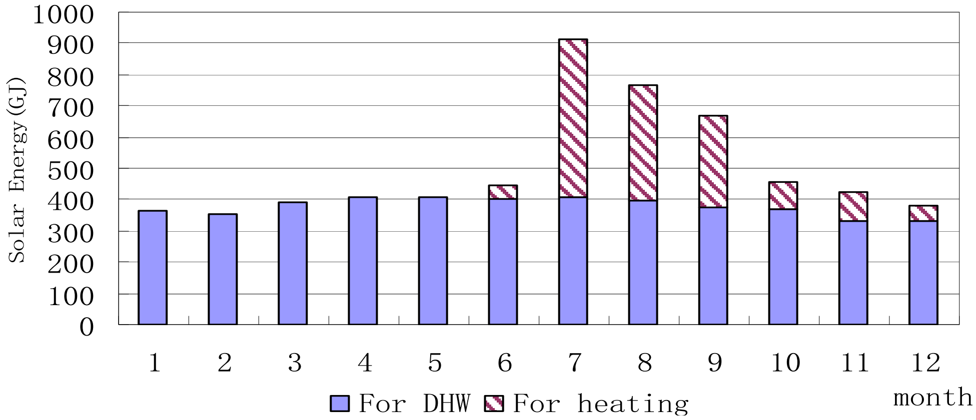

Fig.2 Use of collected solar heat

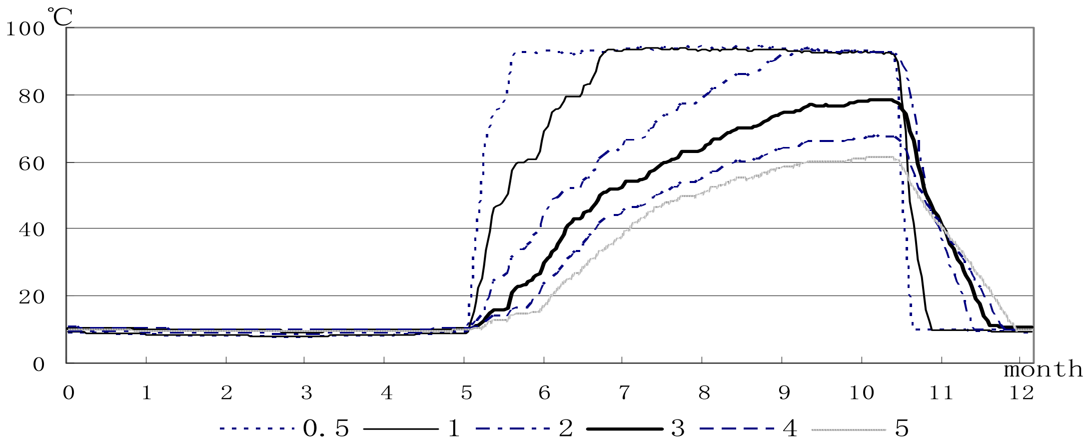

Fig. 4. Yearly temperature variety for different volume of tank

Tab. 2 Cooling load meet by storage tank (GJ)

Month	Total cooling	Direct cooling	Condenser cooling
6	1550	200	270
7	1840	0	0
8	1270	0	0
9	130	0	0

3. EFFECTS OF SEASONAL STORAGE CAPACITY

The volume of seasonal storage is an important parameter of the solar system. This paper use the ratio of storage volume to collector area (Rv) to study the effects on the whole system.

Fig. 4 shows the yearly temperature variety for different volume of tank. The Rv is from 0.5 to 5. From the Fig.4 we can see that the temperature in the tank rise to high level in short period when Rv is smaller than 2. If the Rv is more than 3, the temperature in the tank rises slowly. When the winter coming, the temperature is still in low level and the available temperature difference of storage is small. The capability of storage tank is not utilized efficiently. The optimal Rv is between 2 to 3, the temperature rises to the highest level just at the beginning of winter. Furthermore, the yearly collector efficiency is also higher (shown in Fig. 5).

The larger the volume of the tank, the more the solar energy can be collected (shown in Fig. 6). For the bigger seasonal tank, the energy supplied by the auxiliary boiler is less and the energy saved is more. However, Fig. 5 indicates that when the Rv is more than 3, the annual collector efficiency begins to reduce.

From the above discussion, Rv between 2 and 3 is an optimal value for this system. This conclusion agrees with the European experience of solar heating system with seasonal storage[3].

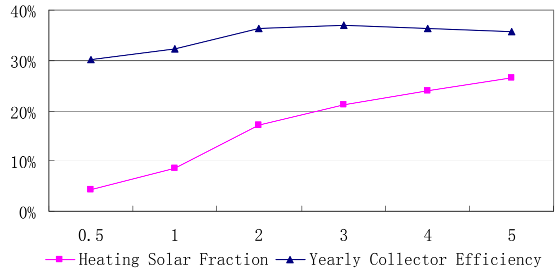

Fig. 5 Solar Fraction and Collector Efficiency

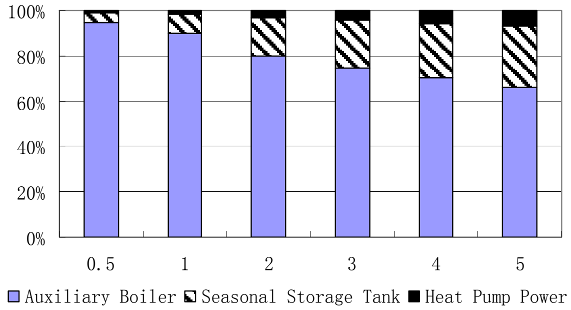

Fig. 7. The Composing of Heating Energy

4. EFFECTS OF OPERATING MODE

From the simulation, it was found that some solar heat can not be collected in spring because seasonal heat storage were used to store cold energy during that period. What will happen if the seasonal storage was only used to store heat and not store cold energy?

This paper defines the operating mode mentioned in section 1.1 as Mode 1, and Mode 2 refer to only storing heat and no storing cold energy.

The results of changing from Mode 1 to Mode 2 are listed in Table 3.

Tab. 3 Changes from Mode 1 to Mode 2

City	Heating Increment (GJ)	Heating fraction	Cooling reduction (10^9kJ)	Cooling fraction reduction
Beijing	+832	+6.7%	-202	-12.75%
Shanghai	+90	+2.6%	-153	-7.92%
Harbin	+2050	+9.3%	-222	-55.84%
Lanzhou	+830	+6.4%	-205	-37.55%
Lhasa	+3440	+23.4%	-9	-100%

Because solar space heating fraction is low (such as 18% for Bejing case), so this effect is very significant. As to Bejing, Harbin, Lanzhou and Lhasa, the improvement in heating in much greater than the reduction in cooling, but Shanghai is not the case. In other words, shanghai would be better to adopt mode 1 and the other four would be better to adopt mode 2.

5 IMPROVEMENT BY DIURNAL STORAGE

Another alternative is to add a diurnal heat storage tank which is parallel to the seasonal tank. When the seasonal storage begin to store cooling energy in the end of space heating season. The solar heat collected will be charged in the diurnal storage and used for space heating. This mode is defined as Mode 3.

The Changes from Mode 1 to Mode 3 of Beijing base case are listed in Table 4. It shows that the solar space fraction is also significant, and the improvement is near to Mode 2. It also was found that a diurnal storage of 75-150L per collector area is enough. This agrees with the European experience of solar heating system with diurnal storage[4].

Tab. 4 Changes from Mode 1 to Mode 2

Diurnal storage (m^3)	Diurnal storage per collector area (L/m^2)	Heating increment (GJ)	Solar space heating fraction increment
500	172.7	+859	+6.92%
434	149.9	+847	+6.82%
289.5	100.0	+803	+6.47%
217	75.0	+760	+6.13%
108.5	37.5	+588	+4.74%

6. CONCLUSIONS

From the simulation and analysis, it shows that:

(1) For most area of China, the solar systems with seasonal storage can save energy;

(2) For areas with cold winter and hot summer, it is suitable to stores heat from summer to winter and store cold energy from winter to summer, however for chilly areas, it is suitable to only store heat from summer to winter;

(3) If the cooling storage is needed, the seasonal storage coupled with short-term storage can raise the solar fraction significantly.

(5) When the ratio of volume of seasonal storage tank to collector areas is 2~3, the system performance is optimal for many areas of China.

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