Optimization analysis on storage tank volume in solar heating system

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Abstract

Based on the analysis of the storage and exothermic process of the storage tank, the energy balance equation was established, and discussed the relationship between storage tank volume and storage temperature difference, as well as that between the tank volume and the max heat storage. The average temperature of the tank and the auxiliary heat added for the system of a typical architecture in Xi’an during the heating season were simulated by TRNSYS. The paper discussed the operating conditions with changing the combination of systems and storage temperature difference, and found that the heat storage time of the tank is great different from the solar radiation time. SHS prefers floor panel heating with lower temperature and the thermal collector form that can ensure storage temperature range of 15°C. Then it gives out the recommended value of required storage tank volume for a unit area of collector.

1. Introduction

Solar heating technology is getting matured, though its application is affected by the instability and low guaranteed rate. The presence of heat storage tank will help to improve the situation, but in the design, its volume is determined primarily by recommended values of the collector area from the relevant specifications manual [1, 2]. There are some researches on the study of determining the storage tank volume at home and abroad. Based on the entire life cycle energy, Yan et al [3] analyzed the selection and design of the solar heating system (SHS), and
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proposed that the heat storage tank volume should be selected according to the collector area. Liu et al. [4] analyzed.

**Nomenclature**

- $Q_{aux}$: the heat supplied for the system by auxiliary heat source, J
- $Q_a$: the effective heat of the heat collector system, J
- $Q_b$: the heat demand of the building, J
- $Q_s$: the heat storage by the tank, J
- $Q_l$: heat loss of the tank, J
- $I_{(\tau)}$: solar radiation intensity on the collector inclination, J/m²
- $T_1$: water temperature at the time of $\tau_1$, K
- $T_2$: water temperature at the time of $\tau_2$, K
- $C_p$: specific heat of the water, J/kg K
- $V$: tank volume, m³
- $T_s$: the water temperature in the tank, K
- $U$: heat loss coefficient of the tank, J/m² K
- $T_a$: outside air temperature, K
- $A_c$: collector area, m²

**Greek symbols**

- $c$: specific heat of the water, J/kg K
- $\rho$: density, kg/m³
- $\eta_{cd}$: instantaneous efficiency of collector
- $\tau_0$: beginning time of the effective heat set respectively
- $\tau_1$: the time heat storage tank begin to store heat
- $\tau_2$: the time heat storage tank finish to store heat
- $\tau_3$: end time of the effective heat set respectively

**Subscripts and superscripts**

- all: the whole day
- stor: heat storage phase
- rele: exothermic phase

the selection of heat storage tank volume in SHS, and gives out the recommended values of storage tank volume required by a unit of collector area in different regions according to the actual situation of the project. Kemal et al. [5] studied the relationship between the collector area and the storage tank volume, found that the rate of storage tank volume to collector area can be between 50 L/m² and 70 L/m² for which the collector efficiency ranges from 0.35 to 0.45. However, these studies have overlooked the temperature difference of the hot water supplied and the ability difference of providing high temperature water, both of which caused by different ends of the cooling system and different kind of collectors, and different storage temperatures need different storage of tanks.

By establishing the energy balance equation of the active SHS and solving the volume expression of storage tank, the author analyzed the factors affecting the size of the storage tank volume and discussed the value difference of the maximum temperature difference when the species of the heat collector and the end of the cooling system are different. By simulating operating conditions of the tank average temperature and the system in different system combinations during the heating season, the paper analyzed the best selection strategy of the heat storage tank volume, which is done under the condition of assuring the heat loss of tank is minimal.
2. Methods

2.1. The storage and release heat model of storage tank

The thermal process of heat storage tank is divided into two phases in the solar heating system, the first phase is heat storage phase, starting at $\tau_1$ moment, from which the heat the system collected is more than the building lost, the remaining heat was stored by the tank. And until the time of $\tau_2$, when the heat the system collected cannot meet the requirement of the consumption, the maximum amount of stored heat is reached.

Then heat storage tank will release the heat, and this stage is called exothermic process. With the releasing of heat, when the heat is unable to meet the caloric needs, the auxiliary heat source begins to work to meet the system requirements in conjunction with the heat storage system. Thus the storage model and exothermic model of storage tank with two phases were established, and both are shown in Figure 1.

![Fig. 1. (a) heat storage phase; (b) exothermic phase.](image)

The energy and mass conservation functions are solved at two phases. During thermal storage phase, the energy conservation expression for each part of the systemis described as follows:

$$Q_{u}^{stor} = Q_{b}^{stor} + Q_{s}^{stor} + Q_{l}^{stor}$$

(1)

The effective heat of the heat collector system[6], heat storage is represented with the heat capacity of the liquid in the tank, and can be expressed as the function follows:

$$Q_{u}^{stor} = \int_{\tau_0}^{\tau_1} I_{0(\tau)} \cdot A \cdot \eta_{cd} d\tau$$

(2)

$$Q_{s}^{stor} = \int_{\tau_1}^{\tau_2} c \rho V \Delta T dt$$

(3)

The energy conservation expression of the exothermic process to the second stage of the heat storage tank is described as follows:

$$Q_{s}^{stor} + Q_{aux}^{ele} = Q_{b}^{ele} + Q_{l}^{ele}$$

(4)
2.2. Analysis of heat storage tank volume

According to equation 3, the volume of heat storage tank is determined by the maximum heat stored and heat storage temperature, the calculation expression is described as follows:

\[ V = \frac{Q_{stor}}{c \rho (T_2 - T_1)} \]  

(5)

The value of which is related with the end form of the system and the collector type. To get the optimum volume of heat storage tank, the assumptions of the tank are made as follows:

1. The water temperature changes little, and that makes small difference of the water density, thus for the heat-releasing process, the change of water density can be ignored.

2. Without considering the thermal stratification in the tank [4], the water temperature is the average temperature.

In this paper, the minimum water tank heat loss is corresponding to the optimal tank volume. Considering the heat exchange between the water tank and the surrounding environment, the storage tank heat loss can be expressed as follows:

\[ Q_{all}^m = \int_0^{24} UA(T_c - T_a)dt \]  

(6)

When the ratio of height to diameter of the cylinder heat storage tank is two, the same volume size of the heat storage is corresponding to the minimum surface area, the formula of volume and surface area is as follows:

\[ A = 2.5 \times (4\pi)^{\frac{1}{2}} V^{\frac{3}{2}} \]  

(7)

In this case, the calculation expression of the corresponding storage tank heat loss is as follows:

\[ Q_{all}^m = \int_0^{24} 2.5U \left(4\pi\right)^{\frac{1}{2}} V^{\frac{3}{2}} (T_c - T_a)dt \]  

(8)

To facilitate the research, the definition of S is the required storage tank volume when one unit collector area is assigned, m³/m².

\[ S = \frac{A_c}{V} \]  

(9)

2.3. Simulation

This paper selected a typical residential building in Xi'an and active solar heating system as the research object, made the entire heating season as simulation time, and analyzed the operating conditions during the entire heating season in different combinations of systems and thermal storage temperature difference et al. With the help of TRNSYS software, we can build a solar heating system model shown in Figure 2, which optimize the operating parameters and heat storage tank design parameters.
The main module functions in TRNSYS are described in Table 1. The description of the building components is assumed by Type 56a.

![Simulation system picture](image)

Table 1. The main components of the TRNSYS simulation program.

| Components                        | Functional description                                      |
|-----------------------------------|------------------------------------------------------------|
| Type 109 (TMY-2 weather data)     | Import Xi’an local weather conditions                      |
| Type 1b (flat-plate solar collector) | Collect solar energy, transport into heat storage tank and output the effective heat |
| Type 56a (multizone building)     | Import architectural models, and output building load      |
| Type 4d (storage tank)            | Change the tank volume parameters, and output the average temperature of the water tank |
| Type 3b (pump)                    | Drive system to circulate                                  |
| Type 2b (control function)        | control the hoist of collector system                      |

3. RESULTS AND DISCUSSION

3.1. The largest heat storage

Select a typical day from the simulation data in the whole heating season and analyze the maximum heat storage of system. According to the simulation and calculation of TRNSYS, the diurnal variation curve of solar radiation intensity, building heat consumption, effective heat set of collector system and auxiliary heat are shown in Figure 3.

In Figure 3, after the emergence of solar radiation, the collector begins to collect solar heat for raising the temperature of the medium inside the collector pipe and compensating for its heat loss, until $\tau_0$, the temperature of the medium inside the pipe is higher than that of water exported, circulating pump works and output effective heat set. However, the heat transported into the storage tank is insufficient to meet the building load, and they are not equal until $\tau_1$. Since the heat loss of system, the heat storage tank begins to store heat at $\tau_1$. The heat storage is end at $\tau_2$, which reached the maximum heat storage. The efficient heat set output is end at $\tau_3$.

As above, the solar radiation beginning is about 1 hour earlier than the effective heat set appearing, and nearly two hours earlier than the heat storage; end time of stored heat is almost 1 hour earlier than the effective set, and prior to solar radiation for 2 hours in general. In Fig. 3, the areas between the curves and the time line are gross value of the physicals, and it can be seen that the total of effective heat set and auxiliary heat is significantly greater than building load, which is because there exists a certain heat loss.
3.2. Heat storage temperature difference

Temperature difference is the difference between maximum temperature and minimum temperature for heat storage tank. The two temperatures are corresponding to the temperature at the end and beginning of heat storage. Its maximum range is limited by the end of the cooling system and the collector type, and the difference of which will result in difference of the minimum heating water temperature and the capacity of providing hot water, and its scope should not exceed the range between the highest temperature of water out of the collector and the lowest temperature of water into the collector.

This paper selected two different types of the heating end form: radiators and radiant floor coils, the desired minimum heating temperature are 55 and 35 °C [7, 8]. Considering 5°C [9] of temperature difference in indirect heating system, the minimum water temperature of the two end forms of the tank is 60°C and 40°C respectively. Two different forms of collectors are selected: the ordinary flat plate collector and special flat plate collector, the outlet water temperatures were 70 and 90°C [10, 11]. Then, different combinations of system are corresponding to different ranges of heat storage temperature difference; an optional range of temperature difference for the above system forms is shown in Table 2.

| End form          | Collector type                | Range of temperature difference (°C) |
|-------------------|-------------------------------|-------------------------------------|
| Radiator          | Ordinary flat plate collector | 10                                  |
|                   | Special flat plate collector  | 30                                  |
| Radiant floor coil| Ordinary flat plate collector | 30                                  |
|                   | Special flat plate collector  | 50                                  |

According to Table 2, selecting different combinations of system makes obvious difference on range of heat storage temperature difference, which directly influences the determination of water tank volume. The curve of volume of water tank changing with variable heat storage temperature difference is shown in Figure 4.
The figure shows that the heat storage tank volume decreases with the increasing of the temperature difference. When the heat storage tank temperature is less than 5°C, the heat storage tank volume appears to be significantly larger with the continuing reduce of the temperature difference. When the temperature difference is higher than 15°C, the heat storage tank volume changes little with the continuing increase of the temperature difference. Then if the tank volume decreased, the heat storage temperature difference will significantly increase, resulting in a substantial increase in the temperature of the heat storage tank.

Through the above analysis, the heat storage temperature difference should be range of 5 to 15°C. In order to choose out the reasonable form of system, we can simulate the influence on average temperature of the heat storage tank when storage tank volume and water temperature of the end are different in the condition that temperature difference is 10°C.

According to Figure 5, the larger the storage tank volume is, the larger its heat capacity is. In the case of a certain heat set and water temperature reaches the requirement, the auxiliary heat required is largest. When the power of the auxiliary heat source is fixed, the greater the heat capacity is, the lower the average temperature of the water tank is, so the two showed significant negative correlation.
When the tank volume and the heating water temperature are small, the heat loss and heat capacity of the tank are small. With increasing time of constant power auxiliary heating system power, the water temperature reaches the heating temperature requirement, and the average temperature of the tank and system heat loss showed a linear variable. While continuing to increase the volume of the tank and heating water temperature, heat capacity and heat loss of tank become larger. Despite constant power auxiliary heating system almost works uninterruptedly, the water temperature requirements still cannot be reached.

As above, the form is quite reasonable with low-floor radiant coils and collector ensuring the realization of 15 °C temperature range of heat storage in the solar heating system.

3.3. Storage tank volume analysis

Through the above analysis, we simulated storage tank volumes varying corresponding to variable average tank temperature and the variable of average auxiliary heat in the heating season when the temperature of the storage tank was 40 °C. Combining the formula of calculating the heat loss, we calculated the daily average heat loss in the heating season, and the result is in Figure 6.

![Figure 6. Variable of heat loss of different volume tank and auxiliary heat](image)

According to figure 6, when S is less than 0.015m³/m², changing the tank volume can do little effect on heat loss, and the heat loss is the minimum when S is 0.01m³/m². The amount of auxiliary heat increases significantly due to the reduction of water tank volume. Though little change happens in the tank heat loss, the increase of the system heat loss causes the amount of auxiliary heat increase. Therefore, considering the heat loss of the tank and auxiliary heat, storage tank volume corresponding to one unit collector area is between 0.01 ~ 0.02m³/m².

4. Conclusion

By analyzing the storage and exothermic process of storage tank in the solar heating system, with the operating condition in TRNSYS Simulation, it can be found from the analysis of the typical day that, the time when the water tank began to regenerate is about 2 hours delay than the time when solar radiation appears, and the time when the water tank stopped storing heat is about 2 hours earlier than the time when the solar radiation disappears. The form with low-floor radiant coils and collector ensuring the realization of 15 °C temperature range of heat storage is quite reasonable in the solar heating system. The recommended value of the heat storage temperature difference in the area is about 5-15 °C, and the storage tank volume corresponding to one unit collector area is between 0.01 ~ 0.02m³/m².
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