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Design of A New High Efficiency Heat Storage System for Small and Medium-sized Photothermal Power Stations

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Abstract. In order to solve the problems of low temperature and high cost of traditional photothermal power generation heat storage system, a new high-temperature solid heat storage system consisting of three subsystems of heat extraction, heat storage and heat utilization is designed. Taking air as heat medium and safe heat-resisting regenerator as heat storage material, the heat preservation characteristics, overall thermal efficiency and flow resistance of the regenerator were analyzed and calculated. The results show that the regenerative system runs steadily, the heat loss of the regenerator is less than 5%, and the overall thermal efficiency of the system is more than 85%, which is better than the general regenerative system.

1. Introduction

Intermittence and instability of solar energy directly affect the continuity and stability of the system in the process of photothermal utilization, and high-temperature heat storage technology is the key to solve this problem. In recent years, it has received great attention from domestic research institutions and related enterprises [1]. In a regenerative system, a complete energy storage cycle consists of three stages: heat storage, storage and heat release [2].

Scholars at home and abroad have done a lot of research on numerical calculation and experiment of photothermal regenerative system. Mu Zhijun [3] et al. carried out an experimental study on the solar photovoltaic integrated photothermal system. The analysis results show that the electrical efficiency of the system is about 7% higher than that of the conventional photovoltaic system. Zheng Jiantao [4] et al. simulated the non-uniform heating of the solar column heat absorber, and N.G. Barton [5] analyzed and compared the effects of two different operation modes on the overall heat storage performance of the system through numerical simulation.

Based on the above research, a high-temperature solid heat storage system is proposed for small and medium-sized solar photothermal power generation projects. High temperature resistant solid particles are used as heat storage and the air is used as a heat medium. Compared with other types of heat storage systems, this system has obvious advantages: (1) The working temperature range of hot medium air is wide, non-toxic and harmless. (2) The regenerator has a wide range of sources, low cost, high-temperature resistance, and the regenerative temperature can reach more than 1000 °C. (3) There is no need to use corrosion resistant materials for the shell and pipeline of the regenerator. (4) The system has good security, low investment and low operating cost. It cannot only generate photothermal power, but also meet the actual industrial production and daily heat demand, and improve the utilization efficiency and scope of solar energy.

2. Overall Design Schemes of the Regenerative System

The design of the regenerative system should meet the following principles:

- The thermal efficiency of the regenerative system is over 85%.
- The system is running continuously and steadily, and the solar energy provides the energy needed by the system.
- The system can meet the requirements of multi-function.
- The flow resistance of the regenerative system is small and the operating cost is low.
- The system should be easy to adjust and operate flexibly to meet other operations such as maintenance.

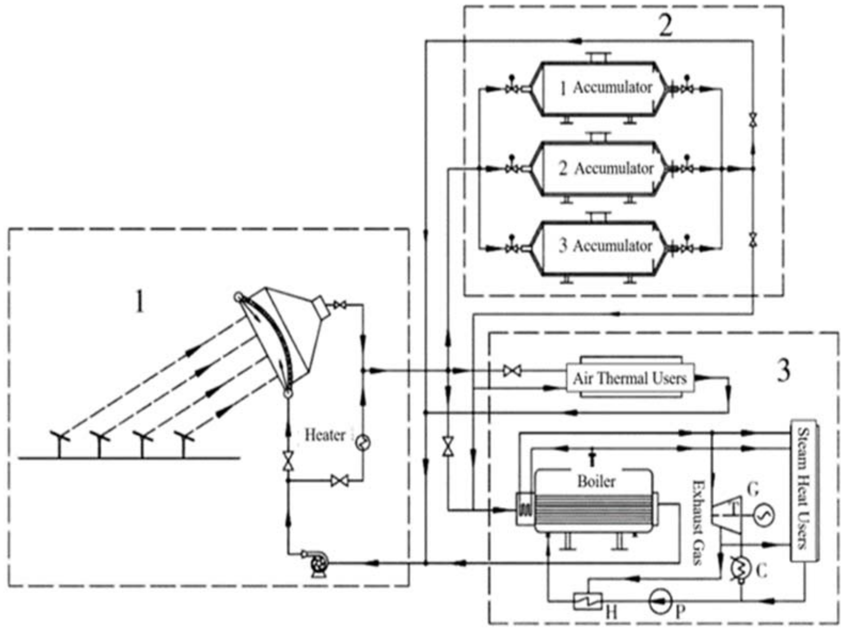

Figure 1. Schematic Diagram of High-Temperature Solid Heat Storage System for Photothermal Power Generation

As shown in Figure 1, the high-temperature solid heat storage system of photothermal power generation consists of three parts: heat extraction subsystem, heat storage subsystem and heat utilization subsystem. A closed loop can be formed between the two subsystems. When the tower solar concentrator arranged in the heat extraction subsystem 1 works [6], the heliostat reflects the solar beam to the collector, and the heat medium at the collector absorbs the solar radiation energy and converts it into high-temperature heat energy. Electric heaters are installed in the end bypass of the heating subsystem to prevent the influence of continuous rainy weather on the operation of the whole system. The regenerator subsystem 2 is composed of several regenerators. The regenerator is filled with regenerative materials, and the high-temperature medium exchanges heat with the regenerative medium to realize the effective storage of heat energy, which solves the problems of intermittent and unstable solar energy. The heat subsystem 3 includes air heating user and steam boiler cogeneration system. Under good lighting conditions, heat is obtained from the collector. One part is supplied to the heating subsystem and the other part is stored in the heat storage subsystem. When the illumination condition is not good, the collector of the collector cannot meet the need of the heat system or in the absence of illumination, the regenerator of the regenerative system carries out heat release to supply the heat subsystem.

3. Optimum Design of Regenerator

3.1. Determination of Structure and Capacity of Regenerator

The structure of the regenerator is shown in Figure 2. The regenerator is arranged horizontally and consists of two parts: the main body of the regenerator and the thermal insulation layer. The filling material of the inner filling layer of the regenerator is ceramic ball-high Al ball ($Al_2O_3 \cdot SiO_2$). The design maximum temperature is 900°C, the external surface temperature of the regenerator is 50°C, and the ambient temperature is 20°C.

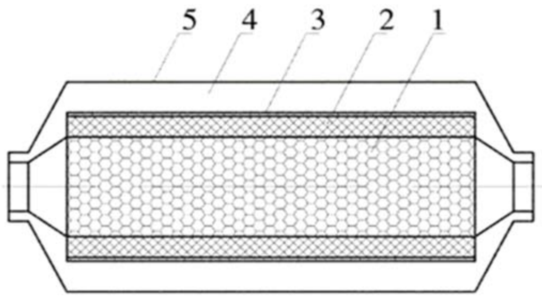

Figure 2. Structural Chart of High-Temperature Solid Regenerator.

In order to minimize the environmental heat loss and take into account the cost and load-bearing factors, the inner wall of the thermal insulation layer of the regenerator is built with refractory brick 2, the tank made of Superalloy steel 3 on the outer wall, and the expanded perlite 4 on the outer wall is used as the thermal insulation layer. In order to reduce the radiation loss of the regenerator, the outer layer of the regenerator is coated with aluminum foil 5 with high reflectivity. The size calculation of each structural material of the regenerator is shown in Table 1.

Table 1. Internal Diameter of Regenerator and Thickness of Insulation Material

Regenerator diameter / mm	Refractory bricks / mm	Steel plate / mm	Expanded perlite / mm
2000	289	6	300

In order to simplify the analysis and calculation, the following assumptions are made for the regenerator:

- The thermal insulation layer of the regenerator has better thermal insulation effect, and the starting temperature of the regenerative material is 300°C.
- The average daily heat storage time of the regenerator is 8 hours.
- The heat storage period is 3 days and 2 days sunshine is better.
- The maximum regenerative temperature of the regenerator is 900°C.

The total heat power of the regenerative system is 1.0 MW. 80% of the heat collected by the collector is used for heat storage and 20% for heat release. There are three regenerators in the regenerative system. In a working cycle, the total heat collected by the system is 57600 MJ, and the heat stored by the regenerative system is 46080 MJ. The relevant calculation of the regenerator is shown in Tables 2 to 4.

Table 2. Relevant Calculation of Regenerative Spheres in a Single Regenerator

Total heat storage of single regenerator / MJ	Diameter of regenerative sphere / m	Volume of single regenerative sphere / m^3	Specific heat capacity / $kJ \cdot (kg \cdot ℃)^{-1}$	Regenerative sphere density / $kg \cdot m^{-3}$
1.5360	0.03	1.41×10^{-5}	1.0	2000
Heat transfer temperature difference / ℃	Total volume of regenerative sphere / m^3	Number of regenerative balls/ Pieces	Total mass of regenerative ball / kg	Total surface area of regenerative sphere / m^2
600	12.8	9.078×10^{5}	25600	2569

Table 3. Relevant Calculation of Hot Air in a Single Regenerator

Thermal Storage	1.293	2.52	1.95	1.066	300	805.8	15360	5.3
Exothermic	1.293	0.71	0.55	1.066	257.7	195.08	13132.8	18.7

Table 4. Relevant Calculations of Heat Accumulators

Diameter of regenerative sphere / mm	Regenerator volume / m^3	Volume voidage of regenerator	Regenerator area voidage	Regenerator Section Area / m^2	Regenerator length / m
0.03	18.055	0.29	0.164	3.14	5.75

Minimum cross-sectional area of flow passage/ m^2	Volume Flow Rate of Gas under Standard Conditions / $m^3 \cdot s^{-1}$	600℃ Volume Flow of Gas / $m^3 \cdot s^{-1}$	Flow Velocity at Minimum Section / $m \cdot s^{-1}$	Flow Velocity at Maximum Cross Section / $m \cdot s^{-1}$	Average velocity / $m \cdot s^{-1}$
0.514	1.95	6.24	12.14	1.99	7.065

3.2. Analysis of Thermal Insulation Characteristics of the Regenerator

Ignoring the thermal resistance between the filling layer and the inner wall of the regenerator, the heat transfer coefficient of the regenerator is as follows:

$$k = \frac{1}{\frac{\sigma_1}{\lambda_1} + \frac{\sigma_2}{\lambda_2} + \frac{1}{h}} \tag{1}$$

In the equation

k - heat transfer coefficient of regenerator / $W \cdot (m^2 \cdot □)^{-1}$;

δ-thickness/m;

λ - thermal conductivity / $W \cdot (m \cdot □)^{-1}$;

h-Convection Heat Transfer Coefficient/ $W \cdot (m^2 \cdot □)^{-1}$;

Subscript 1 - Refractory bricks;

Subscript 2 - Expanded perlite.

In this paper, the thermal insulation characteristics of solid heat accumulator are analyzed by the lumped parameter method. The differential equation of thermal conductivity is as follows:

$$\frac{\partial t}{\partial \tau} = \frac{\dot{\Phi}}{\rho_s c_s} \tag{2}$$

In the equation

t - temperature / □;

τ- heat storage time / h;

ρ-density/$kg \cdot m^{-3}$;

c -constant pressure specific heat capacity / $kJ \cdot (kg \cdot □)^{-1}$;

$\dot{\Phi}$-volume heat source, $\dot{\Phi} = \frac{-A_0 k(t-t_f)}{V_0}$ (volume of V_0 filling layer, heat transfer area of A_0 filling layer)/$W \cdot m^{-3}$

Subscript s - heat storage material.

It can be sorted out:

$$\rho scs V_0 \frac{dt}{d\tau} = -kA_0 (t-t_f)$$

$$\frac{\theta}{\theta_0} = \frac{t-t_f}{t_0-t_f} = exp(-\frac{A_0 k}{\rho_s c_s V_0}) \tag{3}$$

In the formula, θ-excess temperature / ℃.

Filling layer temperature t can be obtained by substituting relevant data.

$$t = 10 + exp(-1.59 \times 10^{-3}\tau) \tag{4}$$

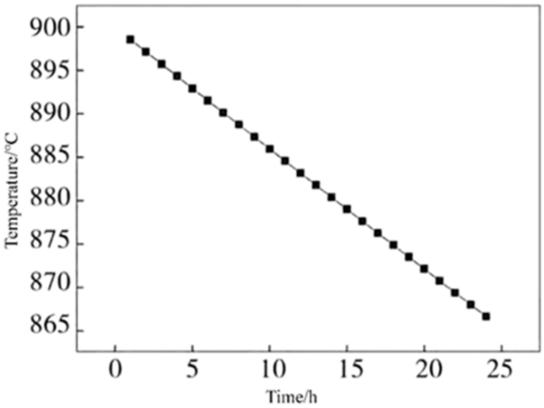

Figure 3. Temperature Variation of Regenerator Filling Layer with Time in One Day

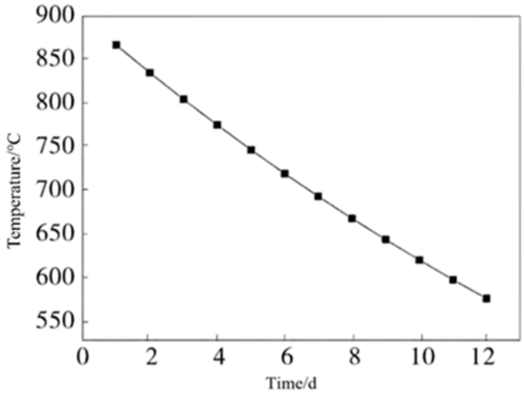

Figure 4. Temperature Variation of Regenerator Filling Layer with Days

Figure 3 and Figure 4 are the relationship between the temperature of the regenerator filling layer and the time in a day and the temperature of the regenerator filling layer with the number of days. From figs. 3 and 4, it can be seen that the temperature of the regenerator filling layer varies linearly with time and the temperature of the regenerator filling layer varies linearly with days. The regenerator keeps the heat for one day, and the temperature drop is about 4.8%. In the practical application process, multiple regenerators are prepared to store heat simultaneously, which basically meets the requirements of industrialization and ensures that the regenerator system can keep heating and generating electricity without long rainy and rainy weather.

4. Thermal Balance and Thermal Efficiency Computation of Systems

4.1. System Heat Balance

The heat loss of the whole system includes the heat loss of the collector, the heat loss of the accumulator, the heat loss of pipes and accessories, and the heat loss of valves and measuring instruments. According to the principle of heat balance, the total power input to the heat storage system should be equal to the algebraic sum of heat storage and heat loss of each part in the heat storage system. That is:

$$Q_0 = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 \tag{5}$$

In the equation:
Q_0 - Total power input to regenerative system / MW;
Q_1 - Heat stored in the regenerator / MW;
Q_2 - heat loss of collector / MW;
Q_3 - heat loss of regenerator / MW;
Q_4 - Heat loss of pipes and accessories / MW;
Q_5 - Heat loss of valves and measuring parts / MW.

4.2. Calculating the Thermal Efficiency of the System

Thermal efficiency of regenerative system:

$$\eta_{xr} = \frac{Q_1}{Q_0} = q_1 \times 100\% = \frac{Q_0-(Q_2+Q_3+Q_4+Q_5)}{Q_0} = 1-(q_2+q_3+q_4+q_5) \times 100\% \tag{6}$$

In the equation:
Q_1 - Total thermal efficiency of regenerative system / [%];
Q_2 - heat loss rate of collector / [%];
Q_3 -heat loss rate of regenerator / [%];
Q_4 -heat loss of pipes and accessories / [%];
Q_5 - Heat dissipation loss rate of valves and measuring parts / [%].

The thermal efficiency of the system is calculated as shown in Table 5 below. The total efficiency of the system can reach 85.4%.

Table 5. Heat Dissipation and Thermal Efficiency of Various Parts of High Temperature Solid Heat Storage System

Total power /MW	Collector heating / [%]	Regenerator heating / [%]	Pipeline heat dissipation / [%]	Valve isothermal compress / [%]	Total heat loss / [%]	efficiency / [%]
0.8	4	3.2	5.6	1.8	14.6	85.4

5. Calculation of Runner Resistance of the Regenerative System

5.1. Calculation of Flow Resistance

The total resistance Δp_z of regenerator system is composed of pipeline resistanceΔp_1, local resistance Δp_2 and resistance loss Δp_3 of solid particle filling layer in the regenerator.

$$\Delta p_z = \Delta p_1 + \Delta p_2 + \Delta p_3$$

The size of the pipes used in the regenerative system is φ630 × 10, the total length of the pipes is 150 m, the mass flow in the pipes is $q_m = 2.52$ kg / s, and the air calculating temperature is 300 ℃. The velocity u = 14.04 m/s and ρ = 615 kg/m^3 of air in a pipe can be calculated as turbulent motion. When 103 < Re < 108, the resistance in pipe can be calculated by Kypnakob formula 7.

$$\Delta p_1 = (1.8\ln Re_1 - 1.5)^{-2} \cdot \frac{L_1}{d_e} \cdot \frac{\rho u^2}{2} \tag{7}$$

In the equation:
u -the velocity of the fluid in the channel / m·s^{-1};
d_e - equivalent diameter / m of flow passage;
L_1- the length of the runner / m.

(1) The local resistance in the system is due to the energy loss caused by the change of flow direction or cross-section area (e.g. valve, elbow, tee and variable diameter section) when air flows. Its local resistance formula is

$$\Delta p_2 = \sum \xi_i \frac{\rho u^2}{2} \tag{8}$$

In the system, the elbow is 90 degrees ξ_1 = 0.75 and the valve is ball-core valve and if is fully open ξ_2 = 6. 4.

(2) General Formula for Resistance Loss of Fluid Flow through Solid Particle Filling Layer 8

$$\Delta p_3 = \left(150 + 1.75\frac{Re_2}{1-\varepsilon}\right) \cdot \frac{\mu G_2}{\rho d_b^2} \cdot \frac{(1-\varepsilon)^2}{\varepsilon^3} \cdot L_2 \tag{9}$$

In the equation:

$$\mathrm{Re}_2 = \frac{G_2 d_b}{\mu}$$

G_2 - mass flow rate at the entrance of filling layer in regenerator / kg · $(m^2 \cdot s)^{-1}$;
L_2 - length of regenerator / m;
d_b - diameter of regenerative ball / m.

5.2. Fan Selection

Because the total resistance of the system is relatively large, the selection of the fan in the regenerative system has certain requirements. The selected fan should ensure that the regenerative system meets the requirements of hot air, airflow rate and pressure head when the regenerative system operates at full load under the given working conditions.

The actual power of the fan is:

$$P = \frac{\beta Q \Delta P_c}{\xi_1 \xi_2} \tag{10}$$

In the equation
Q - fan airflow / $m^3 \cdot h^{-1}$;
β-The capacity reserve coefficient of the motor is 1.3;
ξ_1 - Internal efficiency, 0.8;
ξ_2 - Mechanical efficiency, 0.97.

After calculation, the actual power required by the fan is 46.84 kW, so the final fan type is 6.3A centrifugal blower, and the flow rate is 14763.8 $m^3 \cdot h^{-1}$.

6. Conclusion

(1) The designed high-temperature solid heat storage system can reach 900°C, and can use solar energy for continuous, stable and efficient operation throughout the day.

(2) According to the basic requirements of solid heat storage materials and heat media, air is chosen as heat medium and high Al ball is chosen as heat storage material through comparative optimization analysis; the size and storage time of heat storage device are analyzed and calculated according to the total amount of heat storage and the physical parameters of heat storage materials.

(3) According to the requirements of structural safety, thermal insulation and economy, the structure of regenerator is as follows: inner firebrick + heat-resistant supporting steel plate + expanded perlite + outer Al foil. The lumped parameter method is used to analyze the heat preservation performance of the heat accumulator, and the heat loss of the high-temperature solid heat accumulator is less than 5% per day.

(4) The overall efficiency of the regenerative system is more than 85%. The resistance of the system is analyzed, and the formulas for calculating the resistance of each part are given. The total resistance of the system is calculated based on the average temperature of circulating air, and the type of fan is selected accordingly.

7. References

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