PERFORMANCE ANALYSIS OF HEAT ACCUMULATION OF SOLAR THERMAL GENERATOR UNITS BY COMPUTER NUMERICAL SIMULATION

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Abstract: To explore the intrinsic function and mechanism of heat accumulation performance of solar thermal generator units, the core carrier working substances of heat accumulation of solar thermal generator units are analyzed through computer numerical simulation analysis and simulation experiments, including the selection criteria of working substances, the mechanism of heat accumulation system, the correlation between power generation efficiency and the evaporation temperature of working substance, the correlation between the condensing temperature and condensing pressure of working substance, and the influence of working substance velocity on heat accumulation capacity. The results show that under the same radiation intensity, the greater the flow velocity of the working substance is, the worse the heat accumulation and heat conduction of the working substance is. As the condensing temperature of the working substance increases, the condensing pressure also increases; as the evaporation temperature of the working substance increases, the power generation efficiency of the working substance also increases significantly. If the light intensity is sufficient for the generator units, the remaining energy will be stored in the heat accumulation system. If the light intensity decreases and the collected thermal energy cannot meet the needs of the generator units, the heat accumulation system outputs previously-stored thermal energy for the generator units. In summary, the heat accumulation system based on the high-efficiency working substances is vital for the normal operation of solar thermal generator units. Once the solar radiation intensity cannot meet the needs of power generation, the heat accumulation system will output previously-stored thermal energy; meanwhile, its collection and release of thermal energy depend on the photovoltaic intensity. The constructed hot-oil working substance-based heat accumulation system satisfies the normal operation needs for thermal generator units, which is significant for subsequent research.

Key words: *thermal energy; heat accumulation; solar energy; power generation; working substance*

1. Introduction

With the rapid development and progression of society, all walks of life are becoming increasingly dependent on energy, especially on electric energy. At present, electricity consumption in China is huge. However, electric resources are still in shortage, and there are still many areas where electricity cannot be supplied. In addition, the majority of the power generation mode in China still adopts thermal power. Not only is thermal power generation inefficient, but it also brings huge environmental pollutions. Therefore, it is urgent to find clean energy for power generation. Therefore, the research on solar thermal power generation has become attractive, which has become the current mainstream research direction [1]. Solar thermal power generation includes an important component of heat accumulation [2]. Electricity comes from the circulation and change of other energy forms. At present, the most dominant and clean energy source is solar radiation. The radiated energy is abundant in China at present. The comprehensive combination of solar energy and electric energy is key to technical research. Most thermal generator units receive solar radiation and then convert solar energy into other forms of energy [3]. Solar energy has a wide range of functions in daily life. Whether it is for military, aerospace, industrial, or everyday purposes, solar energy can be a driving force for making a lot of things. Also, solar energy is very prominent in terms of price and environmental protection [4]. However, there are still problems in the heat accumulation link of solar thermal power generation, which are mainly manifested in the relatively low storage and conversion efficiency. Without an efficient heat accumulation system, there is no way to stably perform the conversion and production of electric energy [5, 6]. Since the excess thermal energy is stored in the heat accumulation system to meet the production needs when there is no sunlight, this study uses computer numerical simulation analysis and simulation experiments to study the hybrid heat accumulation control system for solar thermal power generator units [7]. Therefore, the correlation between heat accumulation and working substances can be qualitative and quantitative analyzed [8].

The application of electric energy and the storage of thermal energy are critical in various fields. Therefore, an efficient and stable heat accumulation system is of great significance for solar thermal power generation [9]. Solar energy is abundant clean energy with a high price-quality ratio, which is inexhaustible. Finding an efficient heat accumulation system for solar thermal generator units is the current focus. At present, this field is at an early stage; thus, the research focus of this study is to construct and design a heat accumulation system that satisfies the needs of normal operations of solar thermal power generation [10].

This study uses computer numerical simulation analysis and simulation experiments to analyze and study the heat accumulation performance of solar thermal generator units, as well as the working mechanism and correlation of the heat accumulation system. Research shows that the thermal energy accumulation system is critical for the normal operation of the generator units, and the thermal energy accumulation system is the guarantee for the generating set. The heat accumulation system constructed in this study meets the normal operation needs of the generator units. The innovation of this study is that it mainly analyzes the heat accumulation link of solar thermal generator units, while most of the current research directions are the research on the operating systems of generators. Therefore, this study has significant values for subsequent research on heat accumulation systems.

2. Methodology

2.1. Solar thermal power generation

The principle of solar thermal power generation system is shown in Fig. 1. Solar thermal power generation technology mainly refers to concentrating medium-high-temperature solar thermal power generation, which is classified according to the type of collector and can be divided into the trough systems, the tower systems, and the dish systems [11,12]. Solar heat absorber can be heavily affected by solar radiation energy; therefore, the constant value of solar heat absorber fluctuates steadily, resulting in fluctuations in the pressure of the heat absorber outlets. For the stable operation of the steam turbine, it is necessary to rely on the heat accumulator to release energy in time to compensate for fluctuations in the value of the solar heat absorber. Therefore, by controlling the opening of the regulating valve, the automatic accumulator pressure regulating system at the outlet of the heat accumulator can largely release the energy in a timely manner, which can stabilize the steam pressure before the turbine inlet to a certain degree [13].

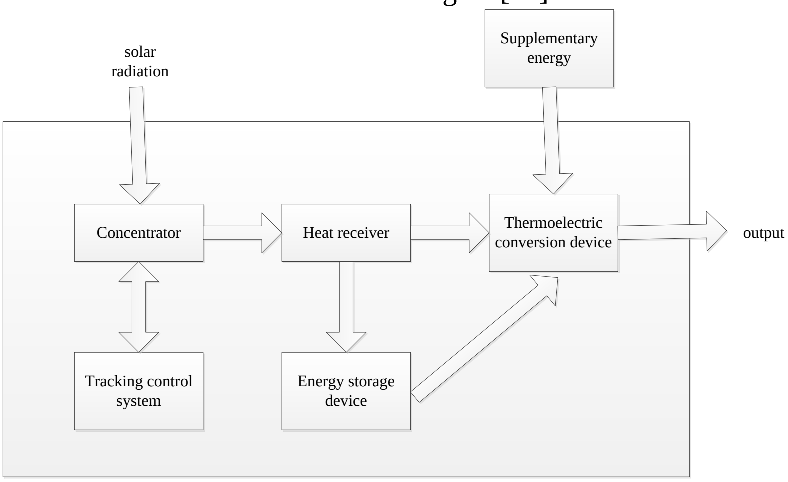

Figure 1 The principle of the solar thermal power generation system

2.2. Solar collector

The solar collector is a device that can absorb the solar radiation energy, transform the solar energy into thermal energy, and transfer the thermal energy to the heat-transferring working substance. It is a key component of the solar energy utilization system [14]. The function of the solar thermal power generation is shown in Fig. 2. There are many ways to classify solar collectors, such as whether they are focused or not, whether to track the sun or according to the operating temperature range [15]. According to the different temperatures of solar thermal sources, solar collectors can be divided into low-temperature collectors (less than 100°C), medium-temperature collectors (100-200°C), and high-temperature collectors (higher than 200°C) [16]. Examples will be given for flat-plate collectors (low-temperature type), vacuum tube collectors (medium-temperature type), and light-concentrating collectors (high-temperature type).

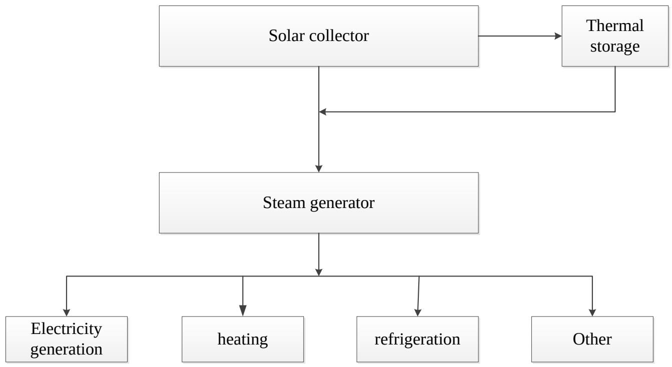

Figure 2 The functions of solar thermal generator units

2.3. Selection principle of energy-storage working substances

The working substance of the solar thermal generator unit is a vital and essential material required by the system. Therefore, the selection of the working substance is a complicated process, and various aspects of requirements need to be considered [17]. Therefore, the needs of all levels can be considered to maintain the long-term and stable work of the solar thermal generator units; meanwhile, no economic, safety and pollution problems will occur. Therefore, the selection of the working substance needs to consider the following aspects:

Environmental protection: Since the solar thermal power generation unit is a clean and pollution-free power generation system, the selected working substance must also be free from environmental pollution. However, most working substances currently have more or fewer pollution problems that cause atmospheric damage; thus, more careful consideration and selection are needed [18].

Chemical and physical properties: Since the role of the working substance is mainly to store and convert energy in the heat accumulation system, it is necessary to study its water solubility, oil solubility, and other properties. It is necessary to keep the values of viscosity and density relatively low. Therefore, the resistance will be reduced a lot. Most importantly, the working substance must have high thermal conductivity so that the heat transfer process can be significantly enhanced and the waste of heat can be reduced. In addition, the stability of the working substance is also critical. The phase change of the working substance cannot occur, and in most cases, it will not explode, burn, or decompose.

Thermodynamic properties: The boiling point of the working substance should not be too high. Even if the boiling point of the working substance is relatively low, the pressure will generally be relatively high, so the manufacturing level of the condenser will be very strict. The condensing pressure can be kept moderate. If the pressure is too small, it will cause air to penetrate from the problem area, causing serious consequences and affecting the heat transfer function. However, the pressure should not be too large, which may also cause the leakage of the working substance.

Price: Solar thermal generators are highly dependent on working substances and need to maintain long-term stable work. Therefore, only if there are economical advantages can long-term stable power generation be maintained, and large-scale economic promotion can be carried out.

2.4. Thermal calculation of heat accumulation system

In analyzing the performance and use of solar collectors, it is necessary to measure the amount of solar radiation heat, which is expressed by the radiation intensity and can be directly measured by a solar radiation meter in the experiment.

The declination angle refers to the angle between the line connecting the sun and the center of the earth and the earth's equatorial plane. The declination angle is calculated by:

$$\delta = 23.45\sin\left(360\times\frac{284+n}{365}\right) \tag{1}$$

The calculation method for the solar altitude angle h is as follows:

$$\sinh = \sin\varphi\sin\delta + \sin\varphi\sin\omega \tag{2}$$

The solar azimuth angle refers to the angle between the projection of the line connecting the sun and the ground on a horizontal plane and the local south direction. The calculation method for the solar azimuth angle is as follows:

$$\sin\alpha = \frac{\cos\delta\sin\omega}{\cosh} \tag{3}$$

The solar incident angle refers to the angle between the sun lights and the normal line of the inclined surface. The calculation method for the incident angle h of the sun is as follows:

$$\cos i = \cos\theta\sinh + \sin\theta\cos(\alpha-\gamma) \tag{4}$$

Calculation equation of atmospheric quality:

$$m = \frac{1}{\sinh} \tag{5}$$

The aperture diameter and focal length of the condenser are two important structural parameters. The correlation between them is as follows:

$$\frac{f}{D_{coll}} = \frac{1}{4\tan(\varphi_{\min}/2)} \tag{6}$$

The focal plane width formed by the condenser emission at the opening of heat absorber can be calculated by the following equation:

$$R_p = \frac{2f}{1+\cos\theta} \tag{7}$$

$$\omega = \frac{4ftg16}{\cos\Psi_{rim}(1+\cos\Psi_{rim})} \tag{8}$$

The energy loss is calculated as follows:

$$\varphi = 1-\exp\left(\frac{1}{2C\sigma_f^2}\right) \tag{9}$$

The distribution error of heat flux density at the focal plane of the heat collection system:

$$\sigma_f^2 = \delta^2\frac{1+2\cos^2\varphi_{rim}}{3\varphi_{rim}\cos\varphi_{rim}\sin\varphi_{rim}} \tag{10}$$

All errors of the condenser:

$$\delta^2 = 4\sigma^2_{slp} + \sigma^2_{spec} + \sigma^2_{w} + \sigma^2_{sun} \tag{11}$$

The energy of the engine can be calculated by the following equation:

$$Q_{engine} = Q_{rec} - Q_{r,refl} - (Q_h + Q_{r,emiss}) \tag{12}$$

The calculation equation of the solar radiant energy of the heat absorber is:

$$Q_{rec} = IA_{dish}\rho\varphi e\tau \tag{13}$$

$$Q_{r,refl} = \left(1 - \alpha_{eff}\right) Q_{rec} \tag{14}$$

$$\alpha_{eff} = \frac{\alpha_{rec}}{\alpha_{rec} + \left(1 - \alpha_{rec}\right)\left(A_{coll} / A_{rec}\right)} \tag{15}$$

The calculation equation of the solar radiant energy of the heat absorber is:

$$\eta_{rec} = \frac{Q_{engine}}{IA_{dish}\rho} \tag{16}$$

Solar power generation is the process of converting radiant energy into electrical energy, which includes two parts, i.e., light-to-heat conversion and thermoelectric conversion. The light-to-heat conversion uses the principle of solar collector heat collection, while the thermoelectric conversion uses the principle of the organic Rankine cycle. At present, the application of the two principles is relatively mature, while the application research combining the two principles is rare, which has a large space for development. The schematic diagram of the pressure waveform in the accumulator is shown in Fig. 3. Based on the two basic principles and the practical experience of waste heat power generation, this study proposes a solar thermal power generation system and evaluates the system performance by experiments.

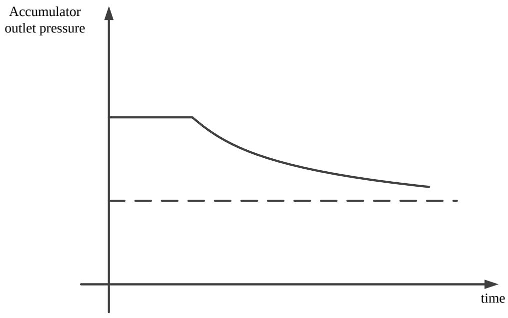

Figure 3 Schematic diagram of pressure waveform in the heat accumulator

2.5. Working principles of the heat accumulator

The working principle of the heat accumulator is shown in Fig. 4. When the steam accumulator outlet regulating valve is closed and the total accumulator inlet valve is opened, the superheated steam from the solar heat absorber first passes through the heat exchanger and exchanges energy with the hot tank; then, the remaining slightly superheated steam enters the steam accumulator containing high-pressure saturated water. At this time, the steam transfers energy to high-pressure saturated water, which causes its temperature and pressure to increase continuously, so that the steam accumulator stores thermal energy. In other words, the steam accumulator stores energy in the form of high-pressure saturated water, and the high-pressure saturated water pressure can be maintained at about 2.60 MPa. When the steam accumulator outlet regulating valve opens and the total accumulator inlet valve closes, the internal pressure of the steam accumulator begins to drop. At the moment of opening, the inside of the steam accumulator began to gradually decline in the form of an exponential curve, and the high-pressure saturated water then became saturated steam with a certain pressure. If the total inlet valve of the heat accumulator and the outlet regulating valve of the steam accumulator are opened at the same time, the superheated steam entering from the total inlet valve of the accumulator will not become high-pressure saturated water but will be directly adjusted from the outlet of the steam accumulator, i.e., the "short-circuit" occurs. In this case, the steam accumulator does not store energy, and the temperature and pressure of the steam accumulator remain unchanged.

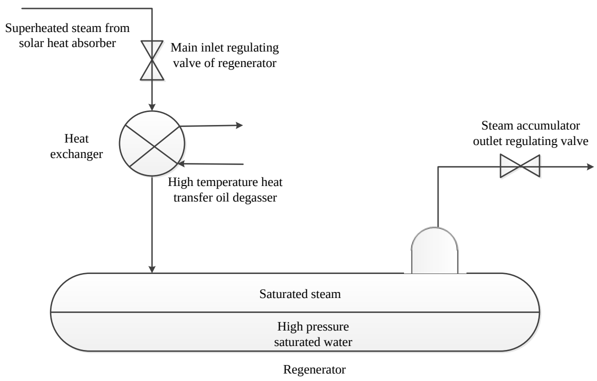

Figure 4 Working principles of the heat accumulator

2.6. The solar thermal power generation system

Solar thermal generator units use the working substance as the core link and product, and then utilize the characteristics of the working substance and the solar collector to perform energy heat exchange. Solar collectors are the key equipment in thermal power generation systems. The overall operating efficiency of a solar thermal power generator unit mainly needs to be combined with the actual circulation effect of the working substance, the working condition of the expander, and the working condition of the solar collector. In general, the temperature range of solar thermal power generator units is around 120°C. The longitudinal section size of the solar collector tube is shown in Fig. 5. Generally, the solar collecting system of the vacuum chamber is mainly used.

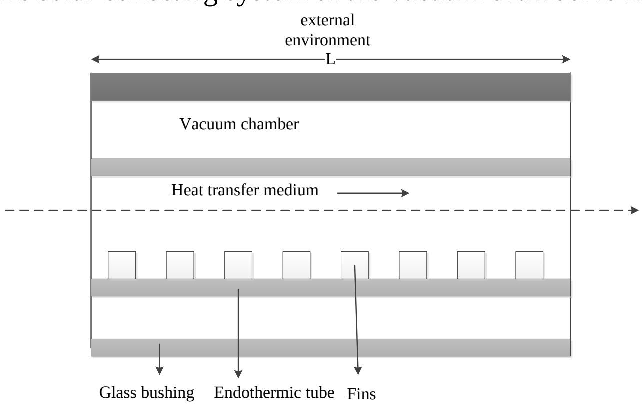

Figure 5 The size of the longitudinal section of collector tubes

Solar thermal generator units generally include three core links. The first is the heat collection link. The second is the power generation link; this link is dominant since it is the purpose of solar thermal power generation; therefore, it is regarded as the core link. Its main equipment includes generators, expansion systems, condensation equipment, liquid storage tanks, evaporation equipment, and related loads. The third is the control and acquisition data system. This link mainly includes pressure meters, flow meters, voltmeters, ammeters, inverters, collectors, recorders, tachometers, and other related equipment.

3. Results and discussion

Figure 6 shows the thermal performance analysis of storage working substances in solar energy thermal generator units. As shown in Fig. 6, the thermally conductive fluid used in this study has an outstanding effect, and the three curves run basically the same trend. With the increase of the radiation intensity of the sun, the outlet temperature of the heat-conducting working substance gradually increases. The velocity of the heat-conducting working substance has a significant effect on the heat accumulation temperature of the heat-conducting oil working substance. Under the same radiation intensity, the greater the flow velocity of the working substance is, the worse the heat accumulation and heat conduction of the working substance is. The velocity of the working substance has a significant effect on the heat accumulation and thermal conductivity of the working substance.

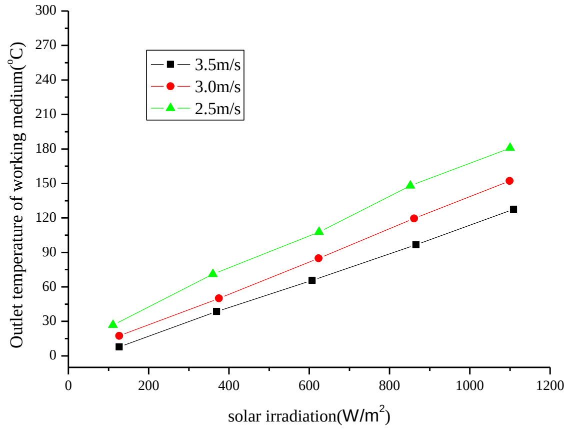

Figure 6 Thermal performance analysis of storage working substances in solar thermal generator units

Figure 7 shows the correlation between condensing pressure and condensing temperature of storage working substances in solar energy thermal generator units. As shown in Fig. 7, the three different working substances based on computer numerical simulations have basically the same realizing trend between condensing pressure and condensing temperature. As the working substance condensing temperature increases, the condensing pressure also increases. The difference is that different working substances exhibit different condensing pressures at the same condensing temperature. In the heat accumulation system, when the amount of radiation is sufficient and the needs of the generator are satisfied, the surplus energy is stored by working substances. Once the solar radiation is insufficient, the storage system will release energy to meet the needs of the generator units. In summary, when the energy of a thermal power unit is insufficient, the energy is released by the heat accumulation system.

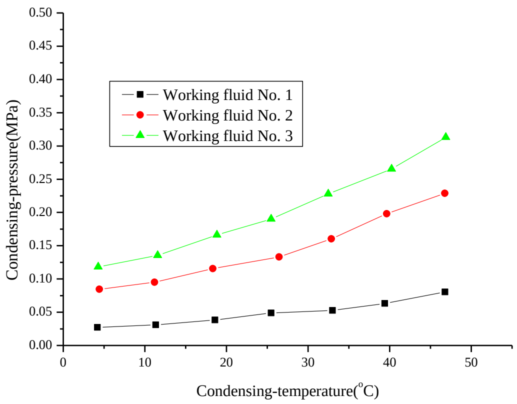

Figure 7 Correlation between condensing pressure and condensing temperature of storage working substances in solar thermal generator units

Figure 8 shows the correlation between power generation efficiency and evaporation temperature of storage working substances in solar energy thermal generator units As shown in Fig. 8, the correlation between the evaporation temperature of the storage working substance and the power generation efficiency under the numerical simulation based on the computer shows a positive trend in general. As the evaporation temperature of the working substance increases, the power generation efficiency of the working substance also increases significantly. There are differences in power generation efficiency between different working substances, but the correlation between power generation efficiency and the evaporation temperature is basically the same among various working substances. It can be seen that the evaporation temperature of the working substance has a significant effect on the efficiency of power generation.

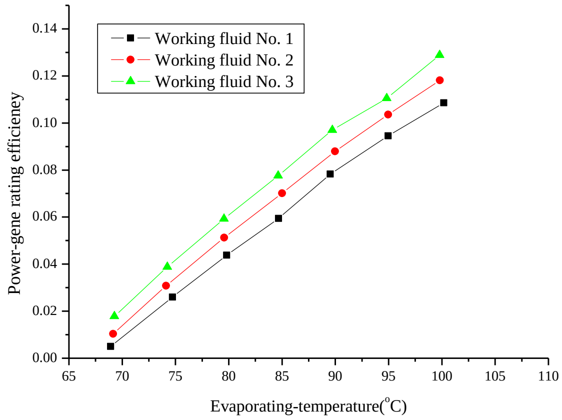

Figure 8 Correlation between power generation efficiency and evaporation temperature of storage working substances in solar thermal generator units

4. Conclusion

In this study, the core carrier working substances of heat accumulation of solar thermal generator units are analyzed through computer numerical simulation analysis and simulation experiments, including the selection criteria of working substances, the mechanism of heat accumulation system, the correlation between power generation efficiency and the evaporation temperature of working substance, the correlation between the condensing temperature and condensing pressure of working substance, and the influence of working substance velocity on heat accumulation capacity. The results show that under the same radiation intensity, the greater the flow velocity of the working substance is, the worse the heat accumulation and heat conduction of the working substance is. The selection of the working substance should consider factors of environmental protection, economy, physical chemistry, and thermodynamics. The research results show that as the condensing temperature of the working substance increases, the condensing pressure also increases. As the evaporation temperature of the working substance increases, the power generation efficiency of the working substance also increases significantly. The mechanism of the heat accumulation system is that in summer, if the light intensity is sufficient for the generator units, the remaining energy will be stored in the heat accumulation system. If the light intensity decreases and the collected thermal energy cannot meet the needs of the generator units, the heat accumulation system outputs previously-stored thermal energy for the generator units. This study also has some deficiencies in the research process, which are mainly caused by the fact that the obtained conclusions on the heat accumulation system are more from the experimental and theoretical stages. In actual operations, there will be many factors and problems. These external factors have been ignored in the simulation experiment; therefore, the results obtained are slightly less convincing. Still, the research in this study provides a valuable reference for the research of photovoltaic fuel cell storage systems from a qualitative perspective.

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