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Research paper

Thermodynamic analysis of an idealised solar tower thermal power plant

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HIGHLIGHTS

- Built an idealized thermodynamic model for solar tower thermal power plants.
- Analyze the influence of various parameters on thermal and exergy efficiencies.
- The optimum temperature would increase with the concentration ratio.
- The endoreversible engine efficiency would have an optimum value.

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ABSTRACT

In the real solar tower thermal power system, it is widely acknowledged that the thermodynamic irreversibility, such as convective and radiative loss on tower receiver, and thermal resistance in heat exchangers, is unavoidable. With above factors in mind, this paper presents an ideal model of the solar tower thermal power system to analyze the influence of various parameters on thermal and exergy conversion efficiencies, including receiver working temperature, concentration ratio, endoreversible heat engine efficiency and so forth. And therefore the variation of maximum thermal conversion efficiency in terms of concentration ratio and endoreversible heat engine efficiency could be theoretically obtained. The results indicate that raising the receiver working temperature could initially increase both thermal and exergy conversion efficiencies until an optimum temperature is reached. The optimum temperature would also increase with the concentration ratio. Additionally, the concentration ratio has a positive effect on the thermal conversion efficiency: increasing the concentration ratio could raise the conversion efficiency until the concentration ratio is extremely high, after which there will be a slow drop. Lastly, the endoreversible engine efficiency also has significant influence on the thermal conversion efficiency, it will increase the thermal conversion efficiency until it reaches the maximum and optimum value, and then the conversion efficiency will drop dramatically.

1. Introduction

Solar tower thermal power plant is regarded as one of the most promising solar power technologies. Among the dozens of solar tower thermal power plants in operation or construction around the world, the maximum power output could reach 100 MW [1]. The solar tower power plant mainly consists of two relatively independent systems: solar collector and steam power generation system. The solar collector system includes an array of heliostats and a solar tower receiver, aiming to convert the solar radiation into the high temperature thermal energy. The steam power system comprises steam generator in the tower and power conversion heat engine, whose purpose is to convert the high temperature thermal energy into power output. Generally, for these two independent systems, when the operation temperature increases, the efficiency of solar collector will decrease whilst the efficiency of steam power system will increase. Therefore a trade-off is needed to solve the conflict of different operation temperature requirements for these two systems.

According to the second law of thermodynamics, a reversible heat engine has the maximum power conversion efficiency; while

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the real heat engine in operation is always irreversible as it could always contain irreversible processes to some extent. Despite of this, the analysis of an idealised solar thermal power system is still beneficial because it could help to gain knowledge about the influential parameters and the deviation between a real and ideal systems. In the solar thermal application, Salah [2], Chen [3], Ronan [4], Sahin [5], Tamer [6]and Koyun [7] took a series of theoretical analysis of solar-driven heat engines; the optimal operation conditions were analyzed, the optimal correlation between the maximum power output and receiver temperature was given, which proved that the efficiency of reversible heat engine has restrictive relation with the maximum power output, while not indefinitely increasing the efficiency of reversible heat engine. Through analyzing the solar tower thermal power system from the view of thermodynamics, it is realized that the irreversible process mainly comes from the thermal resistance between system components, or called external irreversibility. Curzon and Ahlborn [8] analyzed the reversible engine system with external irreversibility, they concluded that the overall system efficiency did not only depend on heat transfer coefficient, but also the heat reservoir temperature. Chacartegui et al. [9] undertook a thermodynamic investigation for solar-driven thermal power systems with different thermal cycles and compared their efficiencies. Sahin [10] and Khaliq [11] took finite-time thermodynamic analysis of solar-driven power system with heat transfer resistance respectively; they also contributed the optimal operation condition for solar power system with Rankine heat-engine. Spelling [12] studied the thermoeconomics for a solar tower combined-cycle power plant, and built a thermoeconomic model. Behar [13]summarized centralized solar receiver solar thermal power plants and evaluated the influence of system structure parameters on the system performance, and the direction of future development was also mentioned. Sahin [14] took a performance analysis of an endoreversible heat engine based on a new thermoeconomics optimization criterion and proposed an optimal operation condition.

The above studies have promoted the development of solar tower thermal power plants. However, they did not analyze the relationship between the input and output power for the idealised solar tower thermal power plant, and neither did the optimal interrelation between various parameters. Therefore, under condition of finite-time and finite heat transfer coefficient, it is necessary to have a deeper investigation for the ideal solar tower thermal power plants so that the correlation between crucial parameters, such as concentration ratio, receiver temperature, and reversible heat engine efficiency could be obtained. As a result, this paper presents a theoretical model for an idealised solar tower thermal power system based on the first and second laws of thermodynamics. It also analyzes the internal and external irreversibility for the system and gives the optimal operation curve for the whole system.

2. Model of idealised solar tower thermal power plants

The components of the solar tower thermal power system are quite complicated as well as its control system. Assuming that the system can work under stable condition and track the solar position accurately, a simplified system configuration could be drawn as Fig. 1. The thermodynamic process between each component is also indicated in Fig. 1. It can be observed from Fig. 1 that the system takes into account the radiative and convective loss on the tower receiver, and the heat transfer resistance between components in thermodynamic process as well.

The solar-driven tower heat engine is normally installed on the ground. When the influence of the atmosphere on the solar radiation is considered, and only the direct solar radiation can be absorbed, the total amount of the solar radiation received is:

$$Q_s = A_R C \alpha_R \beta f \sigma T_s^4 \tag{1}$$

Where A_R is the area of the receiver; α_R is the absorptivity of the receiver; C is the concentration ratio of the solar tower collector system; β is the ratio of the direct solar radiation relative to the global solar radiation.; since the sun is assumed to be absolute black body, $f\sigma T_s^4$ is the solar constant, it shows the solar radiation on the outer atmosphere of the earth, which can be expressed by I_R.

Most of the solar energy received by the receiver is delivered to the next heat reservoir, but some heat energy is lost through convection and radiation. These two factors can be expressed by

$$Q_{conv} = h_{conv} A_R (T_R - T_0) \tag{2}$$

$$Q_{rad} = \varepsilon_R A_R \sigma T_R^4 \tag{3}$$

Where ε_R is the surface emissivity of the receiver; h_{conv} is the convection coefficient between the receiver and the atmosphere.

Therefore, the total solar energy which is delivered to the heat engine system is:

$$Q = Q_s - Q_{conv} - Q_{rad} = A_R\left[C\alpha_R \beta I_R - h_{conv}(T_R - T_0) - \varepsilon_R \sigma T_R^4\right]$$

Given that from the receiver to the heat engine, the product of the heat transfer coefficient and surface area for each heat exchanger is $U_R A_R$; $A_M U_M$; $A_H U_H$, respectively. The product of heat transfer area and coefficient of the condenser is $A_L U_L$. Additionally, it is assumed that there is no heat loss through all the process, and then the following equations can be achieved

$$Q = A_R U_R (T_R - T_M) \tag{4}$$

$$Q = A_M U_M (T_M - T_H) \tag{5}$$

$$Q = A_H U_H (T_H - T_x) \tag{6}$$

$$Q_L = A_L U_L (T_L - T_o) \tag{7}$$

Equation (5) considers this solar-driven tower power system using the molten salt as working fluid. If using water instead, which means the solar receiver is also the driving system for the steam generator, then the Equations (5) and (6) can be integrated into one equation. The proposal of Equation (6) considers that the efficiency of ideal steam power cycle is not the efficiency of Carnot heat engine working between T_H and T_L. The theory of steam Rankine cycle indicates that the ideal Rankine cycle efficiency is smaller than that of Carnot cycle working between the same heat reservoirs. In order to discuss the system using the Carnot heat engine,T_X, which is lower than T_H, is defined, and it is assumed that the efficiency of Rankine cycle working between T_H and T_L is as same as that of Carnot heat engine working betweenT_X and T_L [10]. Since the heat engine is endoreversible, the following equation could be given by the Carnot principle:

$$\eta = 1 - \frac{T_L}{T_x} \tag{8}$$

$$Q_L = Q\frac{T_L}{T_x} \tag{9}$$

According to Equations (4), (5), and (6):