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Thermal and Exergy Efficiency Analysis of Receiver for Solar Thermal Power Plant System

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ABSTRACT

The purpose of this research is to analyses the thermal energy and the exergy efficiency of the focal point receiver in a solar power generation system. Heliostats are used as reflectors, directing sunlight towards the focal point receiver. The receiver transfers thermal energy to the first working medium, which is molten salt. Subsequently, the thermal energy from the molten salt is transferred to the second working medium, water. Once heated, the water boils and becomes steam, which can then drive a steam turbine to generate electricity. This research specifically analyses the thermal energy and assesses the exergy efficiency at the focal point receiver only, using the Engineering Equation Solver (EES) program to assist in calculations and to compare with past research. The thermal efficiency increases with higher Direct Normal Irradiation (DNI) values, where DNI ranges from 100 to 300 W/m^2, showing a rapid increase in thermal efficiency. Then, the thermal efficiency gradually increases as the DNI ranges from 300 to 700 W/m^2, and remains nearly constant at levels above 700 W/m^2. The exergy efficiency also increases rapidly as DNI values range from 100 to 400 W/m^2, then it gradually increases when DNI values range from 300 to 700 W/m^2, and remains nearly constant at levels above 700 W/m^2.

1. Introduction

Solar thermal energy is a sustainable and renewable energy source with high potential. Solar thermal technology plays an important role in addressing the problems of climate change and energy security. The conversion of solar energy into steam is one of the most efficient ways to utilize solar thermal energy. Steam can be used to drive turbines for electricity generation or in various industrial processes. Solar concentrators are the primary devices used to convert solar energy into heat. The efficiency of solar concentrators depends on several factors, such as the type of collector, the shape of the concentrator, the materials used in its construction, and the conditions of use.

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A concentrator is a crucial component of a solar panel, as it focuses sunlight from a broad area onto a heat-receiving point. There are various types of concentrators, each with specific advantages and disadvantages depending on the application, materials, and manufacturing methods. Concentrators can mainly be divided into three categories. (1) Lens Concentrators, Convex Lens: this type of lens focuses light toward a focal point and is commonly used in telescopes, microscopes, and camera lenses. Concave Lens: In contrast, a concave lens disperses light, causing the rays to spread out from one another. This type of lens is frequently used in eyeglasses for correcting nearsightedness and in some camera lenses. Aspheric Lens: This asymmetrical lens minimizes light distortion and is typically employed in high-quality cameras for clearer, more accurate images. (2) Mirror-Based Concentrators, Convex Mirror: A convex mirror focuses light toward a focal point and is commonly used in telescopes and solar heaters for efficient light collection. Concave Mirror: A concave mirror, on the other hand, spreads light away from itself, making it useful in devices like farsighted glasses and vehicle rearview mirrors. Parabolic Mirror: Shaped like a paraboloid, this mirror concentrates reflected light at a single focal point. It is commonly used in applications such as flashlights, car headlights, and some telescopes. (3) Fiber Optic Concentrators, Single-Core Fiber Optics: These fibers have a very small core through which light travels by reflecting off the internal walls. They are commonly used in telecommunication systems for transmitting data over long distances. Multimode Fiber: Multimode fibers have larger cores, allowing light to travel through the core in multiple pathways. They are often used in shorter-distance applications, such as in local area networks (LANs) and computer networks.

Solar concentrators are a technology that utilizes mirrors to reflect and concentrate solar energy onto a receiver, thereby raising the temperature of a working fluid. This heated fluid can then be used to drive turbines or transmit energy for electricity generation [1-3]. The increased temperature allows for more efficient use of the energy cycle, improving the overall efficiency of the power generation process [4,5]. An efficient heliostat field also helps to reduce the environmental impact related to energy production [6]. For energy production in a tower-type solar thermal system, DNI (Direct Normal Irradiance) first undergoes atmospheric attenuation, then reaches the heliostat, and finally reaches the heat receiver through reflection by the heliostat. In this process, DNI is mainly affected by absorption and reflection from clouds, aerosols, water vapor, and ozone [7].

The heat storage systems in these plants use both saturated steam and superheated steam. Efficiency decreases when the steam is released below a certain temperature. These systems are designed specifically for the steam cycle and must be used in conjunction with components such as a steam turbine, condenser, water pump, and other related equipment.

According to the report from the International Energy Agency, the future will face severe air pollution and environmental issues [8]. It is inferred that governments should reform traditional processes with clean technology [9-12]. Today, saturated steam collectors are commonly used in hot water plants [13,14]. These systems can store steam at a constant pressure but can only discharge it below a specified pressure. Steam discharge can be achieved in two ways: through a sliding pressure mechanism or via a constant pressure stage within a saturated module [15].

Generally, solar thermal technology relies on the principle of concentrating solar radiation to produce steam, which can then be used to generate electricity through conventional energy cycles. One of the primary engineering challenges in developing solar thermal power plants is the collection of solar energy, which has a relatively low density. To achieve effective concentration, most systems use glass mirrors due to their high reflectivity. A semicircular-shaped coil tube was used as the receiver of a solar thermal power plant. This shape has higher efficiency compared to others, according to the report by Maulana *et al.,* [16] and Yasar *et al.,* [17]. However, other materials are currently under development to better meet the requirements of solar thermal power systems. Both point-focusing and line-focusing systems are employed, as illustrated in Figure 1.

This research aims to analyze the thermal efficiency and exergy efficiency of the light receiver using the Engineering Equation Solver (EES) program. The EES program will assist in calculations and enable comparisons with past research. The study's results can be used to further analyze and enhance solar power generation systems.

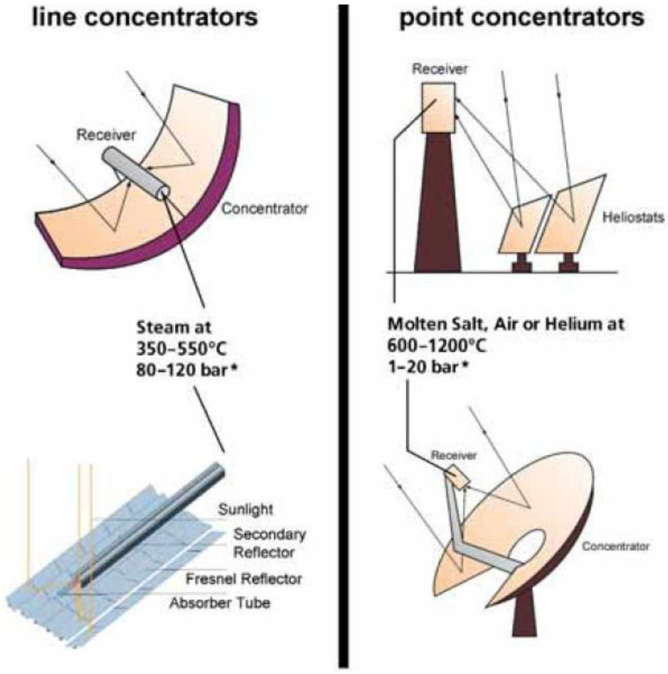

Fig. 1. Different types of photoreceptors Left: Line concentrators and Right: Point concentrators [5]

2. Methodology

2.1 Solar Power Generation System

Figure 2 shows a schematic diagram of a solar power generation system, which is divided into two parts. The first part generates solar thermal energy and consists of a heliostat, a receiver, and a molten salt and steam heat exchanger. The second part generates steam and is connected to the heat exchanger, comprising a steam turbine, a condenser, and a water pump.

In the operation of the system, the glass array absorbs heat from the sun and reflects it to the heat receiver. Inside the heat receiver, a set of heat exchange pipes transfers the heat to the molten salt. The heat from the molten salt is then transferred to the water in the heat exchanger, producing steam that drives the steam turbine to generate electricity. Afterward, the steam condenses into water droplets in the condenser and flows back to the heat exchanger to be reheated and converted into steam.

This research presents a preliminary analysis, focusing only on the thermal and exergy efficiency of the light receiver.

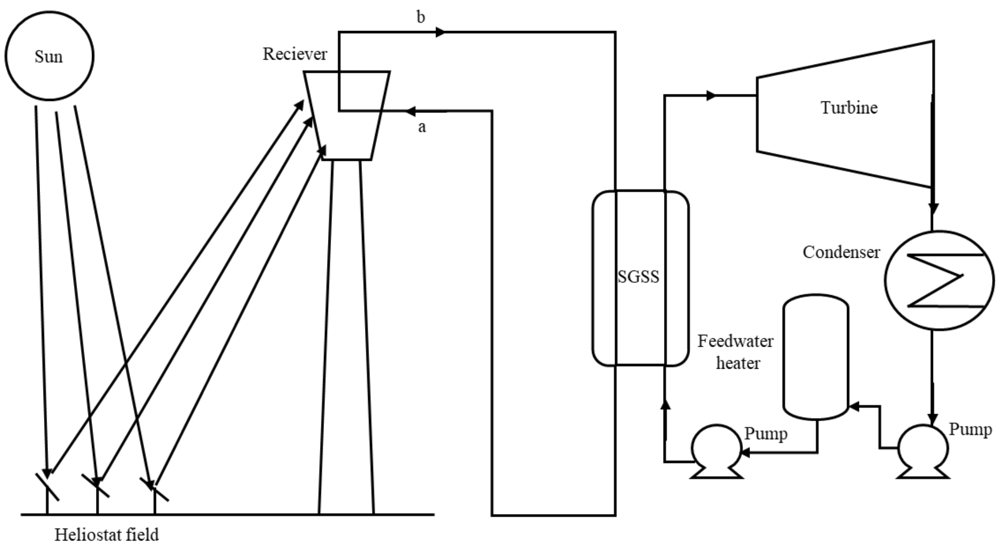

Fig. 2. Schematic diagram of the solar power generation system

2.2 Calculation of Thermal Efficiency of Light Receivers

The receiver of a solar power generation system consists of a number of heliostats arranged in a row with a total receiving area equal to Aape. The main function of the heliostat field is to reflect and concentrate sunlight to a central receiver. The total amount of radiation received (Q) is a ratio to the total area, calculated from the equation $Q=Ahq^*$, where q^* is the amount of solar radiation received per unit area. Here, the direct normal radiation (DNI) is used. DNI varies with various factors such as geographic location, weather conditions, and time of day. In this analysis, q^* is assumed to be constant and the system is operating at steady state. The thermal energy generated by the solar array can be calculated from Eq. (1) [18].

$$\dot{Q}_{rec,\,in} = \eta_{field} DNI\, A_{Hel} N_{Hel} \tag{1}$$

η_{field} is the receiving efficiency of the receiving mirror assembly, A_{Hel} and N_{Hel} are the area and number of mirrors, respectively.

In the operation of the receiver system, $\dot{Q}_{rec,\,in}$ is extracted and part of the energy is transferred to the flowing liquid (e.g. molten salt). The remaining energy is lost to the surroundings by radiation, convection and reflection. The energy balance for the energy receiver system is

$$Q^*_{rec,\,u} = \dot{Q}_{rec,\,in} - \dot{Q}_{rec,\,loss} \tag{2}$$

where $\dot{Q}_{rec,\,loss}$ is

$$\dot{Q}_{rec,\,loss} = \dot{Q}_{red} + \dot{Q}_{convec} + \dot{Q}_{ref} \tag{3}$$

The first term of the radiant heat loss rate is defined as

$$\dot{Q}_{red} = \varepsilon\, \sigma\, A_{rec,sur} F_r \left(T^4_{rec,sur} - T^4_a \right) \tag{4}$$

$$F_r = \frac{A_{ape}}{A_{rec,sur}} \tag{5}$$

where ε denotes the radiation coefficient, σ represents the Stefane-Boltzmann constant, $A_{rec,sur}$ represents the surface area of the receiver, F_r represents the view factor, and $T_{rec,sur}$ and T_a represent the surface temperature of the receiver and the ambient temperature, respectively.

Also, the convective heat loss rate can be calculated as follows:

$$\dot{Q}_{convec} = \dot{Q}_{convec,\,for} + \dot{Q}_{convec,\,nach} \tag{6}$$

$$\dot{Q}_{convec,\,for} = h_{air,\,for,\,insi}\, A_{ape} \left(T_{rec,sur} - T_a \right) \tag{7}$$

$$\dot{Q}_{convec,\,nach} = 0.81 \left(T_{rec,sur} - T_a \right)^{0.426} \left(T_{rec,sur} - T_a \right) A_{rec,sur} \tag{8}$$

where $\dot{Q}_{convec,\,for}$ means forced convection heat loss rates and $\dot{Q}_{convec,\,nach}$ means natural convection heat loss rates, $h_{air,\,for,\,insi}$ means the heat transfer coefficient, and $A_{rec,sur}$ means the aperture area.

Finally, the reflected heat loss rate is obtained from the equation

$$\dot{Q}_{ref} = \dot{Q}_{rec,\,in} F_r\, \rho_{rec,sur} \tag{9}$$

$\rho_{rec,sur}$ is the reflection coefficient of the receiver. The energy efficiency of the solar receiver subsystem can be calculated from

$$\eta_{I,\,rec} = \frac{\dot{Q}_{rec,\,in}}{Q^*_{rec,u}} \tag{10}$$

2.3 Calculation of the Exergy Efficiency of the Receiver

Central receivers, which are typically mounted on top of a solar tower, come in various shapes, including cavity and cylindrical receivers. This analysis focuses solely on cavity receivers. During operation, the receiver absorbs the dissipated energy Q^* and transfers a portion of it to the heat transfer fluid (e.g., molten salt) flowing through the receiver. The remaining energy is lost to the surroundings through convective, radiative, reflective, and conductive heat losses [19]. The energy balance and exergy balance for a central receiver are as follows:

$$\dot{E}_{rec} = Q^*_{rec,\,u} \left(1 - \frac{T_a}{T^*} \right) \tag{11}$$

where $\dot{E}_{rec}$ is the exergy of receiver, T_a and T^* are the apparent temperature of the Sun and the ambient temperature, respectively.

The use full exergy absorb by the following molten salt is

$$\dot{E}_{rec,\,abs} = \dot{m}_{ms}((h_{out}-h_{in})-T_0(S_{out}-S_{in})) = \dot{m}_{ms} c_{p,ms}(T_{out}-T_{in}-T_0 \ln(T_{out}-T_{in})) \tag{12}$$

The exergy efficiency of the receiver subsystem is defined as

$$\eta_{II,\,rec} = \frac{\dot{E}_{rec,\,abs}}{\dot{E}_{rec}} \tag{13}$$

From the analysis of the obtained results, the calculation of the exergy efficiency of the receiver is very important to take into account the heat loss including the average surface temperature of the receiver.

Therefore, in the Concentrating solar power (CSP) system, the method of reducing the exergy loss in the receiver subsystem, including in the heliostat field subsystem, should be used. The exergy efficiency has factors affecting the receiver subsystem, which can be analyzed from Eq. (11), Eq. (12) and Eq. (13) as:

$$\eta_{II,rec} = \eta_{I,rec} \frac{1 - T_0 \ln (T_{out} - T_{in}) / (T_{out} - T_{in})}{\left(1 - T_0 / T^*\right)} \tag{14}$$

To calculate the thermal efficiency of the receiver and other unknown values, the Engineering Equation Solver (EES) program was used to assist with the calculations.

In the analysis of the thermal energy efficiency of solar power for electricity production as outlined in the schematic of the solar power generation system, the properties used in the modeling are shown in Table 1.

Table 1
Data used for modelling process

Parameter	Value	Reference
View factor	0.88	Xu *et al.,* [1]
Ambient temperature	293 K	Xu *et al.,* [1]
Tube diameter	0.019 m	Xu *et al.,* [1]
Aperture area	563.54 m^2	Xu *et al.,* [1]
Reflectivity	0.04	Xu *et al.,* [1]
Number of mirrors	600	Cao *et al.,* [18]
High DNI	1 kW/m^2	Sheykhlou *et al.,* [20]
Low DNI	0.2 kW/m^2	Sheykhlou *et al.,* [20]
Optical efficiency of the field (%)	71%	Sheykhlou *et al.,* [20]
Stefane-Boltzmann constant	5.67×10^{-8} W/m^2k^4	Al-Sulaiman *et al.,* [21]
Area of mirrors	121 m^2	Alirahmi *et al.,* [22]
Emissivity coefficient	0.88	Alirahmi *et al.,* [22]
Receiver area	60 m^2	Alirahmi *et al.,* [22]

Figure 3 demonstrates how the efficiency of the energy of the receiver increases with higher Direct Normal Irradiation (DNI). This can be explained by analyzing two main mechanisms of heat loss: emissive and convective, which depend on the surface temperature of the receiver, not the DNI. When DNI increases from 100 to 1000 W/m^2, the surface temperature changes slightly from 510 to 546 ^oC, resulting in a slight increase in heat loss and efficiency proportional to the DNI.

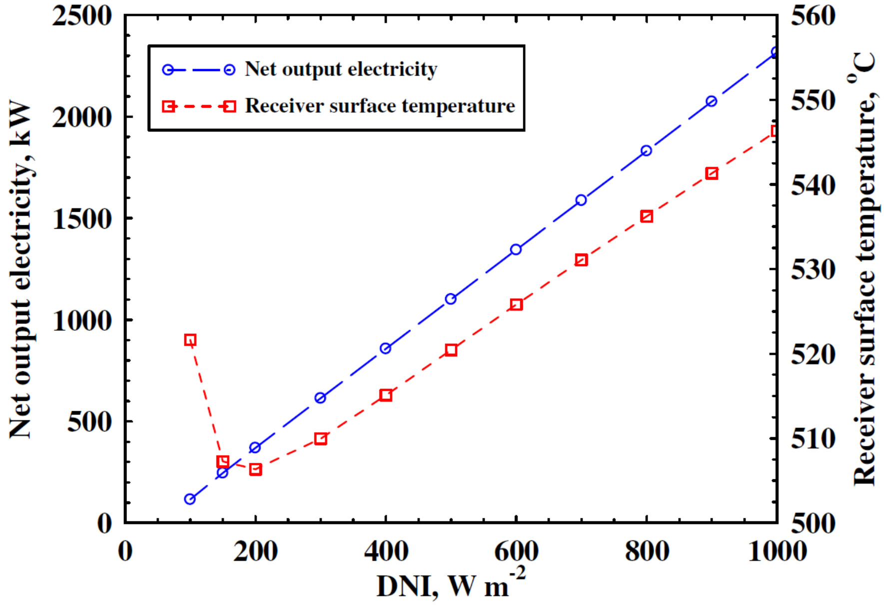

Fig. 3. Net output electricity and surface temperature of the receiver varying with DNI [1]

3. Results

3.1 Thermal Efficiency

Figure 4 shows the thermal efficiency of the receiver in the solar power generation system compared to the Direct Normal Irradiation (DNI) obtained from this research and the work of Xu *et al.,* [1]. The thermal efficiency increases with higher DNI values, where DNI ranges from 100 - 300 W/m^2, showing a rapid increase in thermal efficiency. Then, the thermal efficiency gradually increases as the DNI ranges from 300 - 700 W/m^2. At levels above 700 W/m^2, the thermal efficiency remains nearly constant.

At low DNI values, such as 100 W/m^2, the thermal energy efficiency of the receiver is low due to the limited amount of incident solar energy, resulting in limited energy conversion to thermal energy. Additionally, energy losses in various forms, such as radiation and conduction, may have a greater impact compared to the received energy.

As the DNI value increases, the amount of incident solar energy increases, allowing more energy to be converted into thermal energy, resulting in higher receiver efficiency. Furthermore, energy losses in various forms will have a lesser impact compared to the received energy, leading to overall improved efficiency.

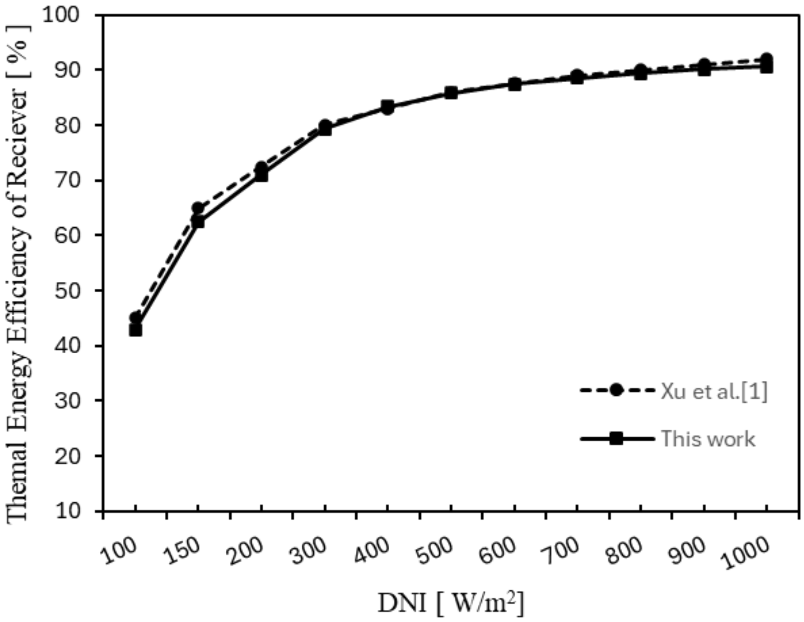

Fig. 4. Thermal efficiency of the receiver of the solar power generation system

3.2 Exergy Efficiency

Figure 5 presents the exergy efficiency of the receiver in a solar power generation system, compared to the Direct Normal Irradiation (DNI) obtained from this research and the work of Xu *et al.,* [1]. The exergy efficiency increases with higher DNI values, where DNI ranges from 100 - 400 W/m^2, showing a rapid increase in efficiency. Then, the exergy efficiency gradually increases as the DNI ranges from 400 - 700 W/m^2. At levels above 700 W/m^2, the exergy efficiency remains nearly constant.

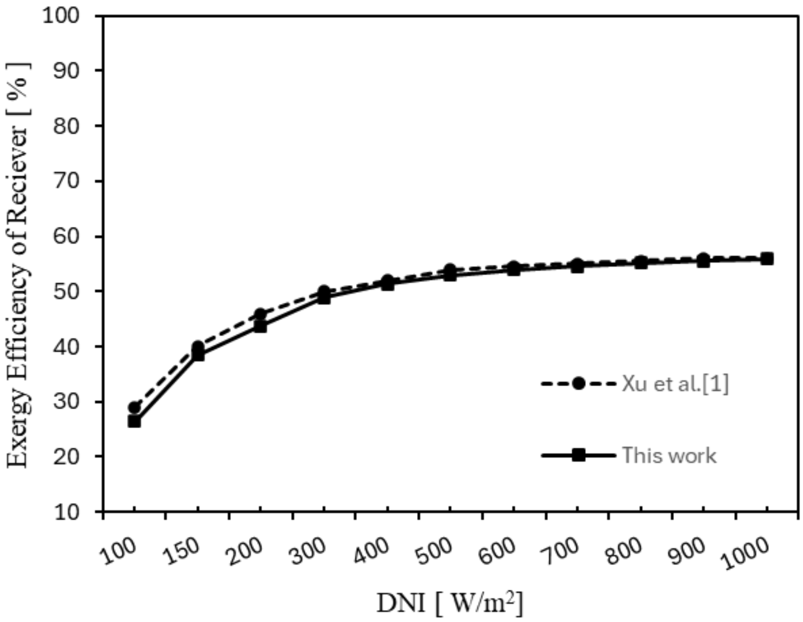

Fig. 5. Exergy efficiency of the receiver of the solar power generation system

In the initial range of low DNI values, such as 0 to 200 W/m², the exergy efficiency of the receiver is low due to several factors. When the DNI is low, the amount of solar energy incident on the receiver is limited, resulting in a restricted amount of energy that can be converted into exergy. During periods of low received energy, energy losses in various forms, such as radiation, conduction, and convection, have a more significant impact relative to the received energy, leading to lower overall efficiency.

As the DNI increases, such as from 200 to 1000 W/m², the amount of solar energy incident on the receiver increases, allowing more energy to be converted into exergy, resulting in higher receiver efficiency. Higher DNI values result in more solar energy incident on the receiver, allowing more energy to be converted into exergy, and at higher DNI values, the system operates at optimal efficiency due to appropriate settings and adjustments. Therefore, the exergy efficiency of the receiver increases as the DNI increases and stabilizes at higher DNI values when the system operates at its maximum efficiency.

When comparing the results of this study with those of Xu *et al.,* [1] it is found that the thermal efficiencies are closely aligned, with differences not exceeding 5%. Moreover, the results of both studies suggest that adjustments to certain variables may have led to better outcomes in current research. Furthermore, an in-depth analysis in terms of using different variables in each case study may help to understand the factors influencing these improvements more comprehensively.

4. Conclusions

Based on the energy and exergy analysis for a solar power tower plant using molten salt as the heat transfer fluid, the results can be concluded as follows. The thermal efficiency goes up fast when DNI is between 100 to 300 W/m^2. After that, it increases slowly as the DNI is between 300 and 700 W/m^2. The exergy efficiency also rises quickly when DNI is between 100 to 400 W/m^2, then it increases more slowly from 400 to 700 W/m^2. Above 700 W/m^2, both thermal and exergy efficiencies almost stay the same. These results can be used to improve the system efficiency and reduce energy losses and production costs. For the future, research should look into making materials for the central receivers that can stand higher temperatures, improving the power cycle efficiency with new processes like high-pressure steam, and finding ways to lower exergy losses in all parts of the system. This will help solar power tower plants become more efficient and lower costs in the future.

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