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Design considerations and construction of an experimental prototype of concentrating solar power tower system in Saudi Arabia

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ABSTRACT

A prototype of a solar power tower system was designed and constructed to produce electricity from solar energy. This prototype of a solar power tower system was constructed and installed at King Abdulaziz University in Saudi Arabia where solar intensity is excessive. Heliostats were implemented to capture the solar rays during daylight. These mirrors are used to direct the solar energy to a solar receiver that is made of alloy steel so that thermal energy is conveyed to a thermal fluid inside the receiver. Based on a detailed selection procedure presented in this article, a final number of ten heliostats were chosen to direct the solar energy to the solar receiver. In addition; two motors were used to control the heliostat rotational and elevation movements. The thermal fluid is a molten salt mixture (which consists of 60% $NaNO_3$ and 40% KNO_3). Cold and hot storage tanks were manufactured from steel and they were insulated with calcium silicate from all sides. A one-meter high and one and a half-meter cylindrical vessel was adopted for each of the cold and hot tanks. In this article, a detailed design analysis of each component is presented. The thermal power transferred to the water in the heat exchanger as it is heated by the molten salt was measured and found to be 11.26 kW. The thermal power given by the molten salt in the heat exchanger was also measured and found to be 12.31 kW. The design thermal power was 13 kW. The percentage error in the thermal power obtained is about 5.3%.

1. Introduction

A solar tower power plant as a means for converting solar energy into electricity is mentioned widely in the literature. The possible usage of concentrating solar power plant technology was assessed by many researchers [1–6]. Al-Soud and Hrayshat [1] proposed and simulated a system of a 50 MW CSPP to generate electricity and performed and documented the feasibility of this system. Vallentin and Viebahn [7] investigated the possible contribution of concentrated solar power (CSP) in Africa and Europe. They concluded that an installed capacity of 120 GW, 405 GW or even 1000 GW could be reached globally in 2050 in which CSP will meet 13–15% of global electricity demand. They discussed the cost reduction goal in Spain and Algeria as examples, and they showed that greenhouse gases emissions from CSP could be reduced to 18 g CO_2-eq/kW h in 2050. Boudaoud et al. [8] stated that solar tower power plants using molten salts will play an important role in producing electricity in the future.

During the last decade, the utilization of central receiver systems (CRS) gained attention and momentum because of the drastic increase in the price of fossil fuels and due to the environmental effects caused by burning these fossil fuels. Thus, the R&D activities in this area have become an interest of many researchers. It is difficult to summarize all these activities since the CRS systems involve many subsystems that come from different disciplines. However, there are some articles that have good reviews in this field such as [9–13]. Xiudong et al. [14] stated that the solar tower power plant is considered one of the cheapest methods to produce solar electricity on large scale. Generally, five main components comprise an energy block of a central receiver system (CRS): thermal storage tanks; heat transfer fluid; heliostats; receiver; and control [15]. Benammar et al. [16] modeled and simulated a four-main component solar tower power plant: the tower; the heliostats; the steam generator; and the Rankine cycle. They excluded the energy storage component. A general schematic of the energy management block for such a plant is shown in Fig. 1.

Mirrors called heliostats are used in such plants to redirect the solar rays during the daylight to a solar receiver placed on top of a steel tower. Heliostats are controlled by computers to keep their reflective surface perpendicular to the divider of the angle between the directions of the sun and the target as seen from the mirror

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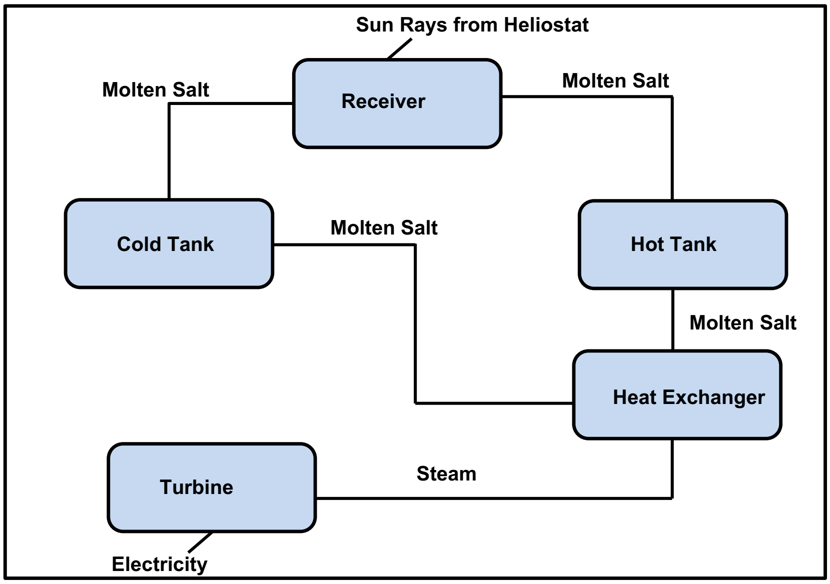
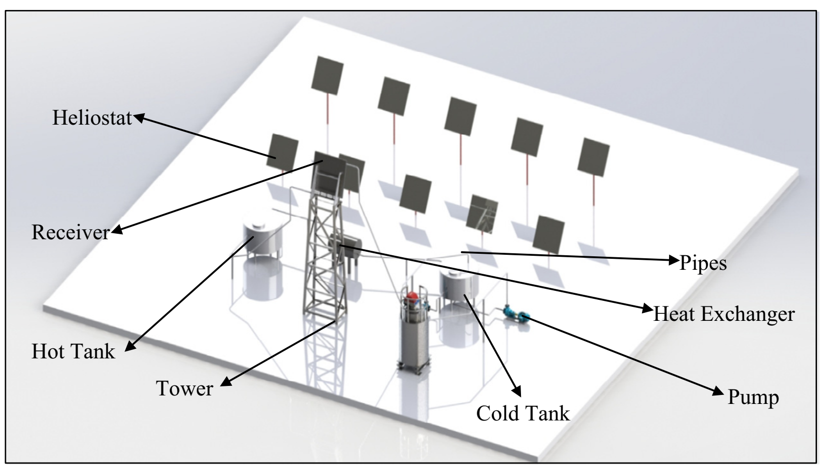


(a)



(b)

Fig. 1. (a) Schematic of the energy management block for the solar tower power plant, (b) schematic of the solar tower power plant prototype for the current study.

[17]. This CSP produces electricity by converting thermal energy carried by heat transfer to electrical power. Collado [18] has presented a simple model to estimate the amount of collected energy by the heliostat field. Huang and Xu [19] developed an algorithm that is capable of estimating the annual energy collected by the heliostat field with an error of less than 0.1% when compared with the method of ray tracing. Different power cycles can be used to convert the thermal energy into electrical power. Rankine cycle is the most popular one used in CSP. In these systems, the working fluid follows a closed loop. However, the utilization of Brayton cycle had also been investigated and documented. In this case the working fluid is a gas; such as air in closed cycles and Nitrogen in open cycles.

Using molten salts as a transfer fluid gave advancement to CSP which enable these systems to store energy and thus operate 24/7. Thus, large tanks filled with molten salts became an icon in such systems. Zalba et al. [20] have done an extensive study on the phase change materials (PCMs) used in latent heat storage systems and they showed the effectiveness of this procedure in storing thermal energy. Yang and Garimella [21] found clear effects of molten-salt by the boundary conditions of the environment to which the tanks are subjected. They developed a complete model for investigating the influences of boundary conditions on thermo cline performance. They found that under non-adiabatic boundary conditions the heat loss from the tank defaced the salt flow and temperature distributions compared to the steady conditions existing in adiabatic thermo clines. They also studied the effect of Reynolds numbers on discharge efficiency of thermo clines under non-adiabatic and adiabatic boundary conditions. When large heat loss at the walls existed, they found that the efficiency of discharge of thermo clines under non- adiabatic boundary conditions increased with the increasing Reynolds number. Ju et al. [22] proposed a new hybrid storage system to control the essential deficiencies of the thermos cline storage system. They concluded that a CSP plant that uses their storage system will be capable of constantly operating and producing steady power even though it operates under adverse weather. Mao [23] conducted a thorough review of geometrical configuration of thermal energy storage tank by citing the relevant theoretical and experimental studies in this area. Almsater et al. [24] achieved a great improvement in the thermal performance of a storage system through employing heat pipes fitted with axial fins compared to having plain heat pipes. Herrmann et al. [25] carried out an engineering study to assess the use of molten salt as another less expensive liquid medium