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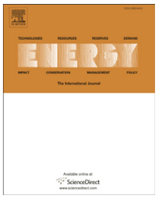

Thermodynamic and economic assessment of a new generation of subcritical and supercritical solar power towers

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ABSTRACT

The feasibility of using more efficient Rankine power blocks in solar power towers (SPTs) with molten salt as the heat transfer fluid has been studied as a method for increasing the global efficiency of these power plants. The temperature and pressure of the main steam and the reheating pressure affect the temperature of the molten salt in the receiver; for temperature increase decreasing the receiver efficiency and increasing the power block efficiency. Therefore, a detailed study of these SPTs has been conducted to determine whether the proposed changes increase the global efficiency of the SPTs.

A total of eight different subcritical and supercritical SPTs have been investigated. To set the most important cost of the SPT, the same heliostat field has been used. The receiver geometry has been optimised for each SPT to maximise the heliostat-receiver efficiency, fulfilling the material limitations.

It has been observed that the pressure at the inlet of the turbine increases the SPT efficiency even more than the temperature. However, special attention has to be paid to the reheating pressure, which is the most influential factor on the SPT efficiency. A high reheating pressure considerably decreases the SPT efficiency. Therefore, the best efficiencies have been obtained for the supercritical SPTs with a low reheating pressure and high temperature. It is closely followed by subcritical SPTs at high pressure and temperature.

The investment cost of the different SPTs also increases with the pressure and the temperature of the PB, with subcritical SPTs being less expensive than supercritical SPTs. However, the cost increase is balanced by the increase in the efficiency. The same cost per kW_e is found in subcritical SPTs working at 16 MPa and in supercritical SPTs with low reheating pressure.

1. Introduction

One of the main challenges of solar power towers (SPTs) is reducing the levelized cost of electricity (LCOE) to improve their competitiveness with conventional electricity generation. This can be achieved by increasing the overall efficiency of the SPTs [34]. The efficiency of a SPT can be approximately defined as the product of the efficiencies of the three main subsystems of the plant, namely, heliostat field, receiver, and power block (PB), as shown in Equation (1). Optimization on terms of efficiency has to be focused on improving at least one of these subsystems without negatively impacting on the others. A schematic of the main subsystems of a SPT can be seen in Fig. 1.

$$\eta_{SPT} = \eta_{field} \cdot \eta_{rec} \cdot \eta_{PB} \tag{1}$$

Over the past decades, numerous proposals to increase the efficiency of the different subsystems of SPTs have been investigated. For example, Sánchez and Romero [31] developed a methodology to create heliostat layouts based on the yearly energy available, and Boerema et al. [9] and Rodríguez-Sánchez et al. [27] investigated new receiver designs using different tube diameters and bayonet tubes, respectively. Neises et al. [18] tested new materials for the receivers, Boerema et al. [8] compared different heat transfer fluids (HTFs), and McGovern and Smith [16] studied the effects of increasing the outlet temperature of the HTF to employ a

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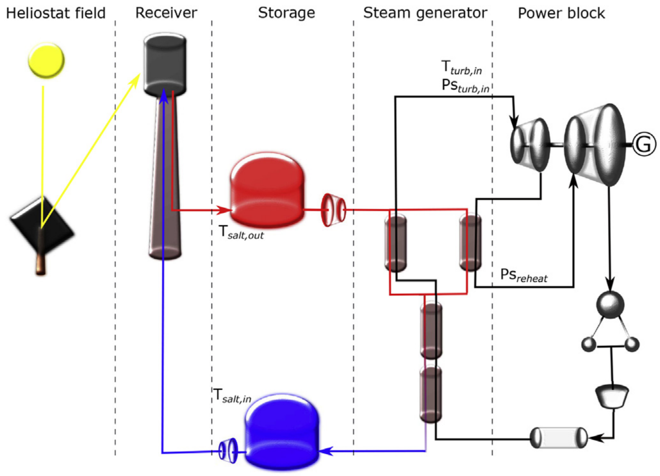

Fig. 1. Schematic of the main subsystems of a solar power tower plant.

supercritical steam PB.

Modern turbines can work at high pressure and temperature, thus increasing the efficiency of the PB with respect to traditional subcritical turbines. It should be taken into account that the advantage of supercritical steam can vanish for mid-scale power plants, around 20–25 MW_e. For small flow rate and low specific volume of steam, as in the case of mid-size turbines and supercritical water pressure respectively, the flow coefficient is low and hence lead to low turbine efficiency [7]. Despite this, it is feasible to adapt existing mid-turbines for supercritical steam in mid-size solar power plants [21]. Singer et al. [35] noted that these turbines could be integrated in power plants with central receiver technology; he studied external and cavity receivers working at 565 °C, 600 °C and 620 °C in several 125 MW_e SPTs, obtaining improvements of approximately 2% in the global plant efficiency; however, they did not obtain a reduction in the LCOE. Neises et al. [18] analysed the driving factors of a SPT, whose HTF was CO_2 at 25 MPa and 650 °C, to investigate the viability of these SPTs. Kolb [13] examined the implementation of a modern PB in a hypothetical 1000 MW_{thl} SPT that would use molten salt as the HTF; he found improvements of 5.4% in the efficiency of the advanced SPTs, although the optical efficiency of the field decreased with the size. Pacheco et al. [21] analysed 14 different subcritical and supercritical 250 MW_e molten-salt SPTs; they examined the effects of modifying the pressure and temperature of the steam, the final feed-water and the return temperature of the salt. Pacheco et al. [21] found that supercritical SPTs have better efficiencies and lower LCOEs than subcritical SPTs. These results were supported by Peterseim and Veeraragavan [22] for 250 MW_e SPTs. Therefore, there appears to be a disparity of results in the application of a supercritical PB in SPTs.

In this study, the feasibility of increasing the global SPT efficiency by improving the PB efficiency has been analysed. A Crescent Dunes-like 110 MW_e subcritical SPT has been compared with other seven subcritical and supercritical SPTs, which possess the same heliostat field size. The analysed SPTs are the combination of different steam pressures (12, 16 and 24 MPa) and temperatures (548 and 580 °C). Moreover, in the supercritical PB, two different reheating pressures (7 and 4.5 MPa) have been tested.

The optimum receiver design has been selected for each studied case, following the design guidelines proposed by Rodríguez-Sánchez et al. [30]. Furthermore, in agreement with the operational conditions of the receiver, different receiver feed pump systems have been selected for each of the analysed SPTs [28].

The heliostat-receiver efficiency using an advanced PB has been studied not only for the design point (nominal load) but also for the entire range of operational conditions covered by the receiver. Finally, the investment cost of each SPT has been calculated to evaluate the viability of the different configurations analysed.

2. Description of the SPTs studied

In this work, different molten-salt SPTs have been analysed to find the SPT design that maximises the global efficiency of the plant and minimises its investment cost. The reference SPT is a 110 MW_e subcritical plant with a solar multiple of 3.8 based on Crescent Dunes [19], located in Tonoas at 38.24°N latitude and 117.35°W longitude. The steam turbine operates with a rated output of 125 MW and a speed of 3600 r. p.m. The inlet temperature and pressure of the turbine are 540 °C and 11.6 MPa, respectively. Moreover, it has three bleeding at pressures of 3.9 MPa (HP turbine), 0.15 MPa (LP turbine) and 0.04 MPa (LP turbine) and a final exhaust condensing pressure of 0.013 MPa; where the pressure of the first bleeding corresponds to the reheating pressure.

The reference SPT (Sub1) has been compared with seven other SPTs. In these plants, the temperature and/or the pressure of the steam at the inlet of the turbine and in the reheat have been modified, as shown in Table 1.

The design point selected for all the SPTs is the spring equinox at solar noon [36]. The same heliostat field has been used for all the SPTs analysed. Therefore, depending on the temperature and pressure ranges of each SPT, the net power has different values. The heliostat field consists of is 10,301 rectangular mirrors, 11.28 m width and 10.36 m height, surrounding the tower. Crescent Dunes' field layout has been gathered from scaled aerial images. Each heliostat is gathered by 35 flat facets, which gives the curvature needed to reduce the spillage losses.

Note that the inlet and exit conditions of the molten salt in receivers Sub3 and Sup3 and in receivers Sub4 and Sup4 are the same. Consequently, there are only 6 different receivers, and the difference in these SPTs is the PB. The different steam conditions correspond to the typical operating ranges of existing turbines [1,25]. Variations in the steam pressure and temperature also affect the HTF temperature on the receiver, as shown in Table 1.

The cylindrical external receivers are formed by vertical tubes arranged in panels. The base of all the analysed receivers is situated on a tower that is 180 m high. All the studied receivers employ solar salt (60% $NaNO_3$ - 40% KNO_3) as the HTF, whose properties has been calculated using the equations pointed by Zavoico [37]. Olivares [20] reported that solar salt in atmospheric air and temperatures lower than 650 °C has a constant nitrite-nitrate ratio, and above that temperature, there is an important decomposition of the salt. However, none of the investigated SPTs exceeded the maximum allowable temperature of 650 °C.

All the receivers are 20.5 m high, with an aspect ratio of 1.14, which is within the recommended range [14]. The remainder of the

Table 1
Main parameters of the eight subcritical and supercritical SPTs analysed.The reheating pressure has been selected according to Alexe and Cenusa [1]; Retzlaff and Ruegger [25], and the PB block efficiency has been obtained from Sano [21]; Pacheco et al. [33].

	Sub1	Sub2	Sub3	Sub4	Sup1	Sup2	Sup3	Sup4
$T_{salt,in}$ [°C]	290	290	307	307	405	405	307	307
$T_{salt,out}$ [°C]	565	600	565	600	565	600	565	600
$T_{turb,in}$ [°C]	548	580	548	580	548	580	548	580
$Ps_{turb,in}$ [MPa]	12	12	16	16	24	24	24	24
Ps_{reheat} [MPa]	3.5	4.66	3.5	4.66	7	7	4.5	4.5
η_{PB} [%]	39.4	40.1	42.2	42.9	44.6	45.2	43.8	44.6

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