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Experimental analysis of charging and discharging processes, with parallel and counter flow arrangements, in a molten salts high temperature pilot plant scale setup

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HIGHLIGHTS

- Charging and discharging processes are evaluated in a two-tank CSP facility at pilot plant scale.
- Two flow arrangements, counter flow and parallel flow are analyzed and discussed.
- Two different temperature ranges are analyzed and discussed.
- 1000 kg of molten salts is used as thermal energy storage (TES) material.
- Therminol VP-1 is used as heat transfer fluid (HTF).

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ABSTRACT

Despite the fact that there are some commercial concentrated solar power plants worldwide, there is currently a lack of experimental reports about the operational characteristics of this type of plants. Therefore, a two-tank molten salts thermal energy storage (TES) pilot plant at the University of Lleida (Spain) was used to analyze charging and discharging processes under real conditions. In this facility, 1000 kg of molten salts are used as TES material and Therminol VP-1 is used as heat transfer fluid (HTF). This facility is equipped with measurement equipment which allows an exhaustive analysis of the processes. In this study, the fact of varying the flow arrangement in the heat exchanger (parallel and counter flow arrangements) and the temperature difference between the molten salts and the HTF have been studied and discussed in terms of temperature profiles, energy and power stored/released from/to both HTF and molten salts, efficiencies and effectiveness. The best working conditions found were counter flow arrangement with a temperature grading of about 65 °C.

1. Introduction

Since 2010, generation of solar thermal electricity from concentrated solar power (CSP) plants has strongly grown worldwide. These plants generate electricity from renewable energy sources while producing no greenhouse gas (GHG) emissions, so it is considered to be a key technology to mitigate climate change and to achieve the reduction goals of GHG. In addition, the flexibility of CSP plants enhances energy security. Pavlovic et al. [1] reviewed the existing CSP plants worldwide in order to identify their technical characteristics and operation conditions, and to extend their construction and use. Moreover, Reddy et al. [2] presented a state of the art of solar thermal power plants. They technically and economically compared three CSP plants case studies with different solar collection technologies in Indian tropical climates: parabolic through collector, parabolic dish collector and solar power tower. They concluded that parabolic dish with Stirling engine generates electricity at lower cost than the other technologies because of its higher efficiency, but has a lower yearly power output. In both studies [1,2], the parabolic through collector technology is highlighted as the most developed and mature technology in current commercially operating plants.

According to the International Energy Agency [3], when combined with thermal storage capacity of several hours of full-capacity generation, CSP plants can continue producing electricity when power demand steps up even when clouds block the Sun, after sundown or in early morning. This effect is known as peak

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Nomenclature

C	heat capacity, J/K
cp	specific heat, J/kg K
E	energy, J
$\dot{m}$	mass flow rate, kg/s
Q	power, W

Greek symbols

ΔT	temperature difference, °C
Δt	process length, s
ε	effectiveness of the heat exchange, –
η	efficiency of the heat exchange, –

Subscripts

act	actual
HTF	heat transfer fluid
in	inlet
max	maximum
min	minimum
out	outlet
salts	molten salts

shaving (Fig. 1). Zhang et al. [4] studied how thermal energy storage (TES) improved the competitiveness of the CSP technology in comparison with different fossil fuel fired backup systems. Those authors highlighted that accurate estimation of the direct daily solar irradiation is needed in order to design CSP and size TES or backup system, and concluded that in the future the solar energy contribution will increase due to technical improvement in solar collection and, in consequence, the required backup will be smaller.

Already in 2010, Medrano et al. [5] reviewed the experiences in TES for power generation, showing the case studies available in the early stage pilot plants (such as Solar One and Solar Two) to commercial cases (such as PS10). Recently, Liu et al. [6] reviewed the current CSP plants and their TES systems and found that, up to March 2015, the CSP market had a total capacity of 5840 MWe worldwide, among which 4800 MWe is operational and 1040 MWe is under construction. Spain had a total operational capacity of 2405 MW and 100 MW were under construction, turning out to be the world's leading country in CSP. Slightly less than half of the installed CSP capacity is integrated with thermal storage. However, taking a look to the facilities which are under construction, it is observed that over 80% of their capacity has energy storage.

Currently, the most developed and used TES system in commercial CSP plants is the indirect two-tank molten salt. This system uses as TES material the eutectic mixture of 60% of $NaNO_3$ and 40% of KNO_3, usually known as molten salts or solar salt, which are stored in two different storage tanks depending on their temperature level. Temperatures usually go from 292 °C at the cold tank to 385 °C at the hot tank. These operational temperatures are due to the salts melting temperature range and to the HTFs thermal stability limit (about 400 °C). TES processes in indirect two-tank molten salt are divided in three steps: charging, storage and discharging. During the charging process, the energy is collected by the heat transfer fluid (HTF) at the solar field (nominal temperatures of 391–393 °C), and transferred to the molten salts in the HTF-molten salts heat exchanger. Molten salts are pumped from the cold tank at 292 °C through the heat exchanger, arriving to the hot tank at a maximum storage temperature of 385 °C, where they are stored. When the energy stored is needed, the discharging process takes place, and the system operates in reverse form.

The behavior of all main components of the two-tank storage system, such storage tanks, have been widely simulated [7] and tested at different scales pilot plant [8,9] and at commercial scale [10] but not the heat exchanger. Hermann et al. [11] stated that heat exchanger should be designed within a small approach (3–10 °C) to maintain HTF supply temperature to the collector field during the charging process and minimize the performance penalty in the power block during the discharging process. Moreover, the heat exchanger should correctly operate under differential pressures between the HTF and molten salts side. Hence, it is crucial to understand the heat transfer process in HTF-molten salts heat exchanger in order to improve the performance and efficiency of the TES system and CSP plants.

Heat transfer processes in heat exchangers have been widely studied in the literature. Kakaç and Liu [12] showed the most common methods for the design, selection and sizing of different types of heat exchangers for different applications. The most widely used heat exchanger in commercial CSP plants is the shell-and-tube heat exchanger because of economic aspects [13]. Experimental and numerical work found in literature studied different features of performance of molten salts and HTF in shell-and-tube heat exchangers [14]. However, current CSP plants are starting to use plate heat exchangers because of their high thermal efficiency, compactness and flexibility against changes in

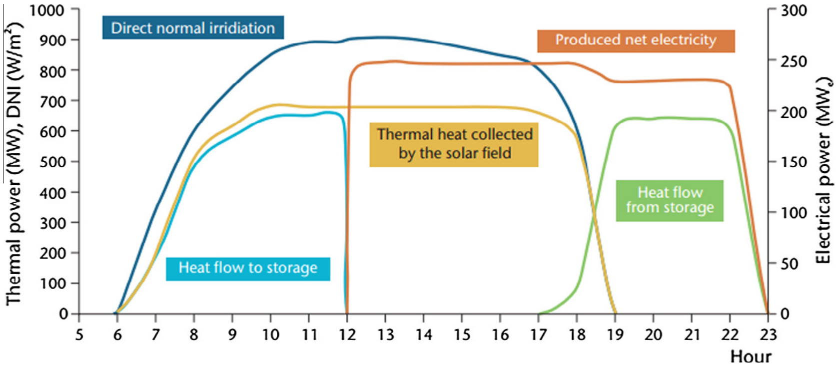

Fig. 1. Peak shaving due to the use of thermal energy storage [3].