Energy Conversion and Management 168 (2018) 320–328

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Mixing enhancement in thermal energy storage molten salt tanks

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ARTICLE INFO

Keywords:
Mixing
CFD
Numerical model
Thermal energy storage
Molten salts
Concentrated solar power plant

ABSTRACT

An appropriate degree of mixing in molten salt tanks for Thermal Energy Storage (TES) in Concentrated Solar Power Plants (CSPPs) is required in order to ensure the safe operation of the tank. Otherwise, cooling due to thermal heat losses is prone to result in a high thermal stratification of the salts and eventually local solidification. In this work, the mixing performance of different configurations of ejectors is investigated by means of Computational Fluid Dynamics (CFD). A set of different ejector configurations has been resolved, modifying the number of ejectors, flow direction, and ejector angle. The best configurations are identified, where the highest fluid circulation capacity is achieved by 10 ejectors directing the jet flow in the tangential direction with an inclination angle of 0° with respect to the tank bottom surface. This is increasing the fluid circulation capacity of the tank by more than 100% with respect to the usual configuration implemented in such tanks (ejectors directed to the tank central vertical axis, at 30° angle). In addition, such configuration ensures an enhanced flow circulation in the bottom part of the tank (with an increase of more than 6 times in the flow velocity in the lower section of the tank), reducing the risk of local salt solidification due to heat loss through the bottom surface. However, the shortest mixing times (95% and 99%) are achieved by the configuration with 10 ejectors pumping flow towards the central tank axis with an inclination angle of 0°.

1. Introduction

One of the promising technologies for renewable electricity generation is Concentrated Solar Power Plants (CSPPs). As an additional benefit, solar thermal power plants have the ability to store thermal energy, which enables the decoupling of the electric power generation from the intermittency of the available solar irradiation. Currently, commercial thermal storage systems are mostly based on a two-tank sensible heat thermal storage with molten salts.

A simplified sketch of a facility integrating such a Thermal Energy Storage (TES) system is presented in Fig. 1. The heated heat transfer fluid (HTF) from the solar field is sent towards the steam generation circuit, and/or to the TES system in order to increase its degree of charge. As mentioned previously, the TES system consists of two molten salt tanks, able to exchange salts via a heat exchanger heated by the HTF from the solar field. During charging operation, molten salts stored in the cold salt tank are heated by a side stream of the HTF not used for steam generation. The heated salts are stored in the hot salt tank until they are later needed when solar energy is not available. In order to heat the HTF, the TES system is used in the opposite or discharge mode, where the salts are transferred from the hot tank to the cold tank through the heat exchanger, heating the HTF which is then sent towards the steam generation circuit. It is worth to mention that some novel systems are being proposed using molten salts directly as HTF [1–3].

Molten Salts Tanks are typically cylindrically shaped tanks with over 20 m diameter [4]. An appropriate degree of mixing within the molten salt tanks is required in order to ensure a safe operation, which is obviously more important in the cold salt tank. Otherwise, despite the thermal insulation being used, cooling due to thermal heat losses are prone to result in thermal stratification of the salts and eventually partial solidification [5–8]. This is particularly important for long stops of the plant (such as during maintenance operations) where up to two-month duration can be expected. For such cases, tanks typically include electrical heaters installed in the bottom, in order to provide heat during long stops compensating the heat losses. Again, it is particularly important to ensure that the heat released by the electrical heaters is uniformly distributed within the tank, avoiding dead zones that could become local cold spots for salts solidification. Mixing could be achieved just by natural convection, but more often a set of ejectors are included in the tank, in order to induce a flow circulation and mixing within the tank volume. How to define the ejector configuration that enhance the mixing performance is the objective of this research work. The approach followed for achieving this objective is the development of a model based on Computational Fluid Dynamics (CFD), as experimental measurements in such large tanks during operation is highly prohibitive in terms of costs and technical difficulties. CFD is commonly

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https://doi.org/10.1016/j.enconman.2018.04.113
Received 27 February 2018; Received in revised form 27 April 2018; Accepted 29 April 2018

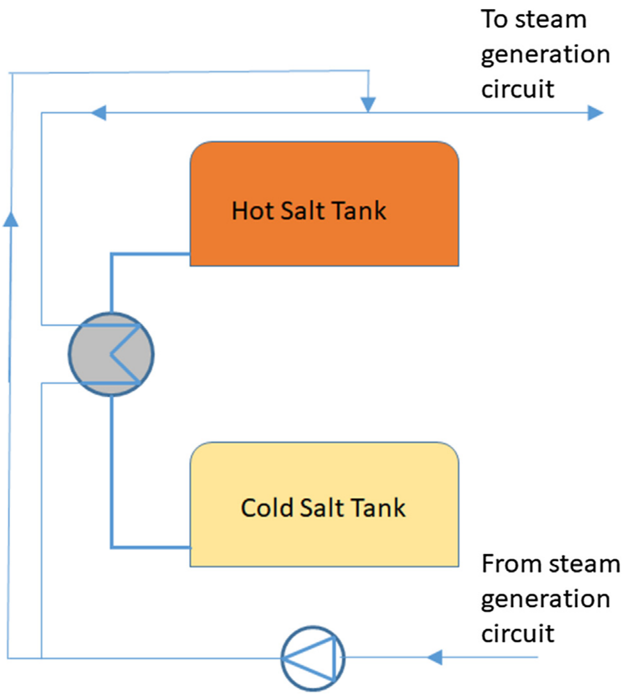

Fig. 1. Simplified Block diagram of for Thermal Energy Storage System for CSPP.

used for the design and research of fluid flow and heat transfer processes associated to CSP [9–12]. Regarding the particular investigations on molten salt tanks, Schulte-Fischedick et al. [13] carried out a 2D and 3D CFD analysis of the cool down behaviour of a molten salt thermal storage system (880 MWh storage tanks). Heat losses, velocities, and temperature distributions were analysed, revealing that the highest heat flux was found at the lower edges of the tanks, leading to local solidification after a relatively short period of time (3.25 days for the empty cool tank). Rivas et al. [14] also integrated the steam generator in a CFD model of a pilot-scale thermocline tank. The bulk and circulation of the molten salts inside the tank and steam generator with steam coils were studied in a transient 2D-axisymmetric simulation. Such works present very useful results relevant for TES tanks, but it is worth to mention that no previous works are found specifically studying the mixing characteristics of molten salts tanks for TES, despite the importance of such systems for the future deployment of solar thermal power plants. Therefore, the objective of this research work is aiming at the analysis and enhancement of mixing in thermal energy storage molten salt tanks.

2. Description of the tank

The tank under analysis is presented in Fig. 2, corresponding to a Cold Salt Tank. The tank diameter used in this study is 36 m, a relatively large tank representative of current technologies, where mixing is becoming relevant to ensure a safe operation. Considering a salt filling height of around 11 m, the tank could store 11.000 m^3 of salts, enough for roughly 2.5 full load operation of a 100 MW CSPP.

The tank is featuring two different salts injection piping rings (Fig. 2). The inner ring is perforated with roughly 100 holes and corresponds to the injection of salts from the charging heat exchanger (Fig. 1). This will be referred to as distribution ring. The outer ring corresponds to the injection of recirculation salts, i.e. salts that are extracted from the tank and injected again via a set of ejectors equally distributed along the ring, in order to achieve the mixing of the salts. This will be referred to as recirculation ring. Salts are pumped out of the tank via a vertical pipe (closest to the external wall in Fig. 2) to re-enter the tank via the recirculation ring.

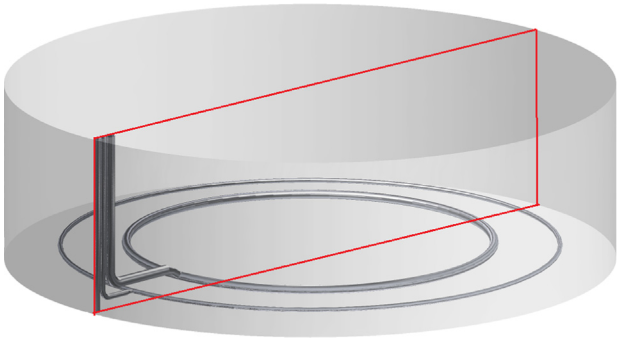

Fig. 2. Tank geometry and main components (inner injection ring, outer recirculation ring, extraction pipe). Symmetry plane depicted in red.

Given the tank symmetry with respect to the middle plane (in red in Fig. 2), the simulation of only one half of the tank is required.

3. Modelling methodology

The model has been developed in the commercial software ANSYS-CFX [15]. The salts used in the tank correspond to a mixture of 60% $NaNO_3$ and 40% KNO_3, where the physical properties of the mixture were obtained from Sandia technical report on CSP design [16] (see Table 1):

According to the data in [16], the following correlations for the physical properties can be derived, which were used for the CFD modelling:

$$\text{Density}(\text{kg/m}^3) = 2090 - 0.636\cdot\text{Temperature} \tag{1}$$

$$\text{Heat capacity}(\text{J/kg °C}) = 1443 + 0.172\cdot\text{Temperature} \tag{2}$$

$$\text{Thermal conductivity}(\text{W/m °C}) = 0.443 + 1.9\text{E}-4\cdot\text{Temperature} \tag{3}$$

$$\begin{aligned}\text{Viscosity}(\text{mPa s}) = {} & 22.714 - 0.120\cdot\text{Temperature} + 2.281\text{E}-4\cdot\text{Temperature}^2 \\ & -1.474\text{E}-7\cdot\text{Temperature}^3\end{aligned} \tag{4}$$

Where the unit of Temperature in Equations (1) to (4) is °C.The model will consider the tank at a high capacity (10.8 m height, which means 11.000 m^3 of salts) as this will be the case where mixing is more challenging for a given design. Salts temperature at typical design point of the cold salt tank (285 °C) is considered, with a recirculation flow of 650 m^3/h.

3.1. Correlations for mixing time estimation

Some preliminary estimations of the mixing times can be carried out based on the tank and ejector basic data and general correlations. As an example, as a first approximation it can be estimated that a free jet may entrain 15 to 20 times its pumped flow rate [17]. Assuming that mixing time (95%) is requiring five flow turnovers, this results in:

$$\theta_{M,approx} = \frac{5V}{20Q} \tag{5}$$

Table 1
Physical properties of 60% $NaNO_3$ and 40% KNO_3 molten salts at cold salt tank [16].

Temperature (°C)	Density (kg/m^3)	Heat capacity (J/kg °C)	Viscosity (mPa s)	Thermal conductivity (W/m °C)
260	1924.64	1488	4.343	0.492
288	1906.97	1492	3.558	0.498
316	1889.31	1497	2.929	0.503