Applied Energy 142 (2015) 56–65

Contents lists available at ScienceDirect

Applied Energy

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

Transient analysis of the cooling process of molten salt thermal storage tanks due to standby heat loss

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HIGHLIGHTS

- A CFD model is proposed to analyze the cooling process during standby periods.
- Different scenarios of thermal losses are considered in the analysis.
- Local crystallization is expected after 3 days in the worst case scenario.
- An adequate safe charging level is proposed to avoid the risk of freezing.

ARTICLE INFO

Article history:
Received 18 July 2014
Received in revised form 17 November 2014
Accepted 29 December 2014
Available online 13 January 2015

Keywords:
Molten salt
TES
Heat loss
CFD
Solidification

ABSTRACT

Molten salts consisting of 60% sodium nitrate and 40% potassium nitrate have been used successfully as a thermal energy collection and storage fluid in different solar thermal plants. However, the relatively high melting point of this mixture (221 °C) represents an important risk of local solidification in the operation of the solar power plants during standby periods. In this work, a computational fluid dynamics (CFD) model is developed to analyze the cooling process of representative state-of-the-art molten salt thermal storage tanks during these standby periods. A comprehensive set of operating conditions is analyzed, covering both hot and cold storage tanks, charging levels, and heat losses. Results show that the onset of local crystallization is highly influenced by the tank charging level. While the risk is relatively high in the case of the minimum charging level, in the case of maximum charging level the risk is minimal as it would require a very long standby period. To summarize the results, this work presents a safe charging level calculation, as a function of the operation temperature and the expected standby duration, which could be used as part of an appropriate operational strategy to avoid the risk of freezing for long standby periods. The model assumptions, the different configurations studied and their results are presented and discussed in detail.

1. Introduction

Solar thermal power plants use the sun's energy to generate electricity on an industrial scale. Concentrating solar thermal power is unique among renewable energy generators because, even though it is variable, it can easily be coupled with thermal energy storage (TES) [1]. The three major divisions within concentrating solar thermal power are parabolic troughs, solar towers, and dish Stirling technology. Most of the existing solar power stations (71.0%) use parabolic troughs to harvest solar energy, as it is a relatively mature technology compared to other technologies. Spain has the most solar thermal power installations in the world, with the U.S. ranked second [2]. As an example, Andasol-1 plant (located in Aldeire, Granada, Spain) is the first two tank indirect storage parabolic trough plant in the world to implement a molten salt thermal storage with a capacity of 49.9 MWe and 7.7 h of thermal storage [3].

The most commercially accepted thermal storage design is an indirect two-tank molten salt storage system where molten salt interacts with the solar field heat transfer fluid (HTF) through a heat exchanger. During the daytime, thermal energy from the solar field is used to maintain a steam turbine at full load and the rest of the solar field production is stored for later use. During cloud transients, storage is discharged to maintain it at full load until the clouds disappear. When the sun sets, storage is fully discharged for production during the night periods [3].

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http://dx.doi.org/10.1016/j.apenergy.2014.12.082
0306-2619/

Nomenclature

Symbols

D	tank interior diameter, m
L	tank height, m
H	molten salt charging level, m
t	time, s
T	temperature, K
Q	heat flux, W
q	heat flux density, W m^{-2}
ρ	density, kg m^{-3}
C_p	specific heat, J kg^{-1} K^{-1}
μ	dynamic viscosity, kg m^{-1} s^{-1}
λ	thermal conductivity, W m^{-1} K^{-1}
m	mass, kg
TES	thermal energy storage
HTF	heat transfer fluid
CFD	computational fluid dynamics
MAX	most unfavorable scenario (maximum heat losses)
MIN	most favorable scenario (minimum heat losses)

Subscripts

o	initial
ms	molten salt
b	bottom
w	wall
s	free surface
t	total
c	crystallization
s	solidification
max	maximum
min	minimum

Since much of this technology is new, there are still possibilities for improving designs and operation strategies. Some examples of these improvements can be found in Refs. [3–8] for CSP plants. Even though all of the currently installed TES systems in utility-scale solar electric plants store energy using sensible heat [1], latent heat storage at high temperature has also received attention recently [9–13] due to its potential to provide significantly enhanced storage quantities when compared to sensible storage systems of the same temperature range. Latent heat storage at low temperatures has also been investigated in many previous works, mainly for heating applications [14–17].

A technical alternative to the two-tank molten salt TES, is the one-tank TES system, within which a portion of the medium at high temperature is separated from a portion at low temperature by a thermocline. Thermal performance of the one-tank thermocline system has also received attention recently [18–20].

Binary molten salts consisting of sodium 60% nitrate and potassium 40% nitrate, with high thermal stability, have been used successfully as a thermal energy collection and storage fluid in different solar thermal plants. Detailed molten salt storage tank thermal models can already be found in open literature. Recently, various authors [21–23] investigated complete thermal models of the problem using diverse assumptions to obtain the thermal losses in a tank based on the geometry and operating conditions of the Andasol-1 commercial trough power plant. Schulte-Fischedick et al. [21] conducted a CFD analysis of the cool down behavior of molten salt thermal storage systems to obtain basic knowledge on heat losses, velocity and temperature distribution, in which the heat losses were previously established using the Finite Element Method (FEM). Zaversky et al. [22] developed a fully transient storage tank model based in the Modelica modeling language and simulated it over different reference days, providing typical weather conditions of a solar thermal power plant location as model input. Rodriguez et al. [23] modeled the molten salt storage tank for CSP plants using a modular object-oriented methodology that considers the transient behavior of the whole system. Although the tank geometry and operating conditions in [21–23] correspond to the Andasol-1 project tank geometry and operating conditions, the results in terms of the heat losses are different, due to the different methodologies and model assumptions used.

Even though the tanks are highly insulated, during standby periods due to maintenance or failure, the temperature of the molten salts inside the tanks (typically 386 °C and 292 °C for the hot and cold tanks, respectively, in parabolic trough collector plants [1,3]) decreases with time. The relatively high melting point of this mixture (238 °C and 221 °C for crystallization/solidification respectively) represents an important risk of local solidification during long standby periods. Molten salt solidification must be avoided because, besides the fact that represents the greatest cost of the TES (approximately 50%) [1], it would cause the collapse of the entire plant. Freezing of salt has to be avoided under all circumstances when unexpected operation conditions or plant outages occur.

While in the literature many works can be found related to the cooling process of water tanks for solar low-temperature applications [24–30], in which, due to the relatively small size of the tank, the flow is typically laminar, only few studies have investigated the cooling process of molten salt tanks, and a number of aspects of their thermal behavior such as the risk of local crystallization remain poorly analyzed.

To the author's knowledge, only in the forementioned work by Schulte-Fischedick et al. [21] are results regarding the onset of local solidification for three different tanks' charging levels reported, using pre-calculated convective boundary conditions. In the present work, a further CFD analysis is developed in order to evaluate the risk of local crystallization and solidification. A comprehensive set of operating conditions is analyzed, covering high and low operating temperature levels, charging levels, and heat losses. As a compendium of the results, a safe charging level calculation is additionally presented as an appropriate operation strategy to avoid the risk of freezing for long standby periods, as a function of the operation temperature and the expected standby duration.

2. Molten salt storage tank cool down process

In this section, the main variables affecting the cool down process of the molten salt storage tank are presented.

2.1. Thermal losses

Fig. 1 shows the sketch of a storage tank filled up to a level H with molten salt.

During standby periods, molten salt inside the storage tanks cools down due to heat loss to the environment. The total heat losses Q_{total} can be subdivided into their three principal components: bottom losses Q_b, wall losses Q_w and free surface losses Q_s.

$$Q_{\text{total}} = Q_b + Q_w + Q_s \tag{1}$$

Although thermal tanks usually include immersion heaters to prevent the salt from freezing in emergency situations [31], electrical