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Heat loss from thermal energy storage ventilated tank foundations

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Abstract

Thermal energy storage tanks are highly insulated in order to minimize the heat losses through the top and lateral walls and the foundation. Typical tanks of state-of-the-art solar power plants include a ventilation system within the foundation in order to ensure that the working temperature reached in the concrete remains below a maximum allowable value.

In the present work, a multilayer analytical model for the estimation of the tank's bottom heat losses in steady state is developed, including separately the quantification of the heat losses due to the ventilation system and the heat loss to the soil. A new correlation for the soil equivalent thermal resistance (which is unknown a priori) is previously obtained using a numerical model which is validated with the results of other authors.

A comprehensive parametric analysis of the variables of interest is made and a set of cases covering a wide range of tank geometries, insulation levels, storage temperatures and maximum allowed concrete temperatures are solved. Finally, the obtained results are summarized, providing a quick method for the estimation of the total bottom heat losses and its components (the ventilation heat losses and the heat loss to the soil). These results provide useful information related to the tank foundation design, such as the quantification of the evacuated heat due to the ventilation system or the selection of an appropriate bottom insulation thickness level depending on the tank geometry, the storage temperature, the ventilation system and the type of soil.

Keywords: TES; Heat loss; Soil; Foundation

1. Introduction

Concentrating solar power (CSP) is unique among renewable energy generators because even though it is variable, like solar photovoltaic and wind, it can easily be highly dispatchable. Most of the currently installed thermal energy storage (TES) systems in utility-scale solar thermal electric plants store energy using sensible heat, employing molten salts in an indirect two-tank design (Kuravi et al., 2013). The denominated cold and hot tanks are at two different temperature levels depending on the solar power plant (SPP) type (usually 292/386 °C for parabolic trough plants and 292/565 °C for central receiver plants). Even though the tanks are insulated, thermal losses from the tank to the environment (which occur through the tank's walls, the roof and the foundation), while relatively small, are important and must be analyzed and minimized during the TES design process in order to improve the TES efficiency.

Heat transfer through the ground has long been recognized as being a substantially more complex problem compared with that through components above ground

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Nomenclature

Symbols

A	tank bottom area (m^2)
C_p	specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
D	tank diameter (m)
N	number of nodes
Q	heat flux (W)
q	heat flux density ($W\ m^{-2}$)
R	tank radius (m)
R'	thermal resistance ($m^2\ K\ W^{-1}$)
T	temperature (°C)
x	radial direction (m)
z	axial direction (m)

Greek letters

k	material thermal conductivity ($W\ m^{-1}\ K^{-1}$)
λ	soil thermal conductivity ($W\ m^{-1}\ K^{-1}$)
ρ	density ($kg\ m^{-3}$)

Subscripts

avg	average
b	base
c	concrete
cv	convective
dom	domain
ext	exterior
ins	insulation
max	maximum
stg	storage
vent	ventilation
x_ext	x direction, nodes located below exterior air (Tables 2 and 3)
x_tank	x direction, nodes located below the tank (Tables 2 and 3)
x_total	x direction, total (Tables 2 and 3)

(Anderson, 1991). Due to the coupled nature of the problem, apart from the foundation construction characteristics, the soil properties also play an important role in the foundation heat losses. The thermal conductivity of soil is a major determinant of ground heat transfer: in first approximation the heat flow through an insulated floor is directly proportional to this quantity (Anderson, 1991).

A very important number of research efforts on ground-coupled heat losses applied to buildings can be found in the literature. Research on ground-coupled losses applied to buildings started during the 1940s and different analytical and semi-analytical methods for determining the earth-contact heat losses can be found in the open literature (Macey, 1949; Delsante et al., 1983; Hagentoft, 1988b; Anderson, 1991; Davies, 1993b). Numerical methods have been also developed to simulate complex systems, where the direct application of analytical solutions was not possible because of the simplifications that are required in order to produce a solution (Richards and Mathews; 1994; Zoras et al., 2001). Methods for the heat loss calculation of building structures in contact with the ground are also included in different design guides, such as ASHRAE (1997), CIBSE (1986), AICVF (1990) or CEN (1992).

Contrary to the case of ground-contact building structures applications, much less information can be found in the literature for high temperature tank foundation heat losses. In some works, different TES tanks sub-models are used as a part of a global model of a SPP to take into account the tank's heat losses in the calculations (Powell and Edgar, 2012; Mawire, 2013; Gabbrielli and Zamparelli, 2009; Rovira et al., 2011). However, in those sub-models, in some cases the simplifications are excessive (for example in Powell and Edgar (2012) it is assumed that no heat transfer occurs from the top or the bottom of each tank). In other cases either only an overall heat transfer coefficient is used to take into account the storage tank total heat losses (Mawire, 2013) (without distinguishing the contributions of the different parts: wall, top, bottom) or no information is provided in the methodology of obtaining the overall heat transfer (Gabbrielli and Zamparelli, 2009; Rovira et al., 2011).

More detailed thermal models to obtain the heat losses in TES tank's plants can be found in references Schulte-Fischedick et al. (2008), Zaversky et al. (2013) and Rodríguez et al. (2013). In these investigations, a tank based on the geometry and operating conditions of the Andasol-1 commercial trough power plant is analyzed and the heat losses are evaluated. Foundation consist of a thin steel layer followed by a thin layer of dry sand, a foam-glass insulation layer and an air-cooled concrete foundation designed to keep the concrete temperature below a maximum admissible value. Although the tank geometry and the operating conditions used were similar, the reported results in terms of the heat losses are different, due to the different methodologies and model assumptions used in each model. Particularly, the foundation heat losses obtained using these complete thermal models were in the range of 23–49 kW for the cold tank and 31–62 kW for the hot tank. These different results and the lack of specific studies applied to TES tank foundation heat losses, suggest the necessity of a more accurate calculation methodology of this ground-coupled heat transfer problem. In the present work, the classical problem of ground-coupled conduction is revised for estimating the foundation heat losses for the practical application of TES tanks.

2. Problem definition

A description of the studied problem is presented in the next paragraphs.