Applied Thermal Engineering 30 (2010) 2643–2651

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Analysis of the experimental behaviour of a 100 kW_{th} latent heat storage system for direct steam generation in solar thermal power plants

Rocío Bayón [a,*], Esther Rojas [a], Loreto Valenzuela [b], Eduardo Zarza [b], Javier León [b]

[a] Solar Concentrating Systems Group, CIEMAT-PSA, Av. Complutense 22, 28040 Madrid, Spain
[b] Solar Concentrating Systems Group, CIEMAT-PSA, Carretera de Senés s/n, 04200 Tabernas, Spain

ARTICLE INFO

Article history:
Received 5 February 2010
Accepted 12 July 2010
Available online 17 July 2010

Keywords:
Thermal storage
Phase change material
Latent heat
EG/PCM sandwich configuration
Direct steam generation
Solar thermal power plants
High temperature

ABSTRACT

A latent heat thermal storage prototype was tested under real working conditions with steam produced by a parabolic-trough collector test facility at the Plataforma Solar de Almería. The prototype contained KNO_3/$NaNO_3$ eutectic mixture as phase change material (PCM) and expanded graphite fins arranged in a “sandwich configuration” for improving thermal conductivity. In this paper, experimental data such as steam quality, PCM temperature distribution, stored/delivered energy and thermal power have been analyzed for a selected day. A mismatch between steam quality results and the corresponding PCM temperature/time curves has been observed. Furthermore, it has been noted that stored/delivered energy and the resulting thermal power are 40 $kW_{th}h$ and 50 kW_{th}, respectively, and hence, lower than the expected from design parameters. The reasons for these deviations seem to be deficient thermal insulation at the top of the prototype, use of working conditions other than design, and also thermal inertia introduced by excess PCM mass. In this paper, we also demonstrate the applicability of the *quasi static* model for describing the general performance of a latent thermal energy storage module with a sandwich configuration. In our particular case, the model fits the experimental data quite well when 8 W/mK is taken as the storage medium thermal conductivity. However, for a more accurate description, a sensible heat exchange term should be introduced in the model.

1. Introduction

Direct steam generation (DSG) in parabolic-trough solar collectors (PTC) is a promising technology for producing electricity by means of concentrated solar thermal energy [1]. Comparing with oil-based PTC technology, DSG process can significantly reduce the cost of electricity produced by solar thermal power plants. On one hand, both the expensive oil and the heat exchanger are eliminated. On the other hand, the use of water allowes increasing heat transfer fluid temperature (up to 550 °C) and hence power block efficiency. The feasibility of DSG technology at commercial scale has already been proven by the DISS projects [2].

Additionally, it is well known that the integration of a heat storage system into a solar thermal power plant could improve both performance and dispatchability [3]. Within the framework of the European DISTOR Project, one of the prototypes evaluated was a latent heat thermal energy storage (TES) module based on a “sandwich configuration” [4,5] and with a rated power of 100 kW_{th}. This prototype was installed at the Plataforma Solar de Almería (PSA) and connected to the DISS facility for testing under real working conditions with steam produced by a PTC loop. The test campaign performed at the PSA proved the feasibility of this kind of latent storage prototype when operating under real conditions [6]. A first evaluation of the experimental results published in a previous work showed that both energy and thermal power of the storage prototype were lower than expected from design parameters [7].

This paper presents a more detailed analysis of these experimental measurements and the main reasons for that unexpected behaviour are identified. Since these deviations are related to TES module design, some improvements for future prototypes are suggested. Additionally, a simplified analytical model, suitable when the storage medium is a composite, has been used to simulate the behaviour of this sandwich-configuration prototype. The general agreement between calculated and experimental data confirmed that this model can be used for designing such a TES module in a first approach. However, to describe every detail of TES behaviour over time, a more accurate treatment is needed. In this way this paper outlines some recommendations for improving the model.

* Corresponding author. Tel.: +34 913466447; fax: +34 3460939.
E-mail address: rocio.bayon@ciemat.es (R. Bayón).

1359-4311/$ – see front matter
doi:10.1016/j.applthermaleng.2010.07.011

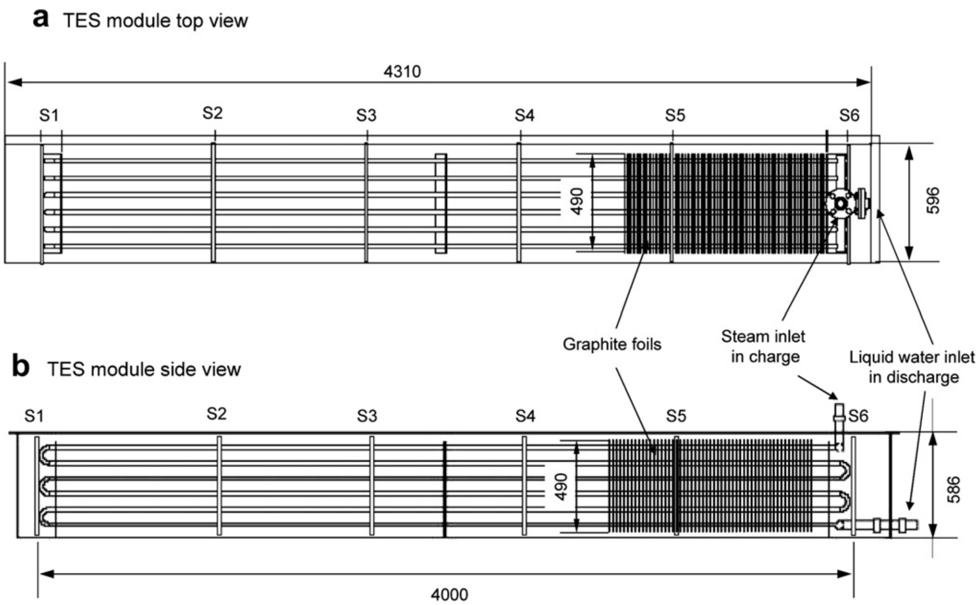

Fig. 1. Sketch of TES prototype dimensions: (a) top-view and (b) side-view (All dimensions are given in mm).

2. Experimental procedure

The storage prototype tested under real conditions consisted of a bundle of 36 parallel tubes comprised of six pipes arranged in six passes. The sketch in Fig. 1 shows a top-view of the TES module (a) and a side-view of the core (b). For the "sandwich configuration" module design the tube bundle is embedded in a block of PCM, the conductivity of which is enhanced by fins made of a conductive material [4,5]. A diagram of the PCM/fins sandwich configuration is shown in Fig. 2a. The PCM was 54%-w KNO_3/46%-w $NaNO_3$ eutectic mixture, and the conductive fins were 490 × 490 mm^2 1-mm-thick expanded graphite (EG) foil spaced 10-mm apart and perpendicular to the pipes (see Figs. 1 and 2). The storage prototype was filled with 2100 kg of PCM with a melting point of 221 °C and latent heat of fusion of about 100 kJ/kg [8]. This means that the maximum stored or delivered latent energy would be about 210 × 10^3 kJ or 58 $kW_{th}h$ and the expected charging/discharging time should be around 35 min for a design power of 100 kW_{th}.

In charge tests, the TES prototype was fed by saturated steam from the DISS-test facility parabolic-trough collectors through an inlet at the top (see Fig. 1) [2]. In discharge tests, saturated water entered through another inlet at the bottom of the prototype (see Fig. 2). Heat transfer fluid (HTF) parameters like mass flow ($\dot{m}$), inlet temperature ($T_{HTF\text{-}in}$) and inlet pressure (P_{in}) were recorded every 5 s during charge/discharge tests. Design working conditions were $\dot{m} = 0.080$ kg/s, saturated steam at $T_{HTF\text{-}in} \sim 235$ °C in charge mode and saturated water at $T_{HTF\text{-}in} \sim 200$ °C in discharge mode [6].

To evaluate the thermal performance of the TES prototype (i.e., thermal power and stored/delivered energy) HTF steam quality (x), and hence steam flow, at module outlet over time must be known. However, steam flow could not be directly obtained since a mixture of liquid water and steam was leaving the storage module. Therefore, to obtain the steam flow, a mixer fed with cold water was used to completely condense the TES outlet mixture and determine its enthalpy, from which steam quality can be calculated by applying an energy balance. The prototype test campaign lasted from the 15th of October to 12th of December 2007. Within this period it was possible to complete only 13 valid charge and 6 valid discharge tests because there were so many cloudy days [9]. Tests performed on the 8th of November were chosen for discussion of TES module performance

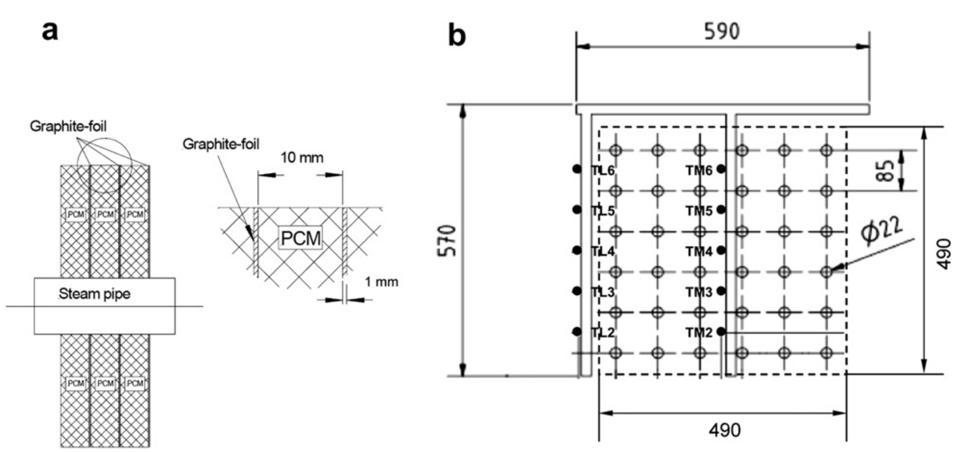

Fig. 2. Scheme of PCM/fins sandwich configuration (a) and tube bundle arrangement inside the storage prototype together with thermocouple positions in sections S2–S5 and graphite foil dimensions (b) (All dimensions are given in mm).