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Design and modeling of a high temperature solar thermal energy storage unit based on molten soda lime silica glass

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Abstract

The present article addresses the design, mathematical modeling and analysis of a high temperature solar thermal energy storage unit based on molten soda-lime silica glass. The 126 kW h_{th} storage unit is aimed to be used as one of the main components of a novel solar power-generation system intended for a continuous operation. The proposed design for the unit, as well as the restrictions imposed by its intended operation inside the power generation system, are thoroughly discussed.

The development of the mathematical model used to calculate the efficiency and performance of the thermal storage unit during the different stages of the work cycle as well as the assumptions and simplifications made are comprehensively explained. The results obtained through the model are exhaustively analyzed. Special attention is paid to the assessment of the behavior of the storage unit to guarantee that the functional requirements are met; the performance of the unit is not evaluated exclusively from an energy standpoint, but an in-depth exergy analysis is also presented.

The overall performance of the TES unit is satisfactory; the unit is capable of supplying the required 4 kW_{th} output throughout the 16-h discharge while it reaches its fully charged state during the subsequent 8-h recharge. The proposed designed for the TES unit exhibits a round trip exergy-efficiency of 59%.

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Keywords: Solar thermal energy storage; Soda-lime silica glass; Sensible heat storage; Thermal storage; Exergy analysis; High temperature energy storage

1. Introduction

Thermal energy storage is of paramount importance to solar based electric power generation systems inasmuch as one of the greatest obstacles encountered is the disparity that exists between the period of availability of the solar resource and the period of energy demand (Hasnain, 1998), which entails the need for an efficient method by which excess energy collected during periods of high solar irradiation can be stored and subsequently retrieved.

There are 3 methods by means of which thermal energy can be stored, being the first two the most broadly used: sensible heat storage (SHS), latent heat storage (LHS) and thermochemical storage. Sensible heat storage implies heating a material without causing a phase change to it; thermal energy is stored as a result of the temperature increase of the storage medium (Dincer and Rosen, 2010). Latent heat storage, on the other hand, involves

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Nomenclature

Acronyms

CSP	concentrated solar power
LHS	latent heat storage
PCM	phase change materials
SHS	sensible heat storage
TES	thermal energy storage

Symbology

A	cross-sectional area (m^2)
C_p	specific heat capacity (J/kg K)
F_{1-2}	radiation shape factor (%)
i	amount of solar radiation (kJ)
k	thermal conductivity (W/m K)
m	mass (kg)
Q	amount of heat transferred (kJ)
Q_{input}	total thermal energy supplied (kJ)
Q_{lost}	total thermal energy lost (kJ)
S	entropy at temperature T (J/K)
S_0	entropy at dead state (J/K)
T	temperature at which heat transfer occurs (K)
T_0	ambient temperature (K)
T_i	initial temperature (K)
T_f	final temperature (K)
T_{Sun}	temperature of the Sun (K)
U	internal energy at temperature T (kJ)
U_0	internal energy at dead state (kJ)
X	exergy of a closed system (kJ)
X_{dest}	total exergy destroyed (kJ)
X_{heat}	exergy transfer by heat (kJ)
X_{in}	total exergy entering the system (kJ)
X_{engine}	exergy supplied to the engine (kJ)
X_{lost}	total exergy lost (kJ)
X_{out}	total exergy leaving the system (kJ)
X_{rad}	exergy lost as radiation (kJ)
X_{sun}	exergy content of solar radiation (kJ)
α	absorptivity
Δt	time step (s)
ΔT	temperature change (K)
Δx	thickness of the element (m)
ΔX_{system}	exergy change of the system (kJ)
η_Q	energy based efficiency (%)
η_X	exergy based efficiency (%)

heating a material until it experiences a phase change; once the phase change temperature has been reached the material absorbs a large amount of energy, known as the latent heat, in order to carry out the transformation, storing thus the supplied heat (Sharma et al., 2009).

Heat storage through the use of phase change materials (PCM) appears to be a promising technology for the future due to the great benefits offered by LHS systems over SHS systems such as higher energy densities and operation at a nearly constant temperature (Zalba et al., 2003; Farid et al., 2004; Sharma and Sagara, 2005; Kenisarin and Mahkamov, 2007; Kenisarin, 2010). A vast amount of research efforts aimed at developing industrial scale LHS prototypes is currently ongoing (Steinmann et al., 2010; Laing et al., 2013; Johnson et al., 2015). However, the poor thermal conductivity of PCM, among other drawbacks inherent to their use, has held back their widespread deployment (Nomura et al., 2010; Liu et al., 2012, 2015; Cárdenas and Leon, 2013); consequently, sensible heat materials in the form rocks, concrete, synthetic oils and molten salts are still the most widely used storage materials in large scale concentrated solar power (CSP) plants nowadays (Fernández et al., 2010; Salomoi et al., 2014; Modi and Perez, 2014; Bauer et al., 2013; Laing and Zunft, 2015).

Authors as Gil et al. (2010), Medrano et al. (2010), Ushak et al. (2015), Bruno et al. (2015) and Steinmann (2015) provide a broader and more detailed overview of the state of the art of thermal energy storage for power generation.

Notwithstanding the advantages of latent heat based storage, there are materials such as soda-lime silica glass that possess a very attractive set of characteristics but their potential as sensible heat storage media has not been sufficiently explored yet. The main objective of the present research work is to design and develop a high temperature thermal energy storage based on molten soda-lime silica glass for driving on a 24/7 basis a commercial 1 kW_e Stirling engine within a novel solar power-generation system; laying thus, the groundwork on the usage of recycled soda-lime silica glass as a thermal energy storage medium.

1.1. The "ELECSOL-TD" solar power-generation system

As an effort to contribute to the global search for clean energy alternatives, the Monterrey Institute of Technology is working toward developing a domestic distributed power generation solution based on solar thermal energy capable of working continuously throughout the day.

Solar radiation is captured by means of a 30 m^2 Fresnel lens with a state of the art reflective blinds system; which reflect solar rays such that they strike in a completely perpendicular way onto the lens surface, allowing it to concentrate radiation on a spot (Ramírez, 2015). The concentration spot strikes onto the reception surface of a thermal energy storage unit (TES) which is the subject of

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